Formability predictions and measurement of 316L stainless steel using self-consistent crystal plasticity

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Abstract. A viscoplastic self-consistent (VPSC) crystal plasticity model was used to describe the mechanical behavior of a 316L stainless steel sample. Mechanical anisotropy of the 316L stainless steel was evidenced in the experimental results collected from the uniaxial tension tests along various directions. EBSD images were obtained from the as-received sample, and a representative population of discrete orientations was created to account for the initial crystallographic texture in the model. The hardening parameters were identified by using the flow stress-strain curve obtained from a bulge test. The model-predicted and experimental flow-stress curves and R-values were compared in order to estimate the adequacy of the VPSC model to describe the anisotropic behaviour of the 316L stainless steel sample. Furthermore, the crystal plasticity model, in conjunction with the Marciniak-Kuczyński approach, was used to predict forming limit diagram. The model was validated by comparing with the experimental flow stress curves from uniaxial tension and bulge tests. The predictive accuracy on forming limit diagram was also estimated by comparing with the experimental forming limit strains obtained through Nakajima tests.

1. Introduction
Formability of sheet metals can be represented by the means of forming limit curve (FLC), which is a collection of principal strain components at the onset of failure. Marciniak and Kuczyński approach (MK), where a preexisting inhomogeneity is assumed, has been widely used in the literature to predict the forming limit strains of various sheet metals [1].

In a previous study, the viscoplastic self-consistent crystal plasticity model [2] was successfully employed to the MK model [3], which makes use of the parallel computing algorithm to reduce the computational time. In this work, the model is applied to a 316L steel and the accuracy of the model is estimated in comparison with the experimental forming limit diagram obtained through a standard Nakajima test procedure.

2. Method

2.1. Model
In the viscoplastic self-consistent crystal plasticity framework, the local strain rate ($\dot{\varepsilon}$) pertaining to individual grain is related to the local stress through a power-law type constitutive relation such as below [4]:

$$\dot{\varepsilon} = \dot{\gamma}_0 \sum_s m^s \left( \frac{m^s \cdot \sigma}{\tau_c^s} \right)^n \text{sgn}(m^s \cdot \sigma),$$  \hspace{1cm} Eq (1)

where $\dot{\gamma}_0$, $m$, $\sigma$, $n$ and $\tau$ are strain rate normalization factor, Schmid tensor, local stress tensor, the strain rate sensitivity and the critical resolved shear stress (CRSS), respectively. Some of the mentioned symbols are appended by the superscript $s$ to indicate that the associated physical quantity pertains to a particular slip system. The CRSS for each slip system is described as a Voce type hardening function suggested in [5], which is written as below:

$$\tau^s = \tau_0^s + (\tau_1^s + \theta_0^s \Gamma)^{1 - \exp \left( \frac{\theta_0^s \Gamma}{\tau_1^s} \right)}$$  \hspace{1cm} Eq (2)

where $\Gamma = \sum_s \Delta \gamma^s$ is the total accumulated shear strain; $\tau_0$, $\tau_1$, $\theta_0$ and $\theta_1$ are hardening parameters.

The macro stress and strain should be equivalent to the weighted average of local stress and strain pertaining to grains sampled in the representative population of discrete orientations. The macroscopic constitutive relation is employed to the Marciniak-Kuczysński approach where a pre-existing inhomogeneity is parameterized using so-called the inhomogeneity factor. Detailed description of the model is available elsewhere [3].

2.2. Experiments

In total 8 separate EBSD data were obtained from the as-received 316L sample at the near surface and the middle section, each of which resulted from an area in the dimension of $500\mu m \times 500\mu m$. The grain size was quantified as 8.7 according to the ASTM scale, which corresponds to the average grain diameter of $18 \mu m$. MTEX [6] was used to obtain the crystallographic orientation distribution by merging all of the EBSD data to account for the texture gradient observed along the thickness direction. Three pole figures from the population of 6000 discrete orientations are shown in Figure 1.

![Figure 1](image1.png)

**Figure 1.** (100), (110) and (111) pole figures of the as-received 316L sample

Bulge test and uniaxial tension tests have been conducted at the strain rate of $2.5 \times 10^{-3}/s$. The bulge test procedure followed the standard (ISO 16908). Nakajima tests were conducted while collecting digital images from the top surface of the deforming specimen. The digital images were analysed using a commercial software (ARAMIS) to obtain the strain at failure according to the standard (ISO 12004:2008).

3. Results

Voce hardening parameters were identified by fitting with the flow stress-strain curve obtained from the bulge test using Simplex method available in SciPy package [7]. The parameters used in VPSC-FLD simulations are shown in Table 1. The evolution of R-values with respect to axial strain is given in Figure 2 (a). The flow stress-strain curve obtained from bulge test is illustrated in Figure 2 (b). The
error bars shown both figures are resulting from the three duplicated tests. Also, note that both experimental results are compared with the corresponding model predictions. In Figure 3 the predicted forming limit diagram of VPSC-FLD is compared with the experimental results from Nakajima tests.

Table 1. Model parameters used for VPSC-FLD calculations

| $\tau_0$ [MPa] | $\tau_1$ [MPa] | $\theta_0$ [MPa] | $\theta_1$ [MPa] | $\dot{\gamma}_0$ in $[s^{-1}]$ | n |
|----------------|----------------|------------------|------------------|-------------------------------|---|
| 149.4          | 337.9          | 732.6            | 0.1789           | $10^{-3}$                     | 20 |

Figure 2. (a) Experimental and model-predicted evolution of R-values in various directions with respect to the axial strain; (b) The flow stress curve obtained by the bulge test and simulation.

Figure 3. Experimental and model predicted forming limit diagram of 316L stainless steel

4. Discussion and Conclusion
The anisotropic response of 316L stainless steel was well captured by the VPSC model. The forming limit diagram predicted by VPSC model was in good agreement with the experimental FLC curve obtained by Nakajima test.

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