Accurate anisotropic material modelling using only tensile tests for hot and cold forming

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Abstract. Accurate material data for simulations require a lot of effort. Advanced yield loci require many different kinds of tests and a Forming Limit Curve (FLC) needs a large amount of samples. Many people use simple material models to reduce the effort of testing, however some models are either not accurate enough (i.e. Hill’48), or do not describe new types of materials (i.e. Keeler). Advanced yield loci describe the anisotropic materials behaviour accurately, but are not widely adopted because of the specialized tests, and data post-processing is a hurdle for many. To overcome these issues, correlations between the advanced yield locus points (biaxial, plane strain and shear) and mechanical properties have been investigated. This resulted in accurate prediction of the advanced stress points using only Rm, Ag and r-values in three directions from which a Vegter yield locus can be constructed with low effort. FLC’s can be predicted with the equations of Abspoel & Scholting depending on total elongation A80, r-value and thickness. Both predictive methods are initially developed for steel, aluminium and stainless steel (BCC and FCC materials). The validity of the predicted Vegter yield locus is investigated with simulation and measurements on both hot and cold formed parts and compared with Hill’48. An adapted specimen geometry, to ensure a homogeneous temperature distribution in the Gleeble hot tensile test, was used to measure the mechanical properties needed to predict a hot Vegter yield locus. Since for hot material, testing of stress states other than uniaxial is really challenging, the prediction for the yield locus adds a lot of value. For the hot FLC an A80 sample with a homogeneous temperature distribution is needed which is due to size limitations not possible in the Gleeble tensile tester. Heating the sample in an industrial type furnace and tensile testing it in a dedicated device is a good alternative to determine the necessary parameters for the FLC prediction.

1. Introduction

Simulations for sheet metal forming with FE programs require accurate input for both process and material data. Material data input consists of hardening data, a yield locus and a FLC. To achieve an accurate material model usually a large set of experimental data is needed. While material models which require only little testing effort often are inaccurate, or not valid for high strength materials. The yield locus for example can be easily constructed with Hill’48 [1] where only data of three tensile tests is needed to construct a yield surface. The newer, more accurate models like the Barlat family [2], [3], BBC2005 [4], Vegter [5], or Vegter lite [6] all require much more specific test data. For the Forming Limit Curve, the Keeler FLC [7] is a model that is often used. A simple model based on the n-value of
the tensile test and the thickness. This model however, is not able to accurately predict the FLC for the newer types of material like for instance multi-phase materials.

For both the yield locus and the FLC solutions for an increased accuracy combined with the reduction of the amounts of tests are found. The authors made a predictive model for the advanced stress points in the yield locus based on a large set of measured yield loci [8]. Similar to Hill’48, only three tensile tests are needed for the yield surface. Validations with FE simulations on pressed parts for cold forming processes showed good results. The predictions are accurate for steel, stainless steel and aluminum.

Abspoel et al. [9] also made an accurate prediction of the FLC based on the tensile test. Also here a large database of tests was investigated and clear correlations between simple mechanical properties, the thickness and the level of the FLC were found. The FLC prediction is also valid for steel, stainless steel and aluminum.

Since both predictive models showed good results for cold forming processes for both BCC and FCC materials, it is interesting to evaluate these materials for hot forming processes. For hot forming processes it is even more difficult to measure strain states other than uniaxial. This makes experimental yield loci and FLC’s hard to measure. The use of a predictive method would be very beneficial. There are some FLC measurements in the literature, for example by Dahan et al. [10], which will be compared to the predicted FLC. For the verification of the yield locus prediction, parts are pressed to a certain height and the strain clouds are compared with the simulations. Besides that also the measured punch forces were compared. For the simulations the hardening curves used are processed according to the procedure as described by Abspoel et al. [11].

2. Predictive methods

2.1. Forming Limit Curve

The prediction method of the FLC by Abspoel & Scholting [9] is based on input from tensile tests. The mechanical properties total elongation A80 and r-value are needed, as well as the thickness of the material. The biaxial point depends on the lowest A80 because in biaxial stretching the necking occurs in the weakest direction. Therefore testing in 0, 45 and 90° with respect to rolling direction is necessary. Four points are predicted, biaxial, plane strain, tensile and an intermediate point between plane strain and biaxial (figure 1).

![Figure 1](image-url)

Figure 1. (a) FLC prediction points, (b) example of a forming steel (c) example of a dual phase steel.

The examples in figure 1 show that Keeler indeed works for forming steels but for a dual phase steel the Keeler equation is not able to predict the FLC where the prediction by Abspoel & Scholting is correct. Also the slope on the left side of the plane strain axis is now following the measured data instead of a 45° slope. The slope is predicted using the r-value.

2.2. Yield criterion

The Vegter criterion is constructed by using the measured stress points for uniaxial, equi-biaxial, plane strain and shear loading conditions and the uniaxial and equi-biaxial strain ratios. The measured data
points, combined with Bezier interpolation between the measured points, result in a very accurate yield locus. A disadvantage of an advanced material model, like the Vegter model, is the requirement of the large amount of tests. Contrary to Hill’48 that only requires three tensile tests. The downside of the simplicity of Hill’48 is the inaccuracy with respect to the yield loci shape. There is a need for more accurate models with easier inputs. Vegter lite and BBC2005 are examples of those easier input models and are a step in the right direction. These models however, rely on scaling factors which for increased accuracy need to be evaluated and still make it complex. To reduce the large amount of tests, a correlation study was done on a large set of yield locus measurements. Clear correlations were found between the mechanical properties of the tensile test and the advanced yield loci points. These correlations use the tensile test data as an input and predict the equi-biaxial, plane strain and shear points in three directions. The mechanical properties tensile strength (Rm), uniform elongation (Ag) and plastic strain ratio (r-value) are the input parameters for the predictive equations. Figure 2 shows the increased accuracy graphically, where the equi-biaxial, plane strain and shear points are predicted from the uniaxial tensile data. In the graph on the right the comparison of the biaxial points for both Hill’48 and Vegter 2017 are shown. Hill’48 does not predict the right biaxial values, while the Vegter 2017 prediction matches the measured points very well.

![Figure 2](image)

**Figure 2.** (a) yield locus prediction 0-90° (b) yield locus prediction 45-135°, (c) correlation for biaxial point.

The use of the predictive model in the Vegter yield criterion is named Vegter 2017. It was verified by comparing measurements and simulations of a large number FLC samples and X-die samples. In figure 3 three examples of the verification for the predictive equations are shown and the comparison with Hill’48.

![Figure 3](image)

**Figure 3.** measured data versus Vegter 2017 and the difference with Hill’48. (a) DX54D+Z, (b) DP1000, (c) AA6016
All materials are predicted very accurate with Vegter 2017. The Hill’48 criterion has the largest deviation for a forming steel. But also for a DP1000 and a AA6016 where the r values are low, the deviation to the measurement is significant.

The verifications of the validity of the predicted yield locus were done by simulating pressed parts in AutoForm and comparing this to measured strain, punch force and temperature data. The AutoForm thermo-solver was used. Besides the predicted yield locus a hardening model including strain rate and temperature dependent curves was used as input for the AutoForm thermosolver. Figure 4 shows the comparison for a fully clamped biaxial Nakazima sample of DP600 material. The strains were optically measured with Aramis and the temperature was measured with a thermocouple and thermal camera. From both measurements, sections across the center of the sample were made to evaluate the temperature and strains. The friction was made as low as possible by using Teflon foil layers and grease in between. This resulted in a friction coefficient in the simulation of 0.01. The advantage of the low friction is that the punch force is now completely dependent on the material model. The punch force in the simulation matches the measured punch force very well for the full trajectory. The sections for the major strain are close to the measured data. In the final stage where necking starts the strains are also well simulated, except for the neck itself, because the simulation cannot predict this. The temperature starting at 27°C and reaching a final temperature of approximately 130 °C is also simulated very well. The measurement with the camera is however more difficult at high strains because the emission coefficient changes slightly (the area is less black). These three properties (force, strain and temperature) are that close to the measurement assuring that the material model represents the reality well.

![Figure 4](image)

**Figure 4.** biaxial sample validation DP600 (a) Simulation model and section, (b) punch forces comparison (c) major strain at section for four heights, (d) temperature at section for four heights.

Furthermore a large number of X-die samples were compared. An example of a zinc coated DP800-HyperForm is shown in figure 5. Temperatures could of course not be measured in a closed die and the strains were measured afterwards with Argus (an optical strain measurement system using gridded sheets). Both the simulated punch force and strain cloud match very well to measured data. Indicating that the material model matches reality.
3. Experimental and modelling

3.1. Hot tensile testing in the Gleeble

To create the models for hot forming, tensile tests in three directions are needed. The hardening curves for the material model for 22MnB5 hot forming steel are measured in a Gleeble. A special sample designed by van Liempt [11] for uniform temperature distribution was used. The homogeneity of the temperature distribution is shown in figure 6.

A set of strain rates and temperatures was tested to determine the parameters of a temperature and strain rate dependent model as described by Abspoel et al. [11]. Tensile testing was done in 0°, 45° and 90° with respect to the rolling direction, to determine the necessary mechanical properties to predict the Vegter 2017 yield criterion.

3.2. Hot tensile testing of an A80 specimen

For the FLC prediction A80 input is necessary. On a Gleeble an A80 sample is not possible due to the size. To accommodate for a homogeneous temperature distribution, a strip is heated in a roller hearth furnace and then quickly transported to a hot friction tester, which was adapted to use it as a tensile testing machine. This hot friction tester is located perpendicular to the press line close to the furnace exit. Figure 7 shows the temperature homogeneity of the furnace heated A80 sample in the strip tester just before the tensile test starts. After positioning, the tensile bar is clamped and the test starts when the desired test temperature is reached. The test is performed at relatively high strain rates ensuring almost uniform temperature during the test and a strain rate that is close to industrial forming conditions.

Figure 5. X-die simulation version measurement for DP800-HyperForm, (a) simulation model, (b) strain cloud comparison, (c) punch force comparison.

Figure 6. homogeneous tensile sample for Gleeble as proposed by van Liempt.
3.3. Modelled hot material data
The resulting modelled strain rate curves for temperatures 500°, 600°, 700°, 800° and 900°C (different colours) and strain rates (0.01, 0.1, 1, 10, 100/s) tested and fitted as described in [11], are shown in figure 8. The tensile test results also showed that the r-values vary with temperature. This results in a temperature dependent yield locus.

![Figure 8.](image)

**Figure 8.** (a) resulting strain rate and temperature dependent hardening data from model (T range 500-900°C strain rate range 0.01-100/s, (b) temperature dependent r-values, (c) predicted temperature dependent yield loci.

![Figure 9.](image)

**Figure 9.** (a) temperature dependent A80, (b) predicted temperature dependent average FLC (mid-plane) in transverse direction.
The FLCs predicted with Abspoel & Scholting equations are shown in figure 9. The A80 and r-values are taken from the A80 samples tested on the adapted hot friction tester. The FLC is compared with strain clouds of necked X-die samples and measurements as found in the literature in paragraph 4.

3.4. X-die forming tests
To validate the predicted yield locus and FLC, X-dies were pressed and compared with simulation results. The blanks were heated in the same roller hearth furnace where the A80 tensile tests were heated and then quickly transported to the press. Pyrometers are used to control the temperature before pressing. The X-die samples were pressed on three temperatures, 800, 700 and 600°C, matching the temperatures of the Gleeble tensile testing to compare the anisotropy values. The blank holder was equipped with nitrogen springs to accommodate a fast closure of the tool. Spacers of sheet thickness were used. Meaning that there was contact between the tool and the blank to avoid excessive wrinkling. Samples without failure were made with a height of 25 mm and samples with failure were made with a height of 27-30 mm. A grid was applied on the samples to measure the strain with photogrammetric software, and the tool was equipped with load cells to measure the punch and blank holder force.

4. Validation
In figure 10, the predicted FLC is compared with a necked X-die sample, a necked part measured by Dahan et. al. [10] and a set of measured Nakazima samples from the same publication by Dahan. Both parts show necking at the same strain level and are close or just over the FLC. The predicted FLC is also close to the necked Nakazima specimens from literature, while the fractured samples are above the FLC (except one in the uniaxial region) and almost all safe measurements are below the FLC. This indicates that the FLC prediction method is not only valid for cold stamped situations (steel, aluminium and stainless steel) but also for hot stamping situations.

![Figure 10](image)

Simulations were done in AutoForm R7 that includes the Vegter model. Figure 10 shows the strains and punch forces measured in the cross die. The simulated punch forces for three temperatures 800°C, 700°C and 600°C match very well with the measured punch forces. Although there is some scatter in the strain cloud measurement, the specific features are recognizable. The material model with its predicted yield locus is a good representation of reality.
5. Conclusions

Both the yield locus and FLC prediction, developed for cold forming, showed good results for hot forming confirming the robustness of the models. It is recommended to use both models and keep evaluating them with pressed parts, measurements on advanced hot yield loci tests (if possible) and hot FLC measurements. Both models reduce the amount of tests significantly, which in the case of high temperatures is a great benefit. The temperature dependent r-values result in a temperature dependent yield locus. Which can now easily be predicted with a low amount of testing effort.

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