A METHOD TO DETERMINE LANKFORD COEFFICIENTS (R-VALUES) FOR ULTRA HIGH STRENGTH LOW ALLOY (UHSLA) STEELS

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Abstract. For Ultra High Strength Low Alloy Steels (UHSLAS) it is difficult to determine Lankford parameters, since the measurement of a stable strain ratio is often not possible. This report presents a method for determining Lankford coefficients for UHSLA Steels. The method is based on a combination of a theoretical material model and on experiences from a material data base. The Hill’48 yield condition is used to calculate the Lankford coefficients as a function of the yield stress. An empirical model based on the BILSTEIN material data base is used to predict the anisotropy. The result from earing test is used as an input parameter for the empirical model. The method is first checked using data from tensile tests. The predicted Lankford coefficients are compared with measured Lankford coefficients. In a further step, this method is applied to low alloyed steels with a yield stress of more than 900 MPa. For these materials the Lankford coefficients could not be measured by tensile tests. Predicted Lankford coefficients are used in the numerical simulation of earing test and compared with experimental results. In summary, it can be stated that the method presented here is suitable for predicting Lankford coefficients in case of an impossible direct measurement.

1. Introduction
A remarkable group of cold rolled, High Strength Steels are the recovery annealed High Strength Low Alloy (HSLA) steels (BILSTEINs ZE grades). The ultra-high-strength materials (UHSLA) of this steel group show yield stresses of 800 to 1000 MPa (and more). They are widely used, e.g. for automotive seating structures. Due to its structure they are often a promising alternative to comparable multi-phase steels. In figure 1 stress-strain curves for these mono-phase steels are displayed. The formability of these materials is shown by butter-dish-tests.

![Stress-strain curves and formability](image)

Figure 1. Stress-strain curves and formability
The material modeling for forming simulations is challenging insofar as the determination of the Lankford coefficients (r-values or strain ratios) is not easy. These parameters are usually measured in tensile tests with strain measurements in width ($\varepsilon_w$) and length directions ($\varepsilon_l$). Then two methods are known to calculate the Lankford coefficient $r$ [1]:

- $r = -\varepsilon_w / (\varepsilon_w + \varepsilon_l)$ ("local approach", $r$ is given for a specific strain)
- $r = -m_r / (1 + m_r)$ with $m_r = d\varepsilon_w / d\varepsilon_l$ ("global approach", $r$ is given for a strain range)

In this work all Lankford coefficients are calculated by the "global approach". In [2] it is proposed to use a strain range between 2% and $A_g - 1\%$ (uniform elongation $A_g$ minus one percent). The determination of a reliable Lankford coefficient should be possible if the two strains can be described by a constant slope in this range. In case of UHSLA steels this is not always possible because a constant slope is not always present or the strain range is not always sufficiently large.

In this paper methods are studied to determine Lankford coefficients in an alternative way. The aim of this method is to provide an alternative approach with as little effort as possible.

2. Alternative methods to determine Lankford coefficients

2.1. Tensile Test and Hill’48 Yield condition

The Hill’48 yield condition is widely used in FEA forming simulations [3]. Usually, the Lankford coefficients are used as input parameters of this yield condition. Then, the yield stresses can be calculated as a function of the angle $\theta$ to the rolling direction: $\sigma_\theta = f(r, \sigma_0, \theta)$. However, it is also possible to use the yield stresses as input parameters and to calculate the Lankford coefficients: $r_{90} = f(r_0, \sigma_0, \sigma_{90})$ and $r_{45} = f(r_0, r_{90}, \sigma_0, \sigma_{45})$.

2.2. Earing test

The Lankford coefficients are the basis for modelling the anisotropy of sheet metals. Another way to make anisotropy visible is the Earing test [4]. Earing occurs during deep drawing of a cylindrical cup and can be described as a periodic variation of wall height $h$ around the diameter of the finished cup (see figure 2).

![Earing Test](image)

Figure 2. Earing

2.2.1. Analytical modelling

It is possible to predict an earing profile by analytical approaches [5-6]. The wall height $h$ can be calculated as a function of the r-values (and the initial yield stresses): $h_\theta = f(r_{\theta+90})$ (simplified Yoon-formula with $\alpha=1, \beta=0$) or $h_\theta = f(r_{90-\theta}, \sigma_{90-\theta}, \sigma_m)$ (Chung formula). In figure 3, predicted and measured mean earing heights for HSLA steels are compared.

The data are taken from the BILSTEIN material data base, where results of tensile tests and earing tests are documented and archived (Lankford coefficients $r_0$, $r_{45}$, $r_{90}$, initial yield stresses $\sigma_0$, $\sigma_{45}$, $\sigma_{90}$, the mean values of the ear peak $h_t$, and the ear valley $h_v$) [7]. Assuming the four valleys are longitudinal and transverse to the rolling direction, the following applies: $h_t = f(r_{45}, \sigma_{45}, \sigma_m)$ and $h_v = \frac{1}{2} (f(r_0, \sigma_0, \sigma_m) + f(r_{90}, \sigma_{90}, \sigma_m))$.

It can be seen in figure 3 that analytical models can describe the influence of anisotropy to the mean earing height $h_v$. But the accuracy of earing prediction is decreasing with increasing earing. Further it can be seen that a better prediction is possible when the initial yield stress is taken into
account. On the other hand, the prediction for the mean ear peak and the mean ear valley is very poor. This means that the analytical approach is not suitable for HSLA steels to calculate Lankford coefficients from the wall height $h$.

![Figure 3. Analytic earing predictions](image)

2.2.2. Empirical modelling
It is well known that the earing height and the planar anisotropy are related, which can be described by a regression line [8]: $h_e = m_h \Delta r + h_0$. This means that it is possible to calculate the planar anisotropy from the earing height. The planar anisotropy is obtained from the Lankford coefficients: $\Delta r = \frac{1}{2}(r_{0.1} + r_{90} - r_{45})$. If two Lankford coefficients are known, the third Lankford coefficient can be calculated from the earing height (via planar anisotropy).

3. Verification

3.1. BILSTEIN material data base
The proposals for the determination of Lankford coefficients are examined using data from the BILSTEIN material database. For this purpose, Lankford coefficients are determined for (Advanced) HSLA steels with yield stresses between 300 and 900 MPa.

3.1.1. Hill’48 yield condition
In figure 4 predicted Lankford coefficients are compared to measurements from tensile tests. The predicted Lankford coefficients were determined from the initial yield stresses using the Hill’48 yield condition. It was assumed that the Lankford coefficient $r_0$ (longitudinal to rolling direction) is known.

![Figure 4. Hill’48 predictions](image)
Figure 4 shows that the prediction of the Hill’48 yield condition is very good for the Lankford coefficient \( r_{90} \) (transverse to rolling direction) and is very poor for the Lankford coefficient \( r_{45} \) (diagonal to rolling direction). The Hill’48 yield condition underestimates \( r_{45} \).

### 3.1.2. Empirical modelling

In figure 5 the predictions of the empirical model are displayed. It was assumed that the respective other Lankford coefficients are known from tensile tests.

![Figure 5. Empirical predictions (via earing)](image)

The predictions for \( r_{45} \) are very good and the predictions for \( r_{90} \) are slightly worse. A comparison of figure 4 and figure 5 leads to the idea that the combination of the two methods (Hill’48 and empirical model) can lead to better results (compare figure 5).

![Figure 6. Combination of Hill’48 predictions and empirical predictions](image)

The Lankford coefficients \( r_{90} \) are determined by the Hill’48 yield condition. This means that \( r_{90} \) is calculated by \( r_0 \), \( \sigma_0 \), and \( \sigma_{90} \). The Lankford coefficients \( r_{45} \) are determined by the empirical model. The Lankford coefficient \( r_{45} \) is calculated by \( h_e \), \( r_0 \) and \( r_{90} \). For this approach it was assumed that the Lankford coefficient \( r_0 \), the yield stresses \( \sigma_0 \) and \( \sigma_{90} \), and the mean earing height \( h_e \) are known.

### 3.2. Lankford coefficients for UHSLA steels

Figure 7 shows the Lankford coefficients determined for Ultra High Strength Low Alloy steels using the methods presented here. The predicted Lankford coefficients are compared to Lankford coefficients determined in tensile tests. For the tensile tests two strain ranges are used:

- between 2\% and \( A_{k_e} \cdot 1\% \),
- between 0\% and \( A_{k_e} \cdot 2\% \).
For the ZE800 both strain ranges show very similar results. The Lankford coefficients for the ZE800 are very reliable.

An expansion of the strain range has almost no influence to the Lankford coefficient $r_0$. This means that this measurement is also very reliable and that $r_0$ is suitable to be the basis for further calculations.

The expansion of the strain range makes it possible to obtain Lankford coefficients $r_{45}$ and $r_{90}$ for the ZE850 and the ZE1000. But the obtained Lankford coefficients do not seem to be reliable due to their height.

### 3.3. FEA prediction of earing tests

In [9] it is shown that earing can be predicted correctly by FEA when a reasonable material model is used. This material model should meet both Lankford coefficients $r_i$ and initial yield stress $\sigma_i$ from tensile tests.

PAM-STAMP 2G (V2012.2) is used to model the cup drawing test. Shell elements are used for the blank and rigid bodies for the tools. The contact between tools and blank is modelled by a nonlinear penalty contact with coulombs friction. The friction value is calibrated by comparing the measured punch force to simulated punch forces.
The anisotropy is modelled by Barlat’2000 yield condition with biaxial measurements from bulge and disk compression test. The Lankford coefficients are determined by the methods proposed before.

In figure 8 the FEA predictions for the earing height are displayed. Poor predictions were made for the Hill’48 method. The earing height is underestimated for all three materials. Comparing this result with Figure 7, it can be seen that too low \( r_{45} \) predictions produce this result. The Hill’48 yield condition is not suitable to predict \( r_{45} \) of UHSLA steels.

For the ZE800 all other earing height predictions are very similar, since the used Lankford coefficients were also very similar.

The prediction accuracy of the empirical earing model depends on the quality of the already known Lankford coefficients. Underestimation (ZE850), overestimating (ZE1000) and good match (ZE800) are possible. The good result for the ZE800 can be explained by a good measurement for \( r_\theta \) and \( r_{90} \).

The best earing prediction for the ZE850 and the ZE1000 is done by the combination of the Hill’48 model with the empirical earing model. Here, \( r_{90} \) is determined by the Hill’48 yield condition. This leads to good results.

4. Conclusion
In this study methods are analyzed to predict Lankford coefficients when a direct measurement by tensile tests is not possible. The best results were achieved with a method, which combines the Hill’48 yield condition (for \( r_{90} \)) with an empirical model of the earing height (for \( r_{45} \)). This means that the Lankford coefficient \( r_\theta \), the yield stresses \( \sigma_\theta \) and \( \sigma_{90} \), and the mean earing height \( h_e \) must be known.

The Lankford coefficients predicted by this method are in good agreement with measurements from tensile tests. When the predicted Lankford coefficients are used in forming simulation of a cup drawing, good earing height predictions are possible.

A disadvantage of this method is that at least one Lankford coefficient must be known. If this constraint is not given, the Lankford coefficients may be determined by a multi-scale model [10].

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