# An Application of Crystal Plasticity to predict Forming Limit Curve of Dual-Phase Steels with Validation

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**Abstract.** In this paper an alternative approach for generating Forming Limit Curve (FLC) of a Dual-Phase (DP800) steel is presented and validated. Investigation was performed using a rate-dependent crystal plasticity (CP) framework solved through a spectral solver and combined subsequently with the Marciniak-Kuczynski (M-K) approach for the evaluation of FLC using the commercial software Digimat. Representative Volume Element (RVE) was constructed using the built-in Voronoi tessellation method within Digimat from the Electron Back Scattering Diffraction (EBSD) measurements on the material. The hardening parameters were calibrated through inverse optimisation to match the experimental uniaxial tensile behaviour of the material. The calibrated model was then used as a virtual testing tool to predict the anisotropic yield behaviour of the DP800 steel and the Yld2000 function was fitted to the predicted anisotropic yield surface. The fitted Yld2000 function was then used to determine the FLC using the M-K approach implemented in Digimat where the sheet necking is modelled through an initial imperfection as a narrow band with reduced thickness. The whole workflow was successfully validated with experimental evaluation of FLC. The results are satisfactory and demonstrate the suitability of the presented workflow for FLC evaluation of advanced steels.

**Keywords:** DP800; Forming Limit Curve; Crystal Plasticity; Yld2000

## 1 Introduction

Sheet metal forming is widely used in many industries such as aerospace, automotive, consumer products etc.. Excessive care to avoid fracture or thinning during the process is needed [1, 2] and Forming Limit Curve (FLC) is the most common failure criterion [3, 4] used for this. However, generating FLC experimentally is extremely time-consuming and costly. In the current paper, a methodology is proposed to predict the FLC of sheet metals using Crystal Plasticity (CP) simulation as a virtual tool, that is both cost and time effective.

### 1.1 Methodology

Firstly the anisotropic yield behaviour of the sheet metal is predicted using the Fast Fourier Transform (FFT) CP solver [5] available in the commercial software Digimat [6]. The macroscopic yield function Barlat2000 (Yld2000) is fitted to the predicted anisotropic yield surface. Subsequently, using the fitted Barlat2000 yield function, FLC of the sheet metal is evaluated through the Marciniak-Kuczynski (M-K) approach [3], also available in Digimat. The predicted FLC is validated against experimental measurements to estimate the accuracy and suitability of the method for advanced steels.

### 1.2 Material

The material under investigation is a dual-phase steel grade 800 (DP800) with 80% of ferrite and 20% martensite respectively. The microstructure and texture of the material is measured through electron back-scattering diffraction (EBSD. Uniaxial tensile tests were conducted under 0, 45 and 90 degrees and the corresponding yield stress and Lankford values are measured.

### 1.3 Numerical simulations

The CPFFT solver available in the Digimat software is used as a virtual tool to predict the anisotropic yielding behaviour of DP800. In order to achieve this, a 3D Representative Volume Element (RVE) is generated using the in-built Voronoi tessellation algorithm. The corresponding phase fractions of ferrite and martensite are assigned to the grains. Texture measured from EBSD is also applied on the RVE. Periodic boundary conditions are employed throughout the analyses. A voxel mesh of size 32x32x32 is used.

The hardening parameters of the individual phases ferrite and martensite are inversely calibrated using the tensile tests in 0 and 45 degree. The calibrated parameters are then used to verify 90 degree tensile test results. The calibrated hardening parameters are provided in the table below. The elastic constants are obtained from the literature. The reference plastic strain rate is assumed as $0.001 s^{-1}$ and the viscoplastic exponent is taken as 0.05.

**Table 1.** Asaro-Needleman hardening parameters

| Phase | Critical shear stress (MPa) | Initial hardening modulus (MPa) | Saturation stress (MPa) |
|---|---|---|---|
| Ferrite | 150 | 1200 | 355 |
| Martensite | 500 | 900 | 400 |

## 2 Results

The predicted anisotropic yield surface and the FLC determined from it are discussed below.

### 2.1 Anisotropic yield surface

The anisotropic yielding behaviour of DP800 is determined by simulating uniaxial (0, 45 and 90 degrees) and biaxial loading on the RVE. The predicted yield surface is shown below in Fig.1.

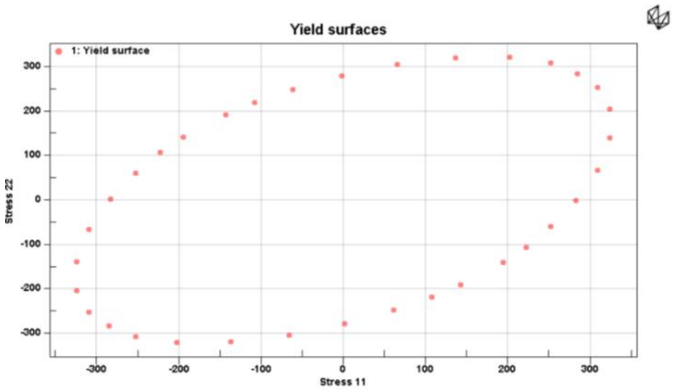


**Fig. 1.** Predicted anisotropic yield surface of DP800 through CP simulations in Digimat software.

### 2.2 Barlat2000 yield function

Barlat2000 (Yld2000) function parameters are fitted using inverse fitting approach to find the function parameters as shown in Fig.2.

### 2.3 FLC prediction

Using the Barlat2000 yield function, FLC of DP800 was predicted using Taylor homogenisation based M-K approach. The imperfection factor is calibrated using uniaxial testing data. The predicted FLC for DP800 steel is shown below in Fig.3.

## 3 Conclusions

A methodology for predicting FLC of DP800 advanced steel using the commercial Digimat CPFFT solver as a virtual tool is presented. Evidence suggests that crystallographic texture exerts considerable influence on FLC.

Furthermore, the shape of the yield surface, material anisotropy are also addressed in a straightforward manner using CP simulations, highlighting its strength as a virtual tool for predicting FLC in advanced steels, in a cost and time efficient way.

In the current work, the validation of the predictions with experimental results is still underway and these will be included in the paper and the presentation in due course.

| Parameter | Fitted value |
|---|---|
| Alpha1 | 0.425487 |
| Alpha2 | 1.59849 |
| Alpha3 | 2.03928 |
| Alpha4 | 0.264444 |
| Alpha5 | 0.739291 |
| Alpha6 | 2.08344 |
| Alpha7 | 0.599556 |
| Alpha8 | 1.0854 |
| Exponent | 7.65843 |

**Fig. 2.** Fitted Barlat2000 function parameters

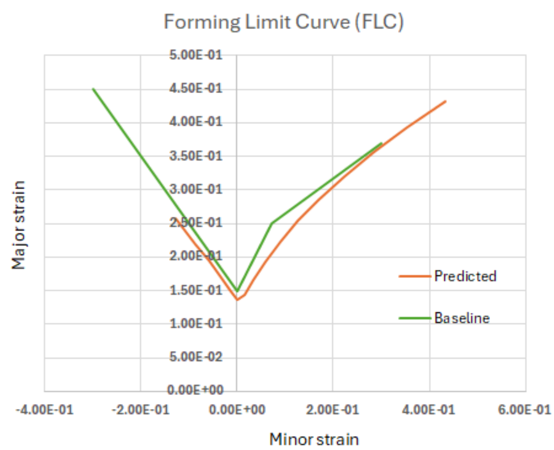


**Fig.3.** Predicted FLC of DP800 steel using M-K approach.

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