Springback Simulation with Complex Hardening Material Models

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Summary:

The rise in the light weight automotive design necessitates the usage of the high strength steels, which increase the springback tendency in the sheet metal forming. Contrary to the conventional steels, the high strength steels showing larger Bauschinger effect require complex hardening material models to predict the springback accurately. Nowadays lots of FEM material models regarding isotropic-kinematic hardening exist as well as a variety of complex measurements to determine the material parameters of these models. In this study, Yoshida-Uemori material model [1, 2] implemented into LS-DYNA via the user material interface is used to perform channel draw tests with various die radii for some steel grades. In order to detect the springback accuracy of this user model, the standard LS-DYNA material models Mat36 and Mat103 have been evaluated. Different test strategies to identify the material parameters by LS-OPT have been investigated to clarify that the test used to calibrate the material model is as important as the material model.

Keywords:

Bauschinger effect, isotropic-kinematic hardening, model calibration, channel draw test, springback

1 Introduction

One of the most important challenges of the sheet metal forming simulation is the precise springback estimation of the high strength steels. The Bauschinger effect the main reason for the springback and rather dominant in case of the high strength steels can be observed when reversing the direction of straining, for instance, compression followed by tension, or shearing (as in a torsion test on a thin-walled tube) followed by shearing in the opposite direction. Simply, the Bauschinger effect is the reduction of the yield stress upon reloading that follows unloading [3]. For the FEM modelling of the Bauschinger effect, the combined isotropic-kinematic hardening concept has been used for a long time. Although lots of material models have been proposed to deal with the Bauschinger effect, the choice of the most proper one is still a conflict for the user. Some crucial questions that the user can confront while performing springback simulations may be arranged as below:

- Is it economical to use the combined hardening material models instead of the isotropic ones for all of the structural parts?
- Are the combined hardening material models always the correct choices for all of the steel grades?
- Does the most complex combined hardening material model yield always the more precise results in comparison to the simple combined one?

Proportional to the complexity of the material model, the number of the material parameters increases. Recently, by means of the useful optimization software like LS-OPT, the user can easily determine the material parameters. Bending-reverse bending and tension-compression tests are some options for the combined hardening material model calibration. At that point the user should be aware of the fact that different experiments as well as the same experiment performed with varying conditions can result in different parameter sets which may affect the springback prediction.

In the context of this study, the springback predictability of a conventional microalloyed steel grade (HSLA) MHZ 340, a dual phase steel DP-K 34/60, a transformation induced plasticity steel (TRIP) RA-K 40/70 and a complex phase steel CP-K 60/80 is investigated via carrying out channel draw simulations. As a material model, the user implemented Yoshida-Uemori material model as well as the standard LS-DYNA material models Mat103 and Mat36 have been utilized. Mat103 is a relatively simple combined isotropic-kinematic hardening material model with respect to the user implemented Yoshida-Uemori, whereas Mat36 represents a basic isotropic one. A yield and cyclic stress-strain curve obtained either from the in-plane tension-compression and compression-tension test, or from the out-of-plane bending and reverse bending experiment are the basis for the LS-OPT based material model validation. Besides, the continuous and interrupted test strategies are discussed to distinguish these from each other from the view of the Bauschinger effect [4].

2 User Implemented Yoshida-Uemori Material Model

An elasto-plastic combined isotropic-kinematic hardening material model originally proposed by Yoshida and Uemori [1, 2] has been implemented as a user model for the shell elements. The time integration of the evolution equations is achieved by using the backward Euler integration scheme. The global solution for the model is obtained either explicitly or implicitly via a consistent material tangent formulation by means of the Newton Raphson method. A Hill48 yield criterion with plane stress and plane isotropy ($r_0=r_{45}=r_{90}$) is employed for the yield and the boundary function.

$$\boldsymbol{\phi} = \sqrt{\boldsymbol{\sigma}_{11}^2 - \frac{2\boldsymbol{r}}{\boldsymbol{r}+1}\boldsymbol{\sigma}_{11}\boldsymbol{\sigma}_{22} + \boldsymbol{\sigma}_{22}^2 + 2\left(\frac{2\boldsymbol{r}+1}{\boldsymbol{r}+1}\right)\boldsymbol{\sigma}_{12}^2} = \sqrt{\hat{\boldsymbol{\sigma}}^T \boldsymbol{T}_A \hat{\boldsymbol{\sigma}}} \tag{1}$$

$$\hat{\boldsymbol{\sigma}} = \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{12} \end{bmatrix} \quad \boldsymbol{T}_A = \begin{bmatrix} 1 & \dfrac{-r}{r+1} & 0 \\ \dfrac{-r}{r+1} & 1 & 0 \\ 0 & 0 & 2\left(\dfrac{2r+1}{r+1}\right) \end{bmatrix} \quad \boldsymbol{\varepsilon}^p = \begin{pmatrix} \varepsilon_{11}^p \\ \varepsilon_{22}^p \\ 2\varepsilon_{12}^p \end{pmatrix}$$

$$\hat{S}_{ef} = \hat{\boldsymbol{\sigma}} - \boldsymbol{\alpha}$$
$$f = \phi(\boldsymbol{\sigma} - \boldsymbol{\alpha}) - Y = 0 \quad \wedge \quad F = \phi(\boldsymbol{\sigma} - \boldsymbol{\beta}) - (B + R) = 0 \tag{2}$$

In equation (2), *f* and *F* are denoting the yield and the boundary functions respectively, where *Y* and *B* are the material parameters while α, β and *R* are the history variables.

$$\boldsymbol{D}^p = \dot{\lambda}\frac{\partial f}{\partial \boldsymbol{\sigma}} \quad \boldsymbol{\varepsilon}^p = \dot{\lambda}\frac{\boldsymbol{T}_A \hat{\boldsymbol{S}}_{ef}}{\sqrt{\hat{\boldsymbol{S}}_{ef}^T \boldsymbol{T}_A \hat{\boldsymbol{S}}_{ef}}} \tag{3}$$

$$\dot{\boldsymbol{\alpha}}* = C\left(\frac{a}{Y}\hat{S}_{ef} - \sqrt{\frac{a}{\bar{\alpha}*}}\boldsymbol{\alpha}*\right)\dot{p} \quad \boldsymbol{\alpha}* = \boldsymbol{\alpha} - \boldsymbol{\beta} \quad \dot{p} = \sqrt{\frac{2}{3}\boldsymbol{D}^p : \boldsymbol{D}^p} \quad \boldsymbol{\alpha} = \begin{pmatrix} \alpha_{11} \\ \alpha_{22} \\ \alpha_{12} \end{pmatrix} \quad \boldsymbol{\beta} = \begin{pmatrix} \beta_{11} \\ \beta_{22} \\ \beta_{12} \end{pmatrix}$$
$$a = B + R - Y \quad \wedge \quad \bar{\alpha}* = \phi(\hat{\alpha}*) = \sqrt{\alpha*_{11}^2 - \frac{2r}{r+1}\alpha*_{11}\,\alpha*_{22} + \alpha*_{22}^2 + 2\left(\frac{2r+1}{r+1}\right)\alpha*_{12}^2} \tag{4}$$

$$\dot{R} = k(R_{sat} - R)\dot{\lambda}X \tag{5}$$

$$\dot{\hat{\boldsymbol{\beta}}}' = k\left(\frac{2}{3}b\boldsymbol{D}^p - \hat{\boldsymbol{\beta}}'\dot{p}\right) \quad \hat{\boldsymbol{\beta}}' = \boldsymbol{P}\hat{\boldsymbol{\beta}} \quad \boldsymbol{P} = \frac{1}{3}\begin{bmatrix} 2 & -1 & 0 \\ -1 & 2 & 0 \\ 0 & 0 & 3 \end{bmatrix} \tag{6}$$

C, R_{sat}, *k* and *b* are the other material parameters of this implementation. In the identity (6), β' denotes the deviatoric component of β.Totally, there are six material parameters (*Y*, *B*, *C*, R_{sat}, *k*, *b*) to be determined by the optimization. The original Yoshida-Uemori material model postulated [1, 2] differs from this implementation via its work hardening stagnation equations. That is, the user model does not regard the identities mentioned.

3 Testing Strategies and Model Calibration

Isotropic hardening material models like Mat36 necessitate simple uniaxial tests without requiring any inverse identification. However, the development of the new complex hardening material models has raised the need for the sophisticated experiments to validate these models by some optimization software. Recently, the availability of the optimization tools working parallel to the FEM programs has extended the possible model calibration test strategies of the sheet metal from an in plane tension-compression or compression-tension test or shear tests to a large variety of experiments. The in plane tension-compression or compression-tension test strategy can be fulfilled either by an interrupted or by a continuous test procedure. In the continuous test procedure, with the aid of special specimen geometry and state of the art testing devices, a direct load reversal without buckling under compression stresses is achievable. On the other hand, the interrupted test procedure allows a load reversal of the secondary specimen manufactured from an initial pre strained one [4].

Bake hardening and ageing are two important material properties increasing the yield strength of the steel sheet. Both of them depend strongly on the amount of the solute carbon content. The diffusion of carbon to dislocations and the pinning of dislocations impairing a subsequent deformation is the mechanism leading to the bake hardening and the ageing. Whilst the ageing effect usually takes place at room temperature in a period of several weeks or months, the bake hardening effect arises at relatively high temperatures within a few minutes (e.g. 20 min, 170 ℃). The ageing phenomenon occurs before forming and painting during storage and transportation of the material [5]. The multiphase and the TRIP steels have a tendency to show the ageing effect because of their high carbon content and complex microstructure. According to the previous researches, a pre deformed dual phase specimen shows around 2/3 of the bake hardening effect if it is stored long enough at room temperature. To check the effect of the ageing on the Bauschinger, the interrupted tests of two 12% pre strained specimens have been carried out. The first specimen was baked at 170 ℃ / 20 min before applying the compression force whereas the other one was directly tested under compression. In Fig. 1, the left diagram summarizes both of the mentioned interrupted tests as a stress-strain curve of DP-K 34/60. Besides, the right diagram depicts the Bauschinger coefficients for a proof strain of 0.2%. According to Fig. 1, regarding the correlation done between the bake hardening and the ageing effect, the Bauschinger coefficient, denoted by β, varies between 0.5 and 0.8 depending on the time interval used for the secondary specimen preparation and the test set-up. Consequently, as the springback takes place directly after the forming, the correct material model identification makes it necessary to use either the continuous test procedure or the interrupted test with the immediate testing of the secondary specimen [4].

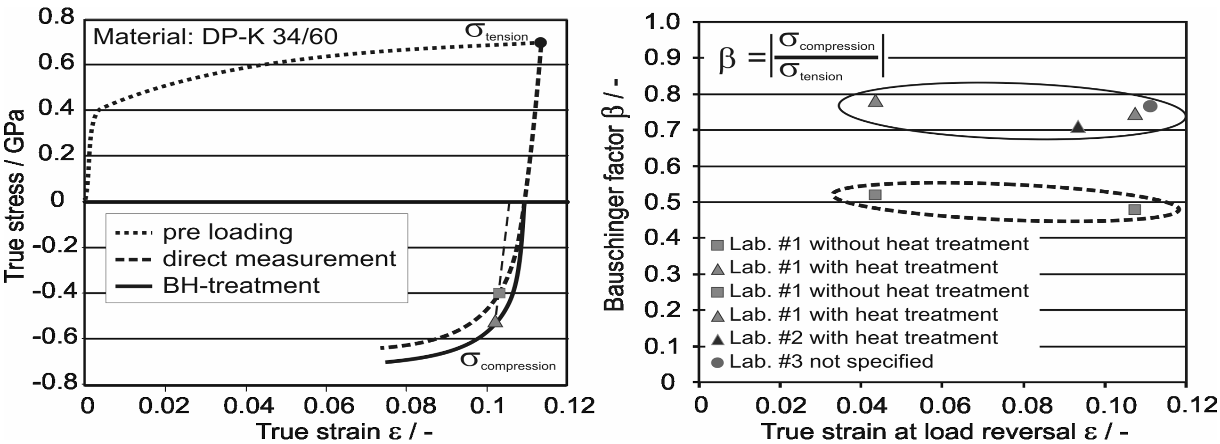

Fig. 1: Bake hardening effect in tension-compression tests [4]

In this study, material parameters were determined either by using the continuous (DP-K 34/60, RA-K 40/70, PM-K 60/80) or the interrupted experiments (MHZ 340) for the inverse identification. The weight factors for the extrapolated tensile curve and the tension-compression test were 0.4 and 0.6 in case of the implemented user model. For Mat103, the parameter α implying the distribution of the kinematic or isotropic hardening and sigy, referring to the yield value, were the only parameters to be identified from the cyclic test. The optimization was accomplished via LS-OPT running parallel to LS-DYNA. Additionally, to analyse whether the in-plane cyclic tension-compression and out-of-plane bending and reverse bending tests yield the same parameter set and the same springback, the behaviour of DP-K 34/60 was evaluated by employing Mat103.

The best fits of the material models in interest for the in-plane cyclic tension-compression and the tensile test are exhibited by figures 2 (DP-K 34/60), 3 (RA-K 40/70), 4 (CP-K 60/80) and 5 (MHZ 340). According to Fig. 2 and Fig. 3, we can easily conclude that Mat103 is unable to result in a smooth behaviour as Yoshida-Uemori does. In other words, it is not flexible enough for the best approximation. Contrary to Fig. 2 and Fig. 3, Fig. 4 shows that Mat103 is almost as good as Yoshida-Uemori material model to meet the experimental curve. Hence, depending on the steel grade, simple combined hardening models like Mat103 may also be the correct choice for the springback prediction. Considering Fig. 5, the deviation between the extrapolated yield curve and Yoshida-Uemori tensile optimization increases after 50% plastic strain. The yield curves were extrapolated by TEM method based on the idea to generate one additional stress point at a strain level of approximately two to four times the uniform elongation from the tensile test [6]. As the calibration up to 50% plastic strain is satisfactory enough, the optimization is acceptable to neglect the deviation occurring in an interval where the experimental measurement of the stresses is not possible. Besides the left diagram of Fig. 5 indicates that the compression part of the cyclic test can be described by an isotropic hardening material model like Mat36 (m=2) with a little error arising from the art of plastification.

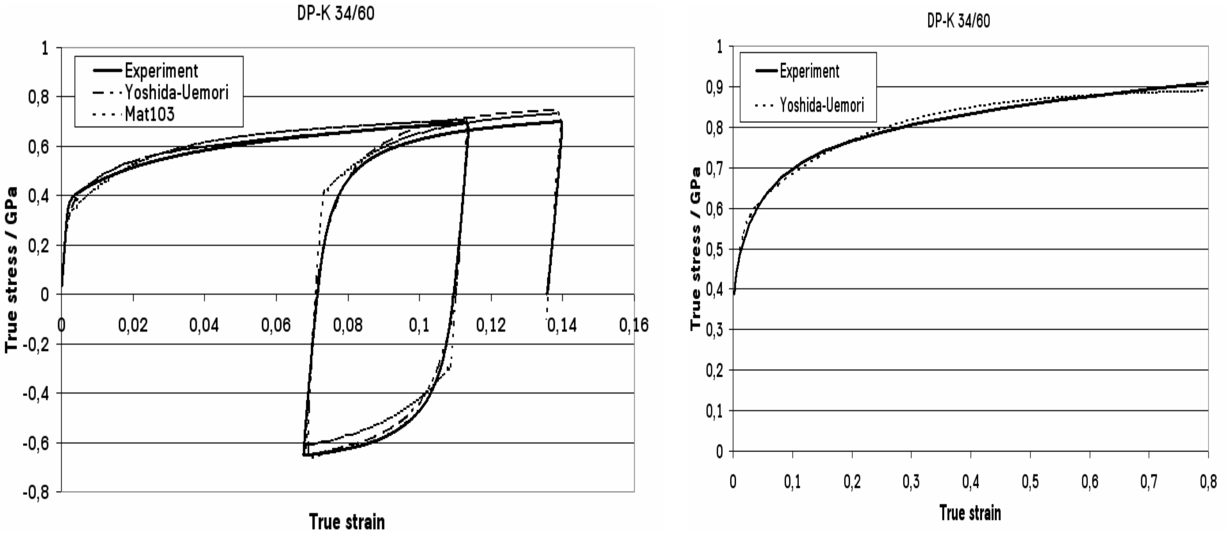

Fig. 2: Material model calibration of Yoshida-Uemori and Mat103 for DP-K 34/60

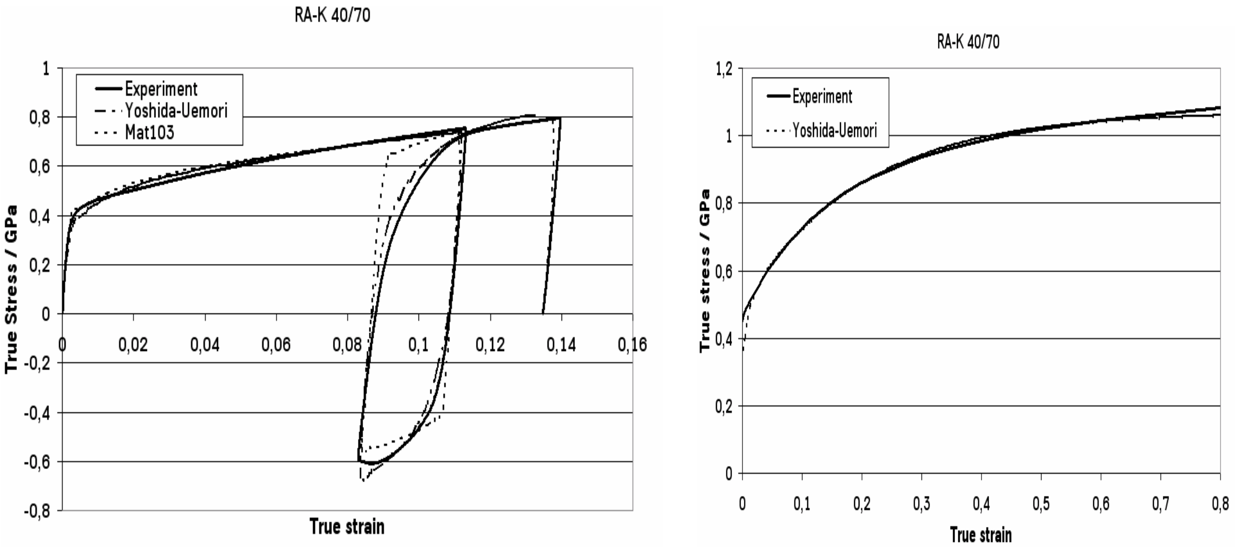

Fig. 3: Material model calibration of Yoshida-Uemori and Mat103 for RA-K 40/70

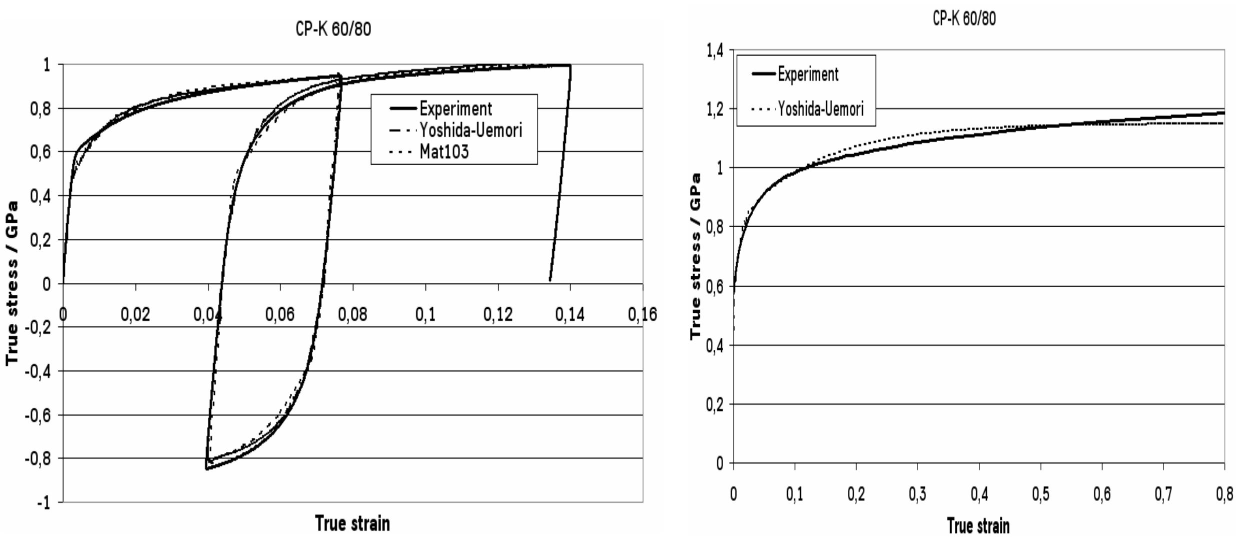

Fig. 4: Material model calibration of Yoshida-Uemori and Mat103 for CP-K 60/80

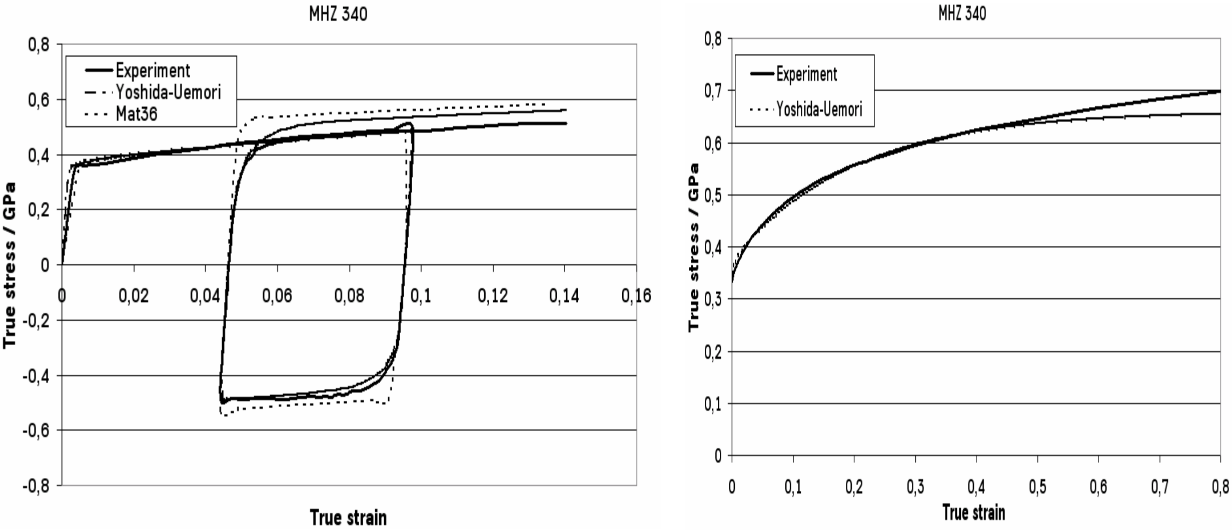

Fig. 5: Material model calibration of Yoshida-Uemori for MHZ 340

The diagram below compares the calibration of Mat103 (out-of-plane) obtained from the bending and reverse bending test [7] with Mat103 (in-plane) validated by means of the cyclic tension-compression test (denoted as Experiment in Fig. 6) for DP-K 34/60. The parameter α referring to the ratio of kinematic to isotropic hardening is 0.47 for Mat103 (in-plane), whereas it has the value of 0.068 for Mat103 (out-of-plane). The large Bauschinger difference of these optimizations makes it essential to research the experiments used for the identification of the combined isotropic-kinematic hardening models further. In the next topic, by keeping this deviation in mind, we can analyze the springback predictions of these two calibrations.

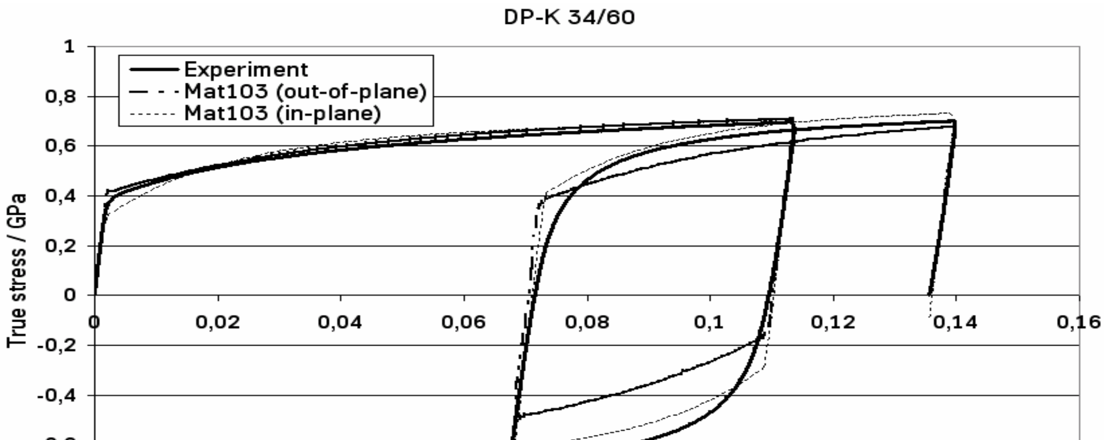

Fig. 6: Hardening characterization of DP-K 34/60 via two different kinds of tests

4 Numerical Applications for Springback Prediction

To investigate the impact of the material model and its calibration on the springback, channel draw tests were performed. The thickness of the steel grades used was 1.5 mm except for DP-K 34/60 having a thickness of 1.4 mm. The experimental set-up is given in Fig. 7. Since the experimental set-up possesses symmetry, only one quarter of the whole geometry was modelled for the FEM simulations. A fully integrated shell element (Element type 16) formulation with 5 integration points through the thickness was utilized for the 1 mm x 1mm in size blank elements. The steel specific friction coefficients were calibrated so that the experimental punch forces were met.

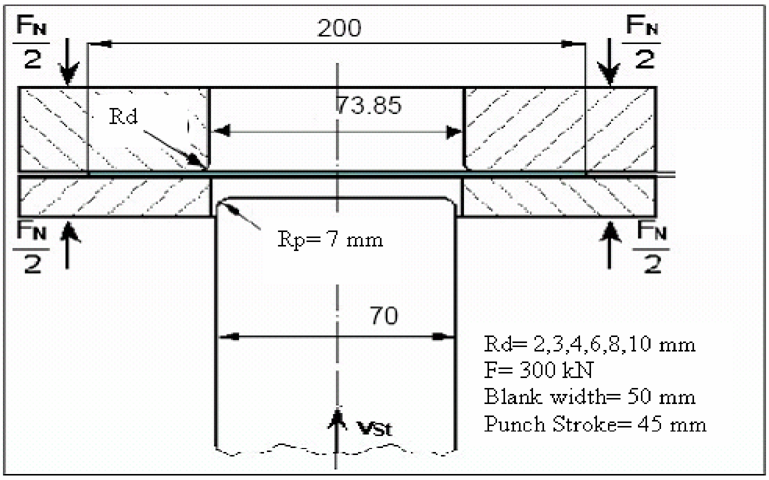

Fig. 7: Experimental set-up for the channel draw test

The quantitative interpretation of the springback forced us to introduce a mean deviation of the simulation geometry from the experimental one. As it is exhibited in Fig. 8, the mean deviation of the simulation was computed via dividing the area between the experiment and the simulation by the profile length. Positive deviations imply lower springback, whilst negative ones refer to more springback in comparison to the experiment. As long as the deviation is below 0.5 / mm, we assume a good correlation of the experiment and the simulation [4].

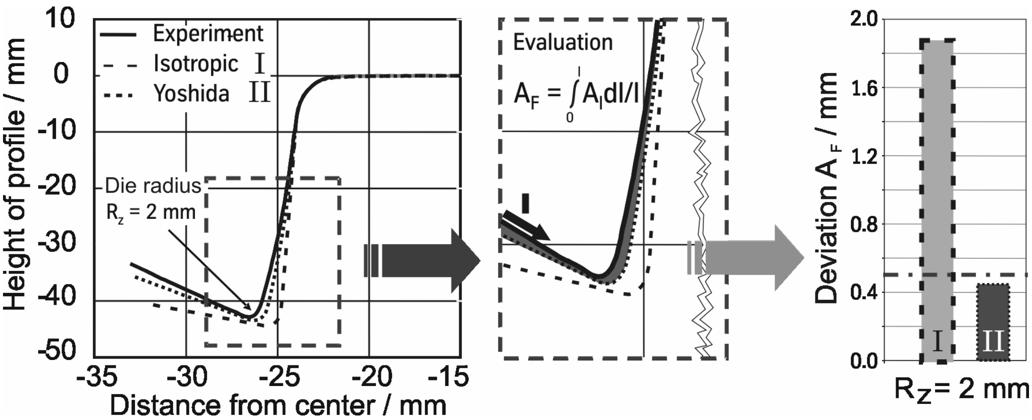

Fig. 8: Evaluation parameter for deviations compared with experimental results [4]

In Fig. 9, the springback prediction errors of the material models discussed in the previous topics are shown for DP-K 34/60. Mat36 (m=2) representing the isotropic hardening material model yields acceptable results as the die radius increases from 2 to 10 mm. The quality of the prediction is generally improved when Mat103 (in-plane) or Mat103 (out-of-plane) were employed instead of the isotropic hardening model for the small die radii. Having Fig. 6 in mind, the most astonishing point to be underlined is the little effect of two different Mat103 model calibrations on the springback. Focusing on the diagram, the prediction errors of both Mat103 calibrations are very close to each other for 2 and 3 mm die radii. Regarding all the results together, the best prediction was obtained by means of the user implemented Yoshida-Uemori material model. However, because of the long computation time of the user implemented Yoshida-Uemori model, it would be economical to use the isotropic hardening model for the large die radii in case of DP-K 34/60. Similarly, in figures 10 and 11 (RA-K 40/70, CP-K 60/80), Mat36 (m=2) is the worst application to forecast the springback for 2 mm die radius. Paying focus on Fig. 4 and Fig. 11, Mat103 may be a substitution for Yoshida-Uemori material model when assessing the springback behaviour of CP-K 60/80. In general, Yoshida-Uemori model is the most reliable to evaluate the springback of three high strength steels in attention. In contrast to the previous statement, Yoshida-Uemori model predicts the springback in the wrong direction (curl-out) for the MHZ 340 profile having a die radius of 2 mm (Fig. 12). As Mat36 (m=2) satisfies the required springback accuracy for the conventional microalloyed steel MHZ 340, the employment of Yoshida-Uemori model for this steel grade would be a waste of time and money necessary to carry out the expensive cyclic tests.

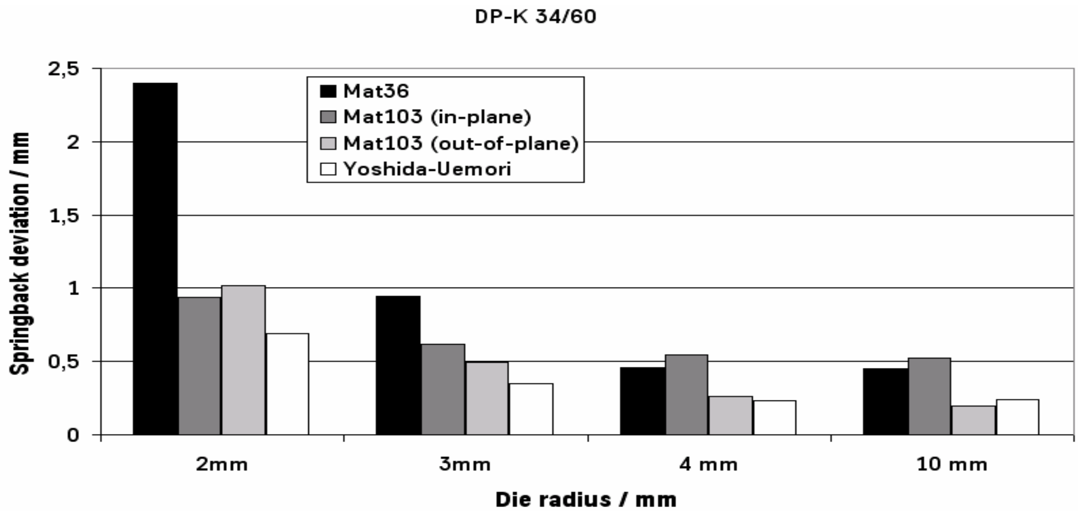

Fig. 9: FEM springback prediction errors for DP-K 34/60

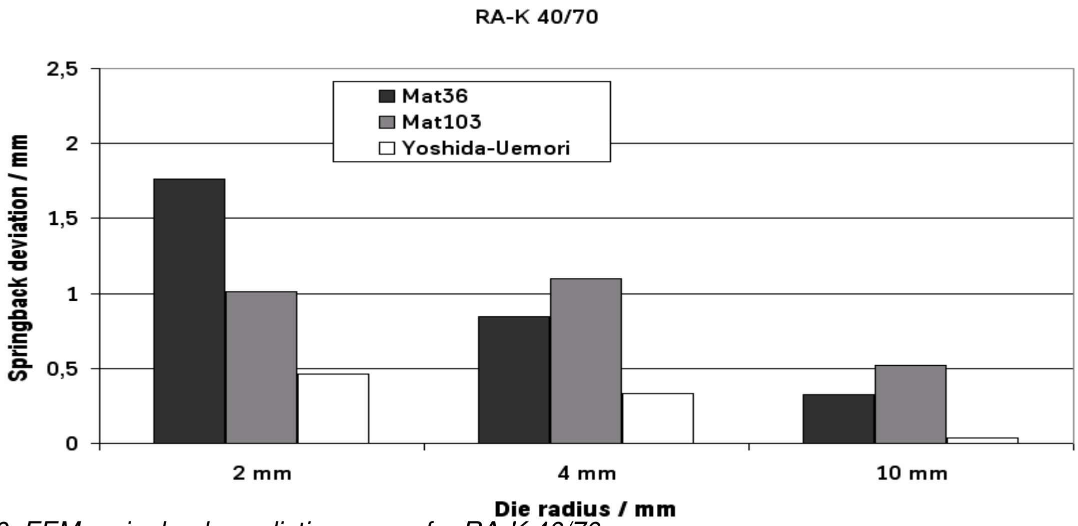

Fig. 10: FEM springback prediction errors for RA-K 40/70

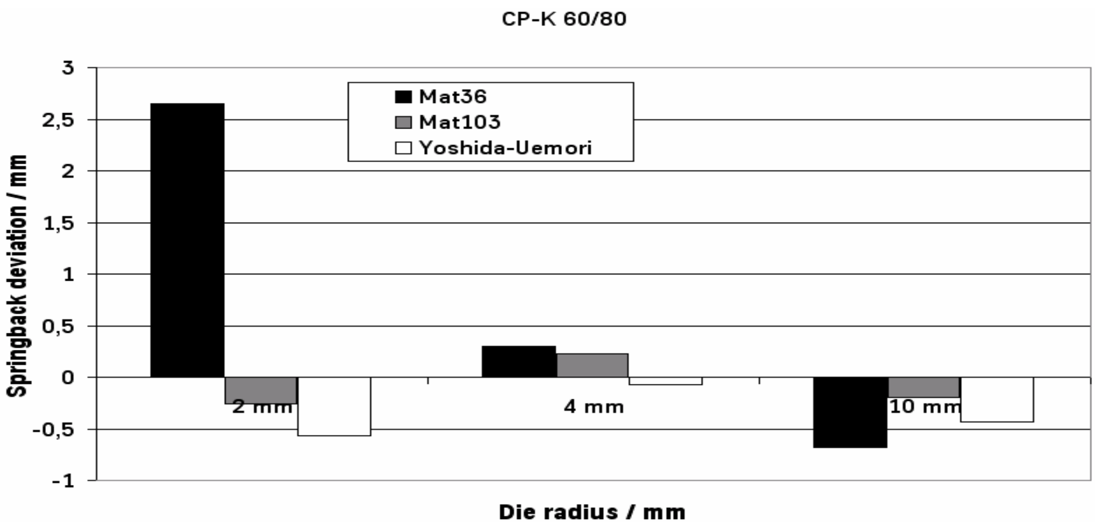

Fig. 11: FEM springback prediction errors for CP-K 60/80

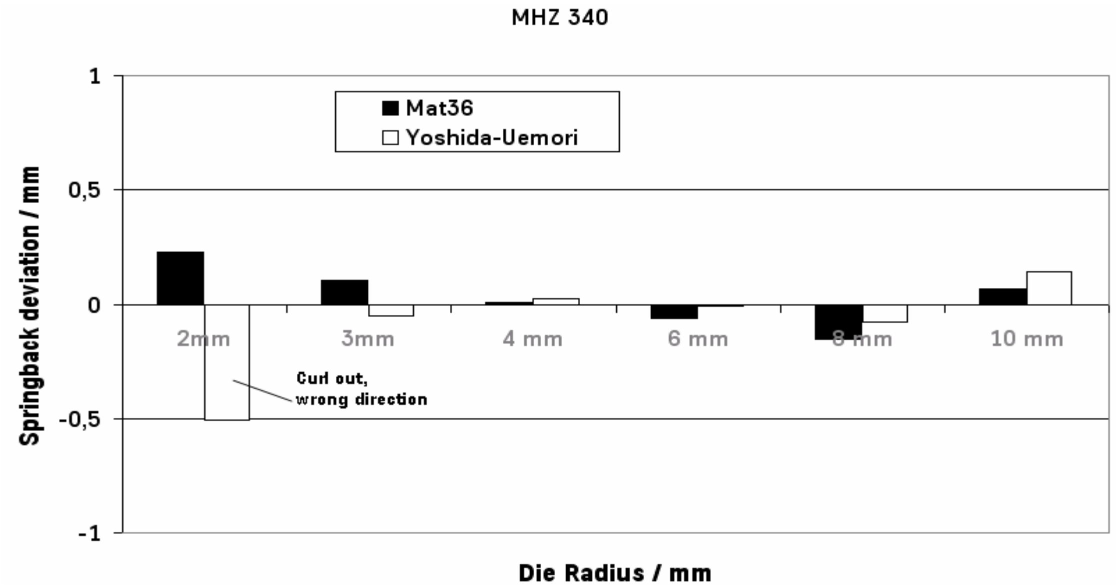

Fig. 12: FEM springback prediction errors for MHZ 340

5 Conclusion

The springback prediction of the high strength steels requires not only sophisticated FEM material models but also state-of-the-art experiments allowing the best fit of them. Despite the existence of several tests to characterize the Bauschinger effect, the parameter validation via these ones does not yield one unique identical parameter set. In other words, these tests, such as cyclic tension-compression and bending-reverse bending tests could not be obtained from each other by FEM. Moreover, to eliminate the aging or the bake hardening effect, the continuous test procedure or the interrupted test with the immediate testing of the secondary specimen should be preferred when performing the cyclic tension-compression test. As two different calibrations of Mat103 estimate almost the same springback for the small die radii (DP-K 34/60), we have to think about whether channel draw experiments presented here are complex enough to distinguish between the hardening models. According to our results, Yoshida-Uemori model is the most reliable and also the most expensive one to detect the springback of the high strength steels. To save some computation time, an isotropic model like Mat36 (m=2) may be employed when simulating a die radius / sheet thickness ratio of >3.0. Additionally, depending on the steel grade, for example for CP-K 60/80, Mat103 can be a substitution for Yoshida-Uemori model. Here we have to emphasize that Mat103 could be calibrated via the simple Bauschinger coefficient. Contrary to the multiphase steels, the springback simulation with the isotropic material model Mat36 (m=2) maintains good results for all the die radii of the conventional microalloyed steel grade investigated.

6 Literature

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