The Application of Crystal Plasticity Material Files in Stamping Simulations

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Abstract. Representative material data are inevitable to execute accurate stamping simulations. These material data are generally generated by performing extensive mechanical material tests. In this research the generation and application of material data from a crystal plasticity-based multiscale model have been studied. The crystal plasticity model enables to generate detailed material properties which can be applied in various yield locus models. The evolution of the anisotropic properties during deformation can be readily taken into account with the crystal plasticity model. The generated material data have been applied in deep drawing simulations of a cross-die. The thickness distribution of the simulation has been compared with experiments. Results showed that crystal plasticity models are a viable alternative for material data generation, having as main advantage that extensive mechanical experiments are avoided.

1. Material Modelling

Reliable material data to describe material behavior are essential in stamping simulations. The bare minimum is one uniaxial tensile test to represent the hardening behavior of the material. However to present the material behavior in multi axial stress space an accurate yield criterion is also required. A basic yield criterion like Hill’48 requires data like the R-values in three directions. More sophisticated material models, such as BBC 2005, also need the biaxial yield stress and the biaxial R-value [1]. Other models like the Vegter yield criterion require even more reference points like the ones from plane strain tensile test and shear test [2]. So, the assessment of accurate forming properties requires in principle a large number of tests.

Today, state of the art multi-scale crystal plasticity modelling is capable to make reliable virtual tests of the entire yield locus. All plastic properties are obtained from a measurement of the microstructure. In the most expedient case, a single X-ray diffraction would be sufficient to obtain the microstructural feature that dominantly controls plastic anisotropy, namely the crystallographic texture [3]. The crystal plasticity models are also able to take evolution of the properties during deformation into account.
If these crystal plasticity models could be applied instead of the physically determined material data this could save a lot of time, effort and cost. In this study the application of material data based on crystal plasticity modelling has been verified. A mild steel (DC04) has been stamped and simulated based on a cross die geometry. The experimental thickness distribution has been compared with simulation. Several variants of material parameters are verified.

1.1. Reference Material Modelling

The material used in this study is a mild steel (DC04) with a thickness of 0.79 mm [4]. Uniaxial tensile tests in three directions (0°, 45° and 90°) are performed. The flow curve in rolling direction (0°) has been approximated with a combined Swift/Hockett-Sherby approach to be used in the stamping simulation:

\[
\sigma = (1 - \alpha) \left( C \left( \varepsilon_{pl}^0 + \varepsilon_0 \right)^m \right) + \alpha \left( \sigma_{Sat} - \left( \sigma_{Sat} - \sigma_i \right) e^{-a\varepsilon_{pl}^0} \right)
\]

Table 1. Hardening parameters to describe the flow curve for the combined Swift/Hockett-Sherby approach for DC04

| \(\alpha\) | \(\varepsilon_0\) | m | C [MPa] | \(\sigma_i\) [MPa] | \(\sigma_{Sat}\) [MPa] | a | p |
|---|---|---|---|---|---|---|---|
| 0.50 | 0.0061 | 0.26 | 561 | 153 | 415 | 6.13 | 0.80 |

The yield stress in rolling direction (\(\sigma_0\)) is 151 MPa and is the reference value for the yield surface description. For the reference simulation the classical Hill’48 and the BBC 2005 models have been applied. For the BBC 2005 the M-value has been set to 6. A bulge test has been applied to obtain the biaxial yield stress \(\sigma_b\). Table 2 gives the parameters for the yield surface definitions, the parameters for the Hill’48 model are printed in bold. The biax r-value \(r_b\) for the BBC 2005 model has not been measured but has been estimated with the Hill’48 model.

Table 2. Measured properties of DC04 for the Hill’48 (bold) and BBC 2005 model; the three yield stresses \(\sigma_0, \sigma_{45}, \sigma_{90}\), biaxial yield stresses \(\sigma_b\) (stresses are expressed as ratio with respect to \(\sigma_0\)) and the three R-values \(r_0, r_{45}, r_{90}\)

| \(\sigma_0\) | \(\sigma_{45}\) | \(\sigma_{90}\) | \(\sigma_b\) | \(r_0\) | \(r_{45}\) | \(r_{90}\) |
|---|---|---|---|---|---|---|
| 1 | 1.099 | 1.079 | 1.272 | 1.83 | 1.39 | 2.11 |

2. Cross Die Experiment

For verification of the various material models cross die experiments have been used. The geometrical data have been listed in Table 3 and Figure 1 shows the geometry of the punch. The clearance between punch and die is 2.3 mm and the die shoulder radius is 7 mm.
Table 3. Geometrical parameters of Cross Die Punch

| Total width [mm] | Leg width [mm] | Radii |
|------------------|----------------|-------|
| 179.4            | 59.4           | 20.0  |

The experiments have been executed with a square blank of 330x330 mm. A constant blank holder force of 350 kN has been applied and the sheet has been lubricated with Teflon to minimize the friction. The punch stroke has been 60 mm which resulted in parts close to fracture.

For verification of the simulations the thickness has been measured at two sections with help of an ultrasonic device. The definition of the two sections (diagonal and meridian) is represented in Figure 2. The origin of the section is in the center of the cross die.

3. Cross Die Simulations

The simulations have been run with AutoForm\textsuperscript{plus} R7.03. AutoForm final validation settings [5] with minor modifications have been applied. Because of the relatively small dimension of the cross die the initial element size has been halved. The step size has been kept constant to obtain a better comparison of the different material models. All simulations have been performed with identical settings only the material models have been exchanged.

3.1. Reference Verification

The thickness along the two sections are represented in figure 3 (meridian) and figure 4 (diagonal), the x-axis represents the section length starting at the center of the cross die. The markers give the measured thicknesses of the experiments. The simulation results are represented with the lines. The red line represents the Hill’48 model and the blue line represents the BBC 2005 model.

For the meridian section the punch radius starts at $s=30$ mm, the vertical wall starts at $s=60$ mm, the die radius starts at $s=90$ mm and the binder starts at $s=101$ mm. For the diagonal section the punch radius starts at $s=70$ mm, the vertical wall starts at $s=100$ mm, the die radius starts at $s=130$ mm and the binder starts at $s=141$ mm.

Generally, the simulated thickness distribution matches the experiments. Both Hill’48 and BBC 2005 give similar results. In the meridian section we see a deviation of 0.03 mm under the punch, with more thinning in the experiment than in the simulations. The thinnest spot at the upper point of the vertical wall ($s=100$) isn’t visible in the simulation. For the binder area the simulations also predict a slightly higher thickness. In the diagonal section we see that the simulations are about 0.02 mm thicker than the experiments. The Hill’48 performs slightly better in the wall area.

Figure 3. Thickness distribution along the meridian section, Experiment, Hill, BBC

Figure 4. Thickness distribution along the diagonal section, Experiment, Hill, BBC

4. Crystal Plasticity Material Files

In this paper, we used the Crystal Plasticity multiscale ALAMEL model to derive plastic properties from texture data. The calculations were performed using VEF software ver. 0.13.1 [6,7]. A typical workflow to derive the yield surface parameters is much straightforward:
1. gather texture data from experiment (X-ray diffraction or large scale EBSD)
2. calculate Orientation Distribution Function (ODF)
3. calculate discrete ODF
4. use the Crystal Plasticity Virtual Experiments that determine essential characteristics of plastic anisotropy in the initial (undeformed) state:
   - r-value and uniaxial yield stresses for a range of tensile directions,
   - biaxial r-value and the corresponding yield stress,
   - plane strain points,
   - several points on the yield locus section and the normal to the yield locus.
5. optionally, calculate strain evolution of these characteristics, and calculate equi-work contours at arbitrary strain levels.

The VEF software fully automates the steps described above. In particular, the material characteristics can be directly computed by the VEF [7].

The texture data of the specific material was not available. Therefore, the anisotropy characteristics were calculated for similar DC04 alloy available in the database and material cards have been generated. The Vegter yield model has been applied since the crystal plasticity model is able to generate all necessary parameter. Table 4 lists the data for the Vegter model where a selection of the data that can be applied for the BBC 2005 model (printed in bold). The calculated values match the measured data from table 2 reasonably well with the largest deviation in the biaxial stress value \( \sigma_b \).

This methodology is able to derive a complete set of material data based on a minimum set of input parameters without performing extensive and costly experiments.

**Table 4.** Parameters determined with crystal plasticity model for Vegter and BBC 2005 (bold);
(stresses are expressed as ratio with respect to \( \sigma_0 \))

| \( \sigma_0 \) | \( \sigma_{45} \) | \( \sigma_{90} \) | \( \sigma_{0\text{-shear}} \) | \( \sigma_{45\text{-shear}} \) | \( \sigma_{90\text{-shear}} \) | \( \sigma_{0\text{-planestrain}} \) | \( \sigma_{45\text{-planestrain}} \) | \( \sigma_{90\text{-planestrain}} \) | \( \sigma_b \) |
|----------------|----------------|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|----------------|
| 1              | 1.031          | 1.001          | 0.537           | 0.565           | 0.537           | 1.225           | 1.235           | 1.240           | 1.093           |
| 2.10           | 1.64           | 2.25           | 0.510           | 0.510           | 0.532           | 0.915           |

Further investigation in the capabilities of crystal plasticity based material cards is done in terms of evolution of the anisotropic properties with a finite deformation. To this end, Virtual Experiments are conducted to track the evolution of a large number of yield points (in casu 1° resolution) from the initial yield locus (undeformed state) to a finite state of deformation. From this, contours of equal plastic work are generated, whereby the initial yield locus effectively coincides with the contour of zero plastic work. Two levels of deformation (plastic work) are chosen, corresponding to the following strain levels in the tensile test along rolling direction (‘reference test’): \( \varepsilon_{\text{ref}} = 0.10 \) (intermediate strain); and \( \varepsilon_{\text{ref}} = 0.20 \) (large strain).

In order to conduct Virtual Experiments of finite deformation, work hardening needs to be introduced. In the crystal plasticity framework, hardening of the microscopic slip systems is prescribed as a function of accumulated plastic slip. The microscopic hardening is calibrated in such a way that the experimental tensile hardening curve along RD based on the data of Table 1 is accurately reproduced.

At the macroscopic level, the predicted hardening behaviour deviates from the isotropic hardening assumption due to evolution of the crystallographic texture with finite deformation. This can be easily observed in Figure 5, in which the 1st quadrant of the equi-work contours is normalized by the stress in the reference test. Most obvious change can be seen at the biaxial stress point which moves out.
5. Cross Die Simulations with Crystal Plasticity Material Files

The result of the crystal plasticity based material files are indicated as VEF and are compared with both the experiments and the reference simulation with the BBC 2005 material model. Both the VEF Vegter and VEF BBC give nearly identical results, the differences are less than 0.01 mm (figure 6 and figure 7). For further investigations we decided to use the BBC 2005 model.

In the meridian section we see less deviation under the punch for the VEF models than for the BBC models, the experiments thins more than simulated. The thinnest area in the wall thins more extreme than the reference simulation and the experiment. For the binder area the VEF model predicts the thickness better than the BBC model calibrated to mechanical experiments. In the diagonal section we see that the VEF models deviates only 0.01 mm from the experiment except the extreme thinning at the punch radius.

The stamping simulations exploiting the crystal plasticity models show good agreement with experiments. The thickness distribution has a little different characteristic than the reference model. When comparing the input data for both models (table 2 and table 4) especially the difference in biaxial stress $\sigma_b$ is remarkable.

An additional set of simulations has been performed taking the evolution of the yield surface into account. In these simulations the work hardening has been taken into account and the yield surfaces are identified at a pre-strain of 0.10 and 0.20 as described in section 4. Figure 8 and Figure 9 show the thickness distribution along the two sections. It is seen that by considering the pre-strain the result is...
improved. The punch and binder area already showed good agreement and for those areas the results don’t change. The thickness distribution in the wall area in meridian section and the punch radius area in the diagonal section move closer to the experimental value. So, taking the pre-strain into account and identifying yield surfaces at those increased strain levels has a positive effect on the simulated thickness distribution.

Figure 8. Thickness distribution along the meridian section, Experiment, BBC, VEF BBC Prestrain 0.10, VEF BBC Prestrain 0.20

Figure 9. Thickness distribution along the diagonal section, Experiment, BBC, VEF BBC Prestrain 0.10, VEF BBC Prestrain 0.20

6. Conclusions
Crystal plasticity based material files can be calculated based on a minimum set of experimental data; only one tensile test and texture data are required. The generated material files can directly be applied in stamping simulations. A cross die stamping experiment with a mild steel DC04 has been used to verify the material files. Thickness distribution along two sections showed good agreement between simulation and experiment. The agreement could be improved in case work hardening has been taken into account in the yield surface representation.

The methodology of creating material files based on crystal plasticity models is a promising technology. Further studies are required to verify its broader application with other materials like aluminum alloys and HSS. Also the evolution of the shape of the yield surface should be studied in more detail. Creating any required yield surface description without extensive material testing should be in reach.

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