Simulation of electrohydraulic free forming of DP600 sheets using a modified Rousselier damage model

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Abstract.
Electrohydraulic forming (EHF) is a high-energy rate pulsed forming process in which the expansion of the plasma channel formed by the discharge of electrical energy between two electrodes immersed in water results in the high-velocity forming of the sheet material. This process is shown to have the capability of increasing the formability of sheet materials beyond conventional limits and being applicable to less ductile materials. In this work, DP600 sheet specimens were deformed in uniaxial tension, plane strain and biaxial tension using electrohydraulic free forming (EHFF). A modified Rousselier ductile damage model was then employed to predict the forming and damage behaviour of these specimens deformed along each strain path. This modified Rousselier model includes a modified Johnson-Cook hardening model as well as a void nucleation function and a void coalescence criterion. The limiting strains, the distribution of the scalar damage variable and the final damage morphology obtained from the numerical simulations were compared to the experimental results in order to evaluate the accuracy of the proposed micromechanical damage model. It is shown that predicted strains, damage accumulation and the final damage geometry of DP600 sheet specimens using the modified Rousselier model are in good agreement with experimental results as well as with those predicted by other phenomenological constitutive models.

1. Introduction
The need for reducing the weight of the vehicles and better fuel consumption leads automotive manufacturers to employ advanced high strength steels (AHSS) and sophisticated aluminium alloys since they demonstrate a combination of good ductility, formability and high strength to weight ratio [1]. Their superior mechanical and forming properties are the result of their composite microstructure where a soft matrix provides sufficient ductility for the forming process while hard phases are responsible for strengthening of the sheet metal [2, 3]. However, sheet metal forming industry requires these engineering materials to show higher levels of formability. Therefore, high strain rate deformation has progressively gained interest in both academia and industry as an effective approach to increase the formability of sheet metals beyond their conventional limits, decrease wrinkling, and reduce springback [4, 5]. Different techniques and technologies such as explosive forming (EF), electromagnetic forming (EMF), and electrohydraulic forming (EHF) can be used to deform materials under high energy rate forming (HERF) processes [6, 7].

Electrohydraulic forming (EHF) is a high-energy rate forming process that directly convert electrical energy into mechanical force that can form a sheet material. In EHF, high-voltage
electrical energy stored in capacitors is discharged between two electrodes that are submerged in a water-filled chamber in order to generate a high-energy shock wave in the water and force the sheet metal into the die cavity. The entire process can be completed within a few hundred microseconds depending on the positioning of the electrodes and the applied energy. Different materials exhibit different forming and damage behaviour when they are deformed in free-forming (EHFF), as shown in figure 1, or die-forming (EHDF) conditions [8–10]. Samei et al. [11, 12] showed significant improvement in the formability of DP600 steel sheets subjected to EHF through the activation of different plastic deformation mechanisms in both ferrite and martensite. Jenab et al. [3, 13] investigated the deformation and damage mechanisms in AA5182 and showed that ductile damage mechanisms were suppressed as a result of die impact during electrohydraulic die forming. Moreover, Rohatgi et al. [14,15] used experimental and numerical methods to quantify the deformation behaviour of AA5182 and DP600 and analyse different strain paths a sheet material experienced when tested under EHFF and EHDF. On the other hand, Gillard et al. [7] and Hassannejadiasl et al. [8] focused on the numerical simulation of EHF to predict loading mechanisms and deformation behaviour of sheet metal specimens using a combined Lagrangian-Eulerian finite element models in ABAQUS and LS-DYNA. However, Maris et al. [9] performed a thorough study and utilized the Johnson-Cook (JC) hardening and damage models (as phenomenological functions) to design and optimize necessary specimen geometries for developing forming limit curves (FLCs) of DP600 and AA5182 under EHFF and then compared their experimental results with those obtained through quasi-static Marciniak tests. In this study, a complete micromechanical damage model which consists of a controlled void nucleation function and a void coalescence criterion along with a modified Johnson-Cook hardening function is used to predict and evaluate the formability and damage behaviour of DP600 sheet specimens subjected to EHFF at different strain paths.

2. Theoretical framework

The Rousselier continuous ductile damage model [16] is an elasto-plastic constitutive model that can predict the damage accumulation for flat to slant localization of porous materials using the void volume fraction ($f$) as a function of a cumulative damage variable ($\beta$). The plastic potential ($\varphi$) is given by:

$$\varphi = \frac{\sigma_{eq}}{1-f} - R(\varepsilon_p, \dot{\varepsilon}_p) + \sigma_1 D f \exp\left(\frac{\sigma_m}{(1-f)\sigma_1}\right) = 0$$

where $\sigma_{eq}$, $R(\varepsilon_p, \dot{\varepsilon}_p)$ and $\sigma_m$ denote the von Mises equivalent stress, flow stress of the material as a function of equivalent true plastic strain ($\varepsilon_p$) and true plastic strain rate ($\dot{\varepsilon}_p$), and mean stress, respectively. $D$ and $\sigma_1$ are damage model constants. The original Rousselier damage model does not consider any secondary void nucleation function and works based on cluster nucleation function in which an initial void volume fraction is introduced to the model at the beginning of the modelling. Recently, based on Chu and Needleman [17], a strain-controlled void nucleation rate is added to the void growth rate ($\dot{f}$) [18–21], as shown in equation (2).
\[ \dot{f} = 3(1 - f) \dot{\varepsilon}_m + A \dot{\varepsilon}_p, \quad A = \frac{f_N}{S_N \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{\varepsilon_p - \varepsilon_N}{S_N} \right)^2 \right] \]  

The plastic limit load (PLL) criterion proposed by Thomason [22] was considered as the void coalescence criterion, and Zhang et al. [23] proposed a function to evaluate the homogeneous deformation mode (\( \sigma_{I} \)) and localized deformation mode in the PLL model based on maximum principal stress (\( \sigma_{I} \)) and principal strains (\( \varepsilon_{I,II,III} \)):

\[ \frac{\sigma_I}{\sigma_{eq}} = \left[ \alpha_t \left( \frac{1 - 1}{\chi} \right)^2 + \beta_t \frac{\sqrt{1 - \pi \chi^2}}{\sqrt{\chi}} \right] (1 - \pi \chi^2) \]  

\[ \chi = \frac{3f}{4\pi} \exp(\varepsilon_I + \varepsilon_{II} + \varepsilon_{III}) \frac{1}{3} \left( \left( \frac{\exp(\varepsilon_{II} + \varepsilon_{III})}{2} \right)^{1/2} \right)^{-1} \]  

In equation (3), \( \alpha_t \) and \( \beta_t \) denote model constants and \( \chi \) is the void space ratio. Since accurate determination of matrix flow stress of the material has significant effect on the numerical prediction of both forming and damage behaviour during a forming process, a modified JC hardening model was utilized in the simulations, as shown in equation (5) [21, 24].

\[ R(\varepsilon_p, \dot{\varepsilon}_p) = (C_1 + C_2 \dot{\varepsilon}_p C_3) \left[ 1 + C_4 \left( \ln \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0} \right) C_5 \right] \]  

3. Results and discussion

To calibrate the Rousselier damage model and determine the constants in the modified JC hardening function, uniaxial tension tests were carried out in a wide range of strain rates from 0.001s\(^{-1}\) to 1000s\(^{-1}\) using ASTM-E8M specimens for quasi-static conditions and sub-size miniature dog-bone specimens for intermediate and high strain rates. Subsequently, the true stress-true strain curves were used to fit the rate-dependent hardening function, and a comprehensive parametric study was conducted based on different \( D \) and \( \sigma_1 \) values in various simulations to find the most accurate engineering flow curves of DP600 sheet specimens compared to experimental ones. Rahmaan et al. [25] presented more details about testing procedures, specimens and measurement techniques and Sarraf et al. [24] thoroughly described both calibration and fitting procedures. It is worth noting that the parameters for the strain-controlled void nucleation function were derived from Ramazani et al. [26] and Butcher et al. [27].

| Table 1. Rousselier damage variables and hardening parameters for DP600 sheet. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| \( D \) | \( \sigma_1 \) (MPa) | \( f_0 \) | \( f_N \) | \( \varepsilon_N \) | \( S_N \) | \( C_1 \) | \( C_2 \) | \( C_3 \) | \( C_4 \) | \( C_5 \) |
| 2.5 | 425 | 0.0007 | 0.02 | 0.35 | 0.11 | 225.35 | 850.16 | 0.3194 | 0.0037 | 1.5715 |

To simulate the EHFF process, DP600 metal sheets were modelled precisely based on actual testing conditions, tooling dimensions and the symmetry of the forming process. No significant planar anisotropy was detected for DP600 sheets [25], therefore, the test specimens were assumed to be isotropic. All tools in the finite element model were considered to be rigid bodies while the DP600 sheet specimen was modelled as a deformable body and was meshed using reduced integration three-dimensional Lagrangian solid elements (C3D8R in the ABAQUS element library). Figure 2 shows uniaxial tension (UT), plane strain (PS) and biaxial tension (BT) specimen geometries used for numerical simulations. The pressure on the sheet specimens was
modelled by as an exponentially decaying function of time proposed by Rohatgi et al. [15]. The proposed Rousselier damage model and the modified JC hardening function were implemented in a user material subroutine (VUMAT) that was employed in three-dimensional dynamic explicit finite element simulation in ABAQUS.

![Meshed specimen geometries](image)

**Figure 2.** Meshed specimen geometries used for finite element simulation of EHFF in (a) uniaxial tension (UT), (b) plane strain (PS) and (c) biaxial tension (BT).

The distribution of the Rousselier scalar damage variable ($\beta$) as a representative of damage accumulation in UT, PS and BT specimens under EHFF is shown in figure 3. It can be seen that the modified Rousselier model with modified JC hardening function could successfully predict the location and geometry of the strain localization in the middle of specimens in all three strain paths. In case of simulating UT, numerical results showed a diffused neck on the gauge section where the geometry of the deformation localization was predicted to be close to a line in the middle of the gauge area, but in BT specimen, the strain seems to be localized on the apex. Therefore, it is expected that the final failure commences from the apex in the latter case.

![Damage accumulation](image)

**Figure 3.** Damage accumulation at the onset of necking in (a) UT, (b) PS and (c) BT.

A time-dependent necking criterion proposed by Sarraf et al. [20] which works based on the second derivative of thickness strain, was employed to determine the limiting strains on the UT, PS and BT test specimens. In this method, an intersection between two bifurcation branches is obtained by considering two polynomial functions that are fitted to each branch of thickness reduction acceleration curve. Figure 4 shows the forming limit curves of DP600 sheet specimens obtained by experimental tests and that numerically predicted by the proposed Rousselier model and the bifurcation analysis. It can be seen that the formability of DP600 sheets is considerably improved under EHFF compared to the quasi-static condition as a result of the high strain rate deformation process. Moreover, the modified Rousselier damage model could predict the EHFF FLC of DP600 in an accurate manner particularly in UT and PS. However, it underestimated the necking strain in case of BT in a very small extent which is similar to the deviation observed by other researchers in their simulations [20, 26].
The distribution of damage on the BT test specimen obtained through numerical simulations and experiments is shown in figure 5. In this figure, two completely different simulation approaches are also compared: Hassannejadasl et al. [8] used Eulerian elements to model the interaction between the water and the sheet specimen, and defined the mechanical and damage behaviour of the deformable sheet material by the JC damage model as a phenomenological constitutive model (figure 5b), whereas in figure 5a, the modified Rousselier damage function as a micromechanical continuous model was employed. Both simulation methods predicted the onset of failure to occur on the apex area and propagated through the wall and edge of the specimen. It is worth noting that even the geometry of damage initiation and propagation predicted by the micromechanical and phenomenological damage models appears to be very similar. It can also be seen that there is a very good agreement between the final geometry of fracture predicted by numerical model and that of obtained via experiment.

4. Summary and conclusions

In this study, the performance of the modified Rousselier damage model, which includes a strain-controlled void nucleation function, a void coalescence criterion and the modified JC hardening model, was evaluated during electrohydraulic free forming (EHFF). In order to fulfil this goal, the ability of this model in predicting formability and damage accumulation of DP600 sheet specimens in three strain paths (UT, PS and BT) was assessed through comparing the distribution of the Rousselier’s scalar damage variable and EHFF FLC with experimental results. Similar to the phenomenological constitutive models, the proposed micromechanical model predicted that the strain localization and damage initiated in the centre of the gauge area and propagated along the wall and edges of the specimens. In case of BT, the severe fracture and
tearing were predicted around the apex area, as can also be seen in experimental observations. In addition, it is shown that the accurate calibration of the proposed damage and hardening models resulted in the successful and accurate prediction of limiting strains in UT, PS and BT, and subsequently the EHFF FLC of DP600 was compared to the experimental one. Therefore, the proposed model can effectively be used in other finite element models for future advances in predicting deformation history and damage behaviour during different metal forming processes.

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