Influence of Yield Condition on the Accuracy of Earing Prediction for Steel Sheets

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Abstract. This paper is dealing with the material modelling of steel sheets and is focused on the input parameters for a correct earing prediction. The cause of earing is the anisotropy of the rolled sheet which is usually modelled by a yield criterion. In a first study earing predictions with the Hill’48 yield criterion and with the Barlat’2000 yield criterion are conducted for different steel grades between 200 and 800 MPa yield strength. A comparison of the results shows that the Barlat’2000 yield criterion leads in almost all cases to a better earing prediction. In a second study the measurements for the Barlat’2000 law were analysed, to find the main parameter influencing the accuracy in earing prediction. The results of this study show that it is not affected by the biaxial measurements, but by the yield strength in 45° regarding to rolling direction.

1. Introduction
Forming simulations by Finite Element Analysis are well-established in the development process of sheet metal parts in order to predict cracks, wrinkles, springback and press forces. One of the main influencing variables on the simulation quality is the material model. Sheet metals usually exhibit a plastic anisotropy influenced by previous processes like hot rolling, cold rolling and annealing. One manifestation of the plastic anisotropy is a phenomenon called earing. Earing occurs during deep drawing of a cylindrical cup and can be described as a periodic variation of wall height around the diameter of the finished cup (see figure 1). In accordance to DIN EN 1669 the anisotropy can be described by the Mean Ear Height $h_e$ and the Earing in percent $Z$.

In figure 2 the correlation between earing and anisotropy can be seen by means of the planar anisotropy. An increasing anisotropy is leading to an increasing earing.
All materials, used in this study, are cold rolled single-phase steels: mild steels (DC04), steels for case hardening (16MnCr5) and high strength low-alloy steels (HC420LA and ZE-grades). BILSTEIN’s ZE-grades are non-standard high strength low-alloy steels, which are usually customized to the specific strip application. This is demonstrated with the help of two variants of a ZE800. These materials are adjusted to different directional characteristics because the application, respectively the position in forming press regarding to rolling direction is different. A similar case is the material DC04-ER. This is a so called “Earing Reduced” mild steel. This material is adjusted to nearly isotropic behavior due to a combination of cold rolling and heat treatment strategy.

Many authors show for aluminum alloys that the accuracy of earing prediction is depending to the chosen yield criterion [1], [2], [3]. For this reason, the influence of the yield criterion on the accuracy of earing prediction is analysed also for steel sheets. The Hill’48 criterion [4] is compared to the Barlat’2000 criterion [5].

2. Earing Prediction
PAM-STAMP 2G (V2012.2) was used to model the cup drawing test. The blank was modelled by shell elements and the tools by rigid bodies. The contact between tools and blank was modelled by a nonlinear penalty contact with coulombs friction. The friction value was calibrated by comparing the measured punch force to simulated punch forces.

The influence of the yield condition to earing prediction can be seen in figure 3, where earing predictions for the Hill’48 and the Barlat’2000 yield criterion are compared.
Both yield conditions can describe the influence of anisotropy to earing. Both models predict bigger ears for materials with higher anisotropy. But a comparison of the results shows that the Barlat’2000 yield criterion leads in almost all cases to a much better earing prediction. The deviation between simulation and experiment for the Barlat’2000 criterion is only small. For the Hill’48 criterion the deviation tends to increase with increasing anisotropy.

3. Input parameters

One difference of the used yield criteria are the input parameters, respectively the measurements for characterization. The input parameters for the Hill’48 criterion are the r-values ($r_{00}$, $r_{45}$, $r_{90}$ from tensile tests). The Barlat’2000 criterion requires the r-values, the yield stresses ($\sigma_{00}$, $\sigma_{45}$, $\sigma_{90}$ from tensile tests), the biaxial yield stress $\sigma_{bi}$ (from hydraulic bulge tests) and the biaxial anisotropy $r_{bi}$ (from disc compression tests). Further it is possible to choose the exponent M. The influence to earing prediction of these input parameters was analysed by using Barlat’2000 models with different input parameter sets (see Table 1).

| Model   | $r_{00}$ | $r_{45}$ | $r_{90}$ | $\sigma_{00}$ | $\sigma_{45}$ | $\sigma_{90}$ | $\sigma_{bi}$ | $r_{bi}$ | M  |
|---------|---------|---------|---------|--------------|--------------|--------------|--------------|---------|----|
| Model M6 | M       | M       | M       | M            | M            | M            | M            | M       | 6  |
| Model M2 | M       | M       | M       | M            | M            | M            | M            | M       | 2  |
| Model Bi | M       | M       | M       | M            | M            | M            | H            | H       | 6  |
| Model ST | M       | M       | M       | M            | H            | H            | H            | H       | 6  |
| Model SD | M       | M       | M       | M            | H            | M            | H            | H       | 6  |
| Model Si | M       | M       | M       | M            | H            | H            | H            | H       | 6  |
| Model Hi | M       | M       | M       | M            | H            | H            | H            | H       | 2  |

M: Measurement; H: Prediction by Hill’48

The input parameters for material model calibration were switched between measurements and predictions from Hill’48 model. The exponent was changed between $M=2$ and $M=6$. The results of these simulations are displayed in figure 4.

![Figure 4](image_url)

Figure 4. Influence of Input Parameters to Earing Prediction.

Comparing model M6 with Bi shows that the results are changing only slightly when biaxial measurements are taken into account. This means that one of the main differences (biaxial measurements) between Barlat’2000 and Hill’48 criterion has nearly no effect to earing prediction. Comparing model M6, M2, Bi and ST with SD, Si and Hi shows that the prediction accuracy is improved strongly when the yield criterion includes the yield strength $\sigma_{45}$. The parameter $\sigma_{45}$ seems to be the main parameter causing the improvement in earing prediction.
In figure 5 the predictions of the yield criteria for material characteristics to the measurements of the material characterization are compared.

![Figure 5. Predictions for material characteristics](image)

As expected the Barlat’2000 predictions for $\sigma_{45}$ are better than the Hill’48 predictions. The predictions for $\sigma_{bi}$ are also better. But as mentioned before, this improvement in the material model has only slightly effects on earing prediction. The effect of $\sigma_{90}$ on earing prediction is small, because both used yield criteria predicts $\sigma_{90}$ very well. Note that this does not mean that $\sigma_{90}$ has no influence on earing prediction. It means only that both yield criteria are suitable to predict $\sigma_{90}$. The influence of the exponent M on earing prediction seems to be unclear. This results from the model calibration. An exponent M=2 for the Barlat’2000 criterion is not suitable to predict all measured material characteristics (e.g. $r_{45}$ for Barlat’2000).

4. Conclusion
For the Hill’48 criterion the prediction accuracy of earing is decreasing with increasing anisotropy. So, it is useful to apply a more complex yield criterion for materials with high anisotropy. The prediction accuracy of the Barlat’2000 criterion is much better than the Hill’48 model. This improvement is caused by considering $\sigma_{45}$ in the yield criterion. The biaxial measurements $\sigma_{bi}$ and $r_{bi}$ do not improve the results. This means that the better prediction accuracy of the Barlat’2000 criterion is caused by the flexibility to meet both $r_i$ and $\sigma_i$ from tensile tests and not by the more complex material characterization (biaxial measurements).

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