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Evolution of plastic anisotropy and strain rate sensitivity

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Abstract. In this study, it is aimed to formulate a constitutive model accounting for the evolving features of the plastic anisotropy, in terms of both stresses and r-values, and the strain rate sensitivity during the plastic deformation. For the model calibration and validation, a bcc ferritic steel is selected. The material parameters are calibrated by tensile experiments under different loading configurations and different strain rates. Nakajima tests are conducted to characterise the cold formability of the selected steel. The model prediction is compared with the experimental results and it is concluded that the formability prediction is significantly improved when considering the evolving features during the plastic deformation.

1. Introduction
Metal forming at room temperature is one of the most frequent used production methods for component making in automotive industry. In addition to process optimization and tool design, the cold formability of metals is, therefore, the main concern from materials and mechanics perspective. Among many influencing factors, the formability permanence of materials is significantly correlated to the plastic flow behaviour. As the plastic deformation of metallic materials very often shows different levels of anisotropy, its accurate description is critical for the formability prediction. Meanwhile, plastic deformation of materials is also related to the loading rate. For the metal forming production in industry, the local strain rate can be at an intermediate region. Even for a quasi-static operations, the local strain rate can also be much higher once necking is triggered. Therefore, the strain rate sensitivity description of materials is another important factor to perform accurate prediction of the formability.

In the line of either constitutive modelling of plastic deformation or formability prediction, tremendous effort has been made on the development of anisotropy [1-3]. However, what is often overlooked is the evolving feature of these plastic flow behaviours during the deformation induced by microstructure evolution, e.g. the anisotropic hardening induced by texture evolution. Several individual contributions have been made on the anisotropic hardening topic [4-7]; however, a complete study considering both the anisotropy and strain rate sensitivity evolution is still missing. Therefore, in the current study, an evolving model considering the anisotropy and strain rate sensitivity evolution during plastic deformation is developed for bcc steels and it is further employed to predict the formability.

2. Modelling strategy
In this study, the basic modelling framework is based on the non-associated Hill48 model. The procedures concerning the choice of the model and its comparison with the non-quadratic associated models can be found in Ref. [7, 8]. The model is not exclusive to study the anisotropy and strain rate
sensitivity, but it provides a simple alternative to couple the evolution features of anisotropy without iterative optimisation of the anisotropic material parameters.

Based on the small strain theory and the rate independent evolving non-associated Hill48 (enHill48) model [7], the rate dependent formulation of the model is developed. The yield function and the flow potential are defined by:

\[ f = \tilde{\sigma}(\sigma) - \sigma_y(\dot{\varepsilon}_p, \dot{\varepsilon}_p^p) \leq 0 \]
\[ g = \tilde{\sigma}(\sigma) - \sigma_y(\dot{\varepsilon}_p, \dot{\varepsilon}_p^p) \leq 0 \] (1)

where \( f \) indicates the yield function while \( g \) is corresponding to the flow potential. \( \tilde{\sigma}(\sigma) \), in general, is a function of stress components, defined in Equation (3) and the subscripts of it are describing the method used for the calculation.

\[ \tilde{\sigma}(\sigma) = \frac{1}{2} [ F (\sigma_{22} - \sigma_{33})^2 + G (\sigma_{33} - \sigma_{11})^2 + H (\sigma_{11} - \sigma_{22})^2 ] + L \sigma_{23}^2 + M \sigma_{13}^2 + N \sigma_{12}^2 \] (3)

\( F, G, H, L, M \) and \( N \) are material coefficients controlling the anisotropy of the yield surface. In the enHill48 model, the stress-based method is used to calculate the yield function while the \( r \)-value-based method is used for the flow potential. Readers are referred to Ref. [7] for details. \( \sigma_y(\dot{\varepsilon}_p, \dot{\varepsilon}_p^p) \) is the flow curve of specific material as a function of the equivalent plastic strain (PEEQ) as well as the strain rate, as described in Equation (4).

\[ \sigma_y(\dot{\varepsilon}_p, \dot{\varepsilon}_p^p) = \begin{cases} A (\dot{\varepsilon}_p + \dot{\varepsilon}_0)^n \left( \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_0} \right)^m, & \dot{\varepsilon}_p > \dot{\varepsilon}_0 \\ A (\dot{\varepsilon}_p + \dot{\varepsilon}_0)^n, & \dot{\varepsilon}_p \leq \dot{\varepsilon}_0 \end{cases} \] (4)

The Swift law is used for the description of the isotropic hardening with the materials parameters, \( A, \dot{\varepsilon}_0, \) and \( n \). The strain rate effect is expressed by the power law equation with the strain rate sensitivity factor, \( m \). \( \dot{\varepsilon}_0 \) is considered as the reference strain rate, which is corresponding to the quasi-static condition in the experimental program. To account for the evolving features, all the material parameters are formulated as a function of the PEEQ.

\[ F, G, H, L, M, N, m = f(\dot{\varepsilon}_p) \] (5)

For the prediction of the forming limit curve, the Marciniak–Kucynski (MK) model [9] is employed, in which a virtual thickness imperfection is introduced as a groove behaving as material or geometric defects in a uniform sheet. The numerical implementation follows the algorithm proposed by Aretz [10]. For simplicity, only the positive minor strain side is investigated, i.e. the imperfection always aligns perpendicular to the major loading axis. The critical principal strains are determined once the incremental PEEQ of the groove zone B (\( \Delta \varepsilon^B \)) over uniform deformation zone A (\( \Delta \varepsilon^A \)) reaches 5.

3. Results and discussion

In this study, a ferritic stainless steel sheet (AISI 439) with 1 mm thickness was investigated. The steel was subjected to cold rolling and annealing production procedures resulting in a strong texture. Detailed microstructure information can be found in Ref. [11].

To characterise the anisotropic properties of the steel, tensile tests under the quasi-static condition and at room temperature were conducted along three loading directions, rolling direction (RD), diagonal direction (DD) and transverse direction (TD). The detailed data and calibration procedure for the enHill48 model can be found in Ref. [7]. In Figure 1, the experimental and predicted stress and \( r \)-value directionalities are compared. It is shown that the enHill48 model captures both directionalities quite well. More importantly, the steel shows very pronounced anisotropic hardening and minor \( r \)-value evolution during the plastic deformation, which is also well described by the model.

To characterise the strain rate sensitivity behaviour of the steel, tensile tests under different strain rates were conducted. In the current study, the quasi-static strain rate, \( 2.778 \times 10^{-4} \) s\(^{-1} \) is referred to as the reference strain rate and three higher strain rates, \( 1 \times 10^{-3} \) s\(^{-1} \), \( 1 \times 10^{-2} \) s\(^{-1} \), and \( 1 \times 10^{-1} \) s\(^{-1} \) are considered. The corresponding true stress–strain curves along the DD direction are shown in Figure 2 (a). The responses for RD and TD directions are similar, but due to the space limit, they are not shown here. It is obvious that a positive strain rate sensitivity parameter is found for the steel. The \( m \) value for different
strain rates are calculated along the deformation history and shown in Figure 2 (b). For all the investigated strain rates, the $m$ value starts with a relatively high value over 0.02 at the beginning of yielding. However, this value decreases significantly over the plastic deformation. At the uniform strain point, this value is below 0.01. This indicates that the strain rate sensitivity parameter has also a strong evolving character over the deformation history.

![Figure 1](image1.png)

**Figure 1.** Comparison between the experimental data and the prediction by the enHill48 model of (a) the stress directionality and (b) the r-value directionality of the AISI 439 steel.

![Figure 2](image2.png)

**Figure 2.** (a) The true stress–strain curves of AISI439 along the DD direction under different strain rates; (b) The strain rate sensitivity parameter $m$ for different strain rates over the deformation history.

It is noted that the flow stresses measured under the intermediate strain rates could be subjected to adiabatic heating condition or at the transition phase from the isothermal condition to adiabatic heating condition. Therefore, a direct manipulation of the strain rate response on these data could be less accurate without the correction of the thermal-induced softening.

For the cold formability characterisation, the Nakajima tests were performed according to the standard (ISO 12004-2). More details of the testing setup can be found in Ref. [12]. The final forming limit curves are presented in Figure 3 with two evaluation methods at necking, the visual method and the position-dependent method. The punch velocity of the Nakajima test was set as 30 mm/min, which would result in a general quasi-static condition for forming. However, the local strain rate of the sample, especially after the diffuse necking is triggered, could be high enough to give a non-negligible influence on the formability assessment. Therefore, an accurate model description of the strain rate sensitivity is necessary for the formability prediction. The numerical prediction by the MK model with different plasticity models is compared with the experimental results on the positive minor strain side. The first model coupled with the MK model is the non-associated Hill48 model, which agrees with experimental data quite well in the vicinity of the plane strain tension region, but diverges from the experiments in the biaxial tension region. When the evolving features of the steel during deformation are considered, it can be seen that the MK prediction improves significantly and agree well with the experimental data.
4. Conclusions

- The investigated bcc steel sheet shows a significant evolving character of the anisotropic parameters as well as the strain rate sensitivity parameter.
- A rate dependent evolving non-associated Hill48 model is developed to account for the anisotropic hardening and the r-value evolution as well as the strain rate sensitivity evolution. The model is further applied to predicting the forming limit curve.

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Figure 3. The forming limit curves measured by the Nakajima tests at the instant of necking based on visual and position dependent method and the prediction by the MK model with different plasticity models for the AISI 439.