Forming limit prediction for AA7075 alloys under hot stamping conditions

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Abstract. In this paper, the forming limits of AA7075 demonstrators with different initial blank shape under hot stamping conditions were predicted using the developed model, named the viscoplastic-Hosford-MK model. The developed model enables the representation of non-isothermal conditions, changes in strain rate and loading path for AA7075 material. Additionally, the developed model was calibrated using the fundamental experiments including uniaxial and formability tests. To assess the capability of the proposed model, the forming limit of AA7075 with different initial blank shape designs were predicted, and the optimal initial blank shape was verified by applying it to the practical forming of a demonstrator AA7075 component.

1. Introduction
With the ever-increasing demand for fuel economy in the aeronautics industry, lightweight and high strength aluminum alloys such as AA7075 have been increasingly used. Research conducted into this material has predominantly focused on the development of manufacturing technologies to process these materials into complex-shaped components. However, the poor ductility of AA7075 at room temperature during processing, has required the development of novel forming technologies, such as Solution Heat treatment, Forming and in-die quenching (HFQTM). In the HFQ forming process, forming and heat treatment operations are performed as a single operation. The heated blank formed between a cold die and punch, results in complex forming conditions involving changes in strain rate, quenching rate and strain path which results in difficulties in modelling the process.

Previous FLD prediction models to predict the forming limit of metal alloys under complex forming conditions, have been comprehensively reviewed by Banabic (2010) [1] and Schwindt et al. (2015) [2] and include the Swift model [3], Hill model [4], the bifurcation analysis based models [5], the ductile fracture models and the Marciniak-Kuczynski (M-K) model [6].

In this study, a developed constitutive model named the unified Viscoplastic-Hosford-MK model was used to predict the forming limit of a high-strength AA7075 demonstrator component produced with a range of initial blank shape designs. The success of these blank shapes have been modelled by the proposed model, with the identified failure regions of each design being confirmed with experimental forming trials.
2. Model description

The proposed Viscoplastic-Hosford-MK model is a combined model incorporating the: viscoplastic material model, anisotropic Hosford yield function and MK model. To model the viscoplastic material response as a function of temperature and strain rate, a mechanism-based viscoplastic material model was utilised [7] and shown by Eqs. 1-10. The viscoplastic flow rules are expressed by Eq. (1) and (2). In Eq. (3), $R_{a,b}$ represents a dislocation-based material hardening term by accounting for the accumulation and annihilation of normalised dislocation density during material deformation as presented by Eq. (4). Additionally, the Arrhenius equations (Eq. (5-11)) are used to calculate the temperature-dependent parameters such as the $K, k, B, C, n_1$ and $E$ constants. In the equations, $n_2$ is a temperature-independent material constant. The anisotropic nature of the material is considered by using the Hosford yield criterion. R-values in the longitudinal ($R_1$) and transverse directions ($R_2$) in the proposed model are set to be 0.69 and 0.73, respectively.

$$
\dot{\varepsilon}_{p_{a,b}} = \left( \frac{\sigma_{a,b} - R_{a,b} - k}{K} \right)^n
$$

(1)

$$
\sigma_{a,b} = E \left( \varepsilon_{p_{a,b}} - \varepsilon_{p_{a,b}} \right)
$$

(2)

$$
R_{a,b} = B \rho_{a,b}^{0.5}
$$

(3)

$$
\dot{\rho}_{a,b} = A(1 - \rho_{a,b}) \dot{\varepsilon}_{p_{a,b}} - C \rho_{a,b}^{n_2}
$$

(4)

$$
K = K_0 \exp \left( \frac{Q_k}{R_s T} \right)
$$

(5)

$$
k = k_0 \exp \left( \frac{Q_k}{R_s T} \right)
$$

(6)

$$
B = B_0 \exp \left( \frac{Q_B}{R_s T} \right)
$$

(7)

$$
C = C_0 \exp \left( -\frac{Q_c}{R_s T} \right)
$$

(8)

$$
E = E_0 \exp \left( \frac{Q_e}{R_s T} \right)
$$

(9)

$$
n = n_0 \exp \left( \frac{Q_n}{R_s T} \right)
$$

(10)

$$
A = A_0 \exp \left( \frac{Q_A}{R_s T} \right)
$$

(11)

$$
R_2 \sigma_{11a,b}^{i} + R_1 \sigma_{22a,b}^{i} + R_1 R_2 \left( \sigma_{11a,b} - \sigma_{22a,b} \right)^i = R_2 \left( R_1 + 1 \right) \sigma_{p_{a,b}}^{i}
$$

(12)

Apart from the modelling of material behaviour, the forming limit of the material is assessed by the M-K model [8] with the assumption of a pre-existing imperfection in the material, denoted as zone $b$. The local thickness in zone $b$ is defined to be thinner than the nominal thickness, denoted as zone $a$. All the stress/strain states and associated parameters for zone $a$ (non-defect zone) and zone $b$ (defect zone) were interlinked by the compatibility and force equilibrium equations shown in Eq. (13-14) where the subscripts $a$ and $b$ represent the parameters in zone $a$ and zone $b$, respectively [9]. To estimate onset of necking, the onset of localised necking is defined as the strain increment through the thickness direction between zone $a$ and zone $b$ reaching a critical value, as shown in Eq. (15).

$$
\varepsilon_{2a} = \varepsilon_{2b}
$$

(13)
\[ \sigma_{ia} = f\sigma_{ib} \]  

\[ \frac{d\varepsilon_{ib}}{d\varepsilon_{ia}} \geq 10, \text{ or } \frac{d\varepsilon_{ib}}{d\varepsilon_{ia}} \geq 10 \]  

3. Experimental details

The uniaxial tensile tests over a range of strain rates and temperatures were conducted in order to calibrate the viscoplastic material responses of the alloy. For the uniaxial tensile test, the AA7075 blanks (thickness: 2mm) were supplied by Schuler Pressen GmbH, in the T6 condition (Solution heat treatment, cold worked and artificially aged). The high temperature isothermal forming limit tests [10] with different temperatures and forming speeds were used to calibrate the proposed model. In the formability test, the test-piece with designed geometry was formed by heating and subsequent stamping. The temperature of the specimens was measured via thermocouple in the forming trials. After the specimen was deformed, surface strain of the deformed part was measured using the ARGUS system provided by GOM. A range of initial blank shape designs were tested as determined from the proposed model. The test-pieces were first heated and soaked at 490°C for 1 minute in a furnace. The specimen was subsequently placed on the tool and formed at a temperature of approximately 480°C and a forming speed of 250 mm/s.

4. Results and discussion

The optimal material constants modelling the viscoplastic behavior, as shown in Table 1, were determined by calibrating to the uniaxial tensile tests. Figure 1(a) and (b) show a close agreement between the predicted and experimental results, with a maximum deviation of 10%.

![Figure 1](image-url)

**Figure 1.** Comparison of the predicted (solid curves) and experimental flow stress curves (symbols) for AA7075 (a) with different strain rates at 400°C (b) with different temperatures at a strain rate of 1/s.
Table 1. Material parameters for AA7075 using viscoplastic material model

| Parameter | AA7075 | Hosford-MK | MK | 
|-----------|--------|-------------|----|
| $K_0$ (MPa) | 0.0563 | 0.0563       | 0.0563 |
| $Q_K$ (J/mol) | 38268.400 | 38268.400 | 38268.400 |
| $k_0$ (MPa) | 0.716 | 0.716 | 0.716 |
| $Q_k$ (J/mol) | 1091.435 | 1091.435 | 1091.435 |
| $B_0$ (MPa) | 6.917 | 6.917 | 6.917 |
| $Q_B$ (J/mol) | 10287.800 | 10287.800 | 10287.800 |
| $C_0$ | 64.780 | 64.780 | 64.780 |
| $n_2$ | 5 | 5 | 5 |
| $Q_c$ (J/mol) | -16875.948 | -16875.948 | -16875.948 |
| $E_0$ (MPa) | 29584.300 | 29584.300 | 29584.300 |
| $Q_e$ (J/mol) | 2402.250 | 2402.250 | 2402.250 |
| $A_0$ | 125.080 | 125.080 | 125.080 |
| $Q_A$ (J/mol) | -2501.970 | -2501.970 | -2501.970 |
| $Q_{e1}$ (J/mol) | 3.408 | 3.408 | 3.408 |
| $Q_{e2}$ (J/mol) | 2382.062 | 2382.062 | 2382.062 |

Additionally, a comparison between FLD experimental results and Viscoplastic-Hosford-MK model results demonstrated a close agreement as shown in Figure 2(a) and (b). The symbols of Figure 2(a) and (b) represent the experimental forming limit curves (FLCs) and the solid lines represent the model results. It can be seen that the model captures the formability behaviour of AA7075 alloy, where formability increases with increased forming temperature and decreases at higher forming speed.

![Figure 2](image-url)

**Figure 2.** Experimental forming limit curves for AA7075 (a) at different temperature with a constant forming speed of 250mm/s (b) with different forming speeds at a constant temperature of 400°C

After calibration of the Viscoplastic-Hosford-MK model, the forming limit of a demonstrator AA7075 L-shaped component was predicted for three different initial blank shape designs. Using a trial-and-error simulation process, the initial blank shape design was optimized as shown in Figure 3. In Figure 3(d),
the blank shape design III was trimmed by two cutting stages, the areas of those cutting phases were presented by shaded areas.

**Figure 3.** Demonstration of Initial blank shape designs (a) Design I (b) Design II (c) Design III (d) Procedures of initial blank shape designs from Design I to Design III

To determine the success of the Viscoplastic-Hosford-MK model, the localised necking of the formed part was predicted including, the temperature, strain rate, and loading path data determined using PAM-STAMP software. The forming limit predictions of the formed parts with three different initial blank shape designs were obtained and presented by PAMSTAMP software in Figure 4.

**Figure 4.** Forming limit prediction of AA7075 L-shaped formed part using the proposed model with different initial blank shape designs: a) Design I, b) Design II and c) Design III

In Figure 4, it was predicted that “Design III” is the optimised initial blank shape design to form the L-shaped component with no predicted localised necking and minimal material usage. To verify the
accuracy of the prediction results, the initial blank shape “Design III” is applied into real forming tests at a forming temperature of 480°C and a forming speed of 250mm/s. Figure 5 shows the AA7075 successfully formed with optimised initial blank under hot stamping conditions without any occurrence of necking.

![Figure 5. AA7075 L-shaped part with determined optimal blank shape were formed at forming temperature of 480°C and forming speed 250mm/s.](image)

5. Conclusion
The forming limit predictions for the hot stamping of an AA7075 L-shaped component with different blank shape designs were made using the developed viscoplastic-Hosford-MK model. It was found that for the formed component, Design III was the optimal design. The design was successfully verified by forming tests.

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