Numerical Analysis of Anisotropic Sheet Metals Based on Non Associated Flow

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ABSTRACT

A numerical analysis based on associated flow rule (AFR) and non-AFR (NAFR) are presented and applied to forming of anisotropic sheet metals. The models are defined in the quadratic form of the Hill'48 anisotropic function under a general three-dimensional stress condition. The anisotropic parameters for the yield function are identified using the directional planar yield stresses, bulge yield stress and shear yield stress, while those for the plastic potential function are identified using the directional r-values. Three different models were implemented into the finite element code, using a dynamic-explicit analysis. Two models (r-values based and **σ**-based) related to AFR and a full expression related to the non-AFR are analyzed for the cup drawing test. Capabilities of the developed model for predicting the anisotropic behavior of sheet metal are investigated by considering cup heights obtained from the simulations. Numerical results were compared with experimental data. Such comparisons and other studies demonstrate that the developed material model considering 3D conditions can improve accuracy when predicting the anisotropic behavior. Furthermore, the simple formulations are efficient and user-friendly for computational analyses and to solve common industrial sheet metal forming problems.

Keywords: Dual-Phase Steels, Sheet Metal Forming, Limiting Drawing Ratio, Swift Test, Deep Drawing Cylindrical Cup

INTRODUCTION

The use of suitable material models is a key point on finite element analysis, for an accurate numerical modeling of sheet metal forming processes. The classical quadratic anisotropic yield criteria, based on the associated flow rule (AFR), has the ability to describe the orthotropic anisotropy for some metals, however they show some limitations in accurately predicting material behavior under complex loading conditions. To improve the numerical predictions, advanced AFR anisotropic models with very complex expressions are being used. However, while accuracy may be improved, the parameter identification process becomes more complex and challenging.

As an alternative, increasing attention has been done to the use of non-associated flow rule (NAFR) formulations (figure 1b), which is able to reproduce simultaneous and independently the plastic flow (r-values) and the plastic yielding (yield stress coefficients).

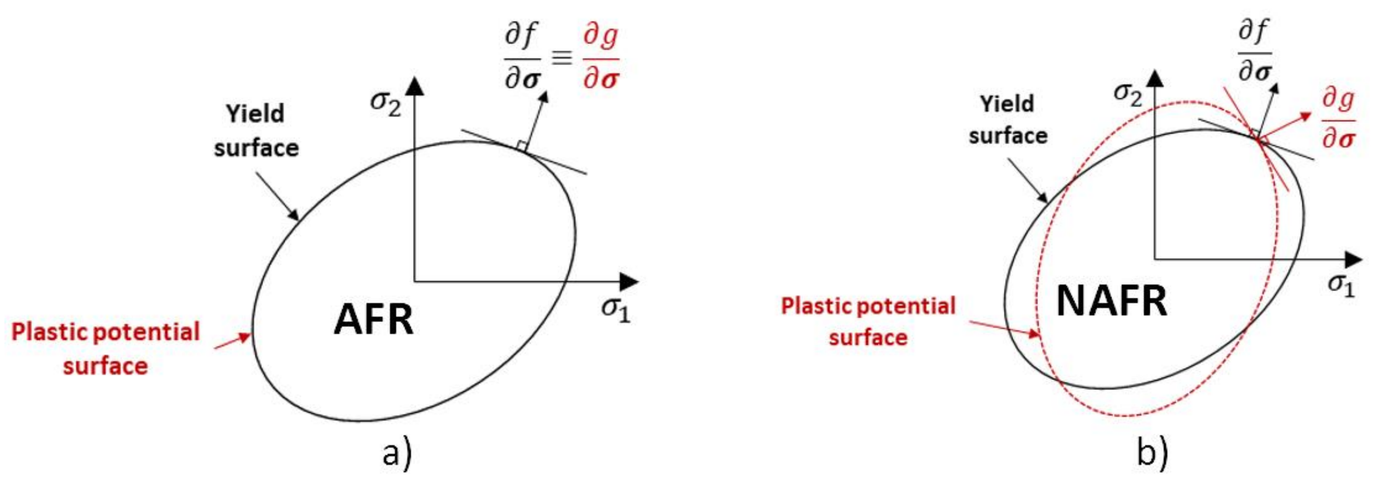

FIGURE 1. Different types of plastic flow directionality: a) associated flow rule; b) non-associated flow rule.

THEORY - HILL'48 ANISOTROPIC YIELD CRITERION

Yield surface

$$f(\boldsymbol{\sigma}) = \sqrt{F^*(\sigma_{22}-\sigma_{33})^2 + G^*(\sigma_{33}-\sigma_{11})^2 + H^*(\sigma_{11}-\sigma_{22})^2 + 2L^*\sigma_{23}^2 + 2M^*\sigma_{31}^2 + 2N^*\sigma_{12}^2}$$

Plastic potential surface

$$g(\boldsymbol{\sigma}) = \sqrt{F(\sigma_{22}-\sigma_{33})^2 + G(\sigma_{33}-\sigma_{11})^2 + H(\sigma_{11}-\sigma_{22})^2 + 2L\sigma_{23}^2 + 2M\sigma_{31}^2 + 2N\sigma_{12}^2}$$

The identification of Hill' 48 criterion parameters was based on r-value and on yield stresses. In case of stress based, two possibilities were considered to calculate the parameter N: based on 3D conditions (S3D) and based on in-plane properties (SiP).

Based on r-values	$F = \frac{r_0}{r_{90}(1+r_0)}$ $\quad G = \frac{1}{r_0+1}$ $\quad H = \frac{r_0}{r_0+1}$ $\quad N = \frac{1}{2}\left(\frac{(r_0+r_{90})(1+2r_{45})}{r_{90}(1+r_0)}\right)$
Based on stresses	$F^* = \frac{\sigma_0^2}{2}\cdot\left(\frac{1}{\sigma_{90}^2}+\frac{1}{\sigma_b^2}-\frac{1}{\sigma_0^2}\right)$ $\quad G^* = \frac{\sigma_0^2}{2}\cdot\left(-\frac{1}{\sigma_{90}^2}+\frac{1}{\sigma_b^2}+\frac{1}{\sigma_0^2}\right)$ $\quad H^* = \frac{\sigma_0^2}{2}\cdot\left(\frac{1}{\sigma_{90}^2}-\frac{1}{\sigma_b^2}+\frac{1}{\sigma_0^2}\right)$ $N_p^* = \frac{\sigma_0^2}{2}\cdot\left(\frac{2}{\sigma_{45}^2}-\frac{1}{\sigma_b^2}\right)$ $\quad N_{3D}^* = \frac{1}{2}\cdot\frac{\sigma_0^2}{\tau_{xy}^2}$

SHEET METAL MATERIAL

Figure 2 presents the hardening behaviour of material, obtained from uniaxial tensile and table 1 the fundamental properties.

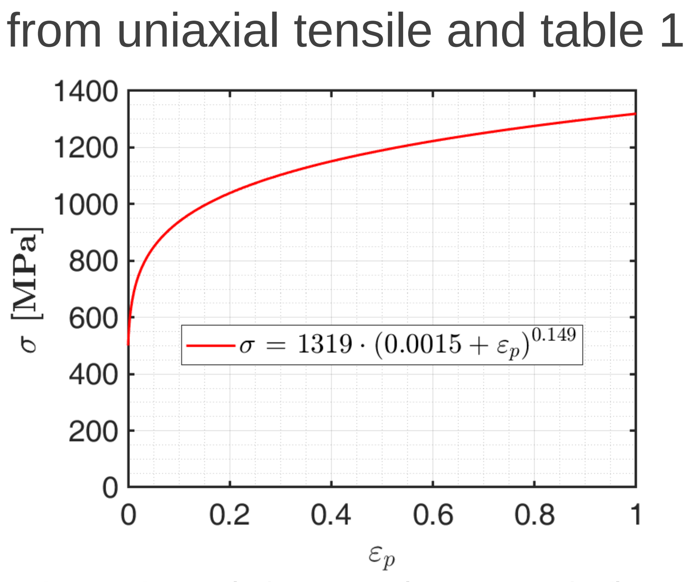

FIGURE 2. Dual-phase steel stress-strain flow curve using the Swift law.

TABLE 1. Fundamental mechanical properties of dual-phase steel.

Property	Value		
Elastic modulus [GPa]	210		
Poisson ratio	0.3		
Thickness [mm]	0.8		
Yield stress [MPa]	0º	45º	90º
	526	538	518
Biaxial stress [MPa]	566		
Shear stress [MPa]	316		
r-values	0º	45º	90º
	0.7	1.05	0.88

APPLICATION - DEEP DRAWING CYLINDRICAL CUP TEST

To evaluate the considered formulations to describe the dual-phase steel behavior, a 3D finite element numerical model of the cylindrical cup test was implemented in Abaqus/Explicit code, using rigid tools with analytical surfaces. The blank is discretized with 8-node linear brick deformable elements with reduced integration (C3D8R, available in the Abaqus library), having three elements along the thickness. Figure 3 presents the obtained cup height evolution profiles for each approach.

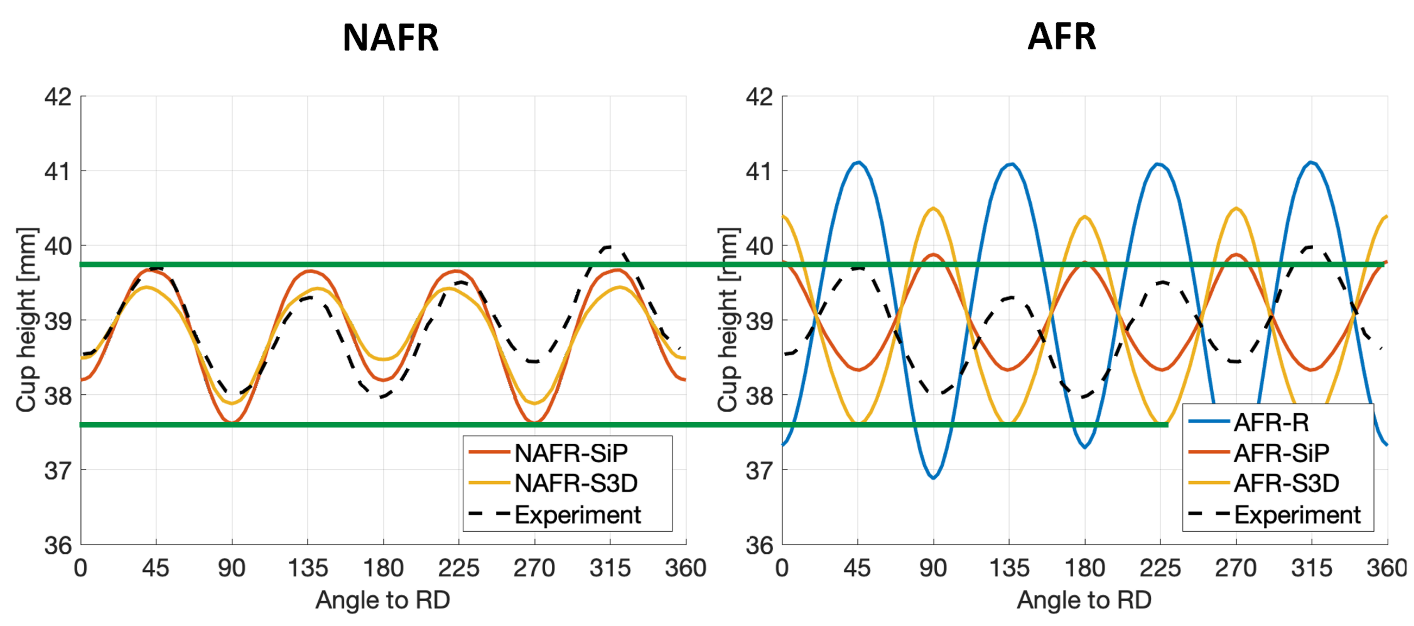

FIGURE 3. Cup height evolution along different angles to the rolling direction for NAFR and AFR approaches and comparison with experimental data.

Comparing the cup height evolution for the two NAFR approaches, using as a reference the associated flow rule based on r-values (AFR-R), it can be observed throughout the results that both approaches (NAFR SiP and NAFR-S3D) predict the cup height and earing more closely to the experimental measurements in trend and accuracy. Although the AFR-R approach predicts the same ears location it has a higher amplitude, while the associated formulations based on stress properties (AFR-SiP and AFR-S3D) predict an opposite evolution of highs and lows of the earing profile.

The different amplitudes obtained by these approaches also cause some difference in contours, especially seen on equivalent plastic strain results (figure 4).

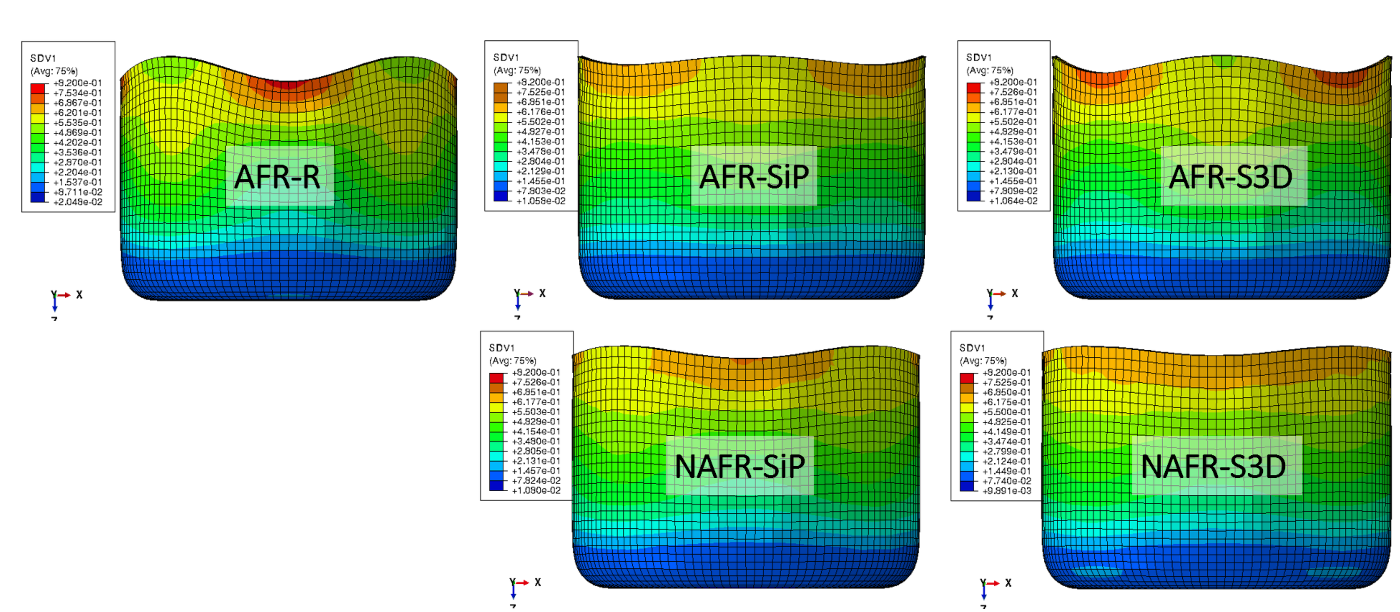

FIGURE 4. Equivalent plastic strain (SDV1) contours using the AFR and NAFR formulations.

CONCLUSIONS

The NAFR model was developed using classical Hill'48 function so that it combines the advantages of simple form and the anisotropic forming prediction. The results of the cup drawing test shows that the proposed NAFR model improves the accuracy of results, as well as provides an effective and efficient approach to anisotropic sheet metal simulation and prediction, which by using the proposed quadratic model could also offer accurate simulation results with reduced material testing. This comparative study also shows that NAFR models can reproduce the experimental anisotropic behavior of cylindrical cups, which is validated by the observed close agreement between experimental and predicted simulation results.

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