Forming simulation for TWIP steel

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Abstract. This paper introduces a new generation of industrially available cold rolled TWIP steel. The TWIP900 is a high manganese steel with approx. 19% manganese and shows a stable austenitic structure at room temperature. The focus of the paper is on the forming behavior, which is remarkable compared to other industrially available sheet metal materials. The key figures of this cold rolled narrow strip are a tensile strength of 900 MPa in combination with an elongation at fracture of 40%. The forming behavior of the material is characterized in tensile tests, bulge tests, and Nakazima tests. A material model for forming simulations is set up and a comparison between different material models is done. Then deep drawing experiments are carried out and numerically simulated. Finally, a flanging and springback study is carried out. A comparison between simulation and experiment demonstrates the good quality of currently industrially applied simulation techniques for TWIP steels.

1. Introduction
The steel materials used in the industry are either ductile or high strength. The special feature of High-Manganese TWIP Steels is that they can be both, high-strength and ductile [1]. An industrially available example of this material group is BILSTEINs TWIP900 (Fe-19Mn-0.4C-Al1).

Figure 1. TWIP steel in comparison to conventional steels (mild and DP steels)
The tensile strength of this cold rolled narrow strip (w<650mm) is approximately 900 MPa in combination with an elongation at fracture of 40%. In figure 1, the TWIP900 is compared to a mild steel DC04 and a high-strength dual phase steel DP800. The DC04 has approximately the same elongation at break and the DP-steel has approximately the same yield strength as the TWIP steel. The tensile strength of this TWIP steel is almost three times that of the mild steel. The elongation at break is twice that of the DP-steel. These remarkable mechanical properties can be explained by the fact that the hardening mechanism is based not only on dislocation gliding but also on twinning (twinning induced plasticity TWIP [1]).

The extraordinary cold formability in combination with the high tensile strength and work hardening exponent allow a new thinking in part and process design. In order to realize the complete lightweight potential for industrial applications, today’s construction actions and rules must be reconsidered. FEA forming simulations are particularly suitable for the development of new part concepts. For this it is necessary that the material behavior is correctly predicted by accurate material models.

Special material models have been developed or proposed for TWIP steels [2-4], as the mechanical behavior of the TWIP steel differs from the one experienced in conventional ferritic grades. An implementation of one of these models in any commercial and industrial used FE-code for forming simulations is not known. On the other hand, it has been shown that the mechanical behavior of TWIP steel can be described using available modeling techniques [5]. In this paper it is analysed if the use of industrial available modeling techniques without special TWIP functions affects the predictive accuracy of forming simulation for the TWIP900.

2. TWIP900
A material model for forming simulations consists of a flow curve and a yield condition. The necking of the sheet is evaluated on the basis of the forming limit curve. Further modelling strategies such as e.g. damage models, kinematic hardening or strain rate models are not used in this study. The idea is to start with simple modeling strategies, and only when they reach their limits further strategies should be applied.

2.1. Material characterization
BILSTEIN is currently carrying out the following test program for forming material cards, which shows a good ratio of effort to use:

- Quasistatic tensile tests in three directions to rolling direction (ISO6892),
- Hydraulic Bulge tests (ISO16808),
- Nakazima tests (ISO12004).

The results from tensile tests and bulge tests for a TWIP900 in 1mm thickness are shown in figure 2.

![Figure 2. Material characterization: results of tensile tests(a) and hydraulic bulge tests (b)](image-url)
The tensile test shows a flow curve that tends to increase linearly. However, the results of the bulge test show that the slope of the stress-strain curve decreases for high strains. When the stress-strain values are converted to a local instantaneous hardening exponent, the result is a curve with a clear maximum. This is remarkable in that the hardening exponent is approximately constant for most conventional steels.

In addition, tensile tests were also carried out diagonally and transversely to the rolling direction and normalized with equation 1 to the results along the rolling direction. 

\[
\bar{\sigma}_l = \frac{\sigma_{l}(\varepsilon)}{\sigma_{00}(\varepsilon)}
\]  

(1)

For conventional steels, the ratio of yield stresses in different directions to the rolling directions (normalized to longitudinal direction) remains approximately constant. The ratio is more or less independent of the strain. For the TWIP steel, there are decreasing stress-ratios, which only become constant at larger strains.

The forming limit curve (FLC) was determined in the Nakazima test according to ISO12004. For steel, the standard recommends a test direction transverse (T) to rolling direction (shaft perpendicular to rolling direction, RD). The preferred failure direction for steel is usually parallel to the rolling direction.

**Figure 3.** Results of Nakazima-tests for TWIP900

But for the equi-biaxial sample \((w=\infty)\), cracks occurred parallel and perpendicular to rolling direction (compare figure 3a). Therefore, the experiments were repeated with the shaft parallel to the rolling direction. The resulting FLC was nearly the same (compare figure 3b). So, the test direction for determining the FLC makes almost no difference for TWIP900.

2.2. Material modelling

A flow curve describes the dependence of stress and plastic strain and is given for strains from zero to at least 1. Since experimental data are available only up to strains of 0.7, the data must be extrapolated using a mathematical approach. In this study the approaches of Swift (equation 2) and Voce (equation 3) are used:

\[
\sigma = \sigma_0 (\varepsilon_0 + \varepsilon)^n
\]  

(2)

\[
\sigma = \sigma_0 + \sigma_{sat}(1 - e^{-C\varepsilon})
\]  

(3)
The approach of Swift (equation 2) is using a constant hardening exponent. As the experimental data show that the hardening exponent is not constant, it is not expected that Swift approach will describe the material well.

Figure 4 shows the extrapolation of the approaches of Swift and Voce.

Figure 4. Comparison of extrapolation approaches for flow curves of TWIP900

Both approaches are able to describe the experimental data. As expected, the results for the Voce approach are better than for the Swift approach. The deviation for the initial yield stress is very large for the Swift approach. Further, the Voce approach describes the slope at the end of the experimental data much better. In the material model of this study the flow curve is given by a table. The content of the table consists of the experimental data from the tensile and bulge test and from the Voce extrapolation.

Another important part of the material model is the yield condition. The yield condition for sheet metal forming takes into account the anisotropy of the material. There are different material models available for this purpose. Most commonly used is the Hill’48 model, as it is particularly easy to determine. A further yield condition is the model Barlat’2000, which allows a more flexible adaptation to measurements. However, more measurements are needed, which makes this model more complex to determine. In contrast to the Hill’48 model, the Barlat’2000 model can only be used for shell elements. In figure 5 both models are compared.

Figure 5. Anisotropy measurements and comparison of different yield conditions

As expected, the Barlat’2000 model shows a much better adaptation to the tensile test results. The Hill’48 model describes the r-values very well, but the deviations for flow stress orthogonal to rolling direction are quite large.
Since the ratio of the yield stresses does not remain constant, the mean value of the strain ratios was used as input parameter for the yield condition. The advantages of this approach have been demonstrated by tensile test simulations in [6].

3. Forming simulation

Two modelling strategies are used to verify the material model. The details of the modelling strategies are shown in table 1.

| Modelling strategy | Element Type | Time-Integration | Software | Friction | Hardening | Plasticity |
|--------------------|--------------|------------------|----------|----------|-----------|------------|
| 1                   | Shell        | explicit         | PAM-STAMP | Coulomb  | Barlat’2000 | isotropic  |
| 2                   | Solid        | implicit         | SIMUFACT | Coulomb  | Hill’48    | isotropic  |

The first model uses shell elements with explicit time integration. In the second model, solid elements with implicit time integration are used. Since the Barlat’2000 model is only applicable to shell elements, the Hill’48 model is used for the second modelling strategy.

In all models Coulomb friction is used. The constant friction value was determined by comparing experimental and numerical punch forces.

3.1. Deep drawing and formability

The main goal of a forming simulation is to predict cracks. A simple forming process in which cracks can occur is deep drawing. Round cups were made according to EN1669 with a punch diameter of 33 mm and drawing ratio $\beta$ of about 1.9.

In the experiments, the blankholder force $F_{BH}$ was increased until cracks occurred. The process setup and experimental results are displayed in figure 6.

Figure 6. Tool setup and experimental results for deep drawing

As expected, no cracks occur at small blank holder forces, and cup base fractures occur at high blankholder forces.

The results of the simulations with modeling strategy 1 (explicit, shell) are shown in figure 7. It was not possible to reproduce the punch forces with a constant friction coefficient. Therefore, the friction has been adjusted so that the punch forces are underestimated for small blank holder forces and overestimated for large blank holder forces.
The evaluation is based on the forming limit curve (FLC). The relative rupture risk $D$ is calculated by equation 4.

$$D = \frac{\varepsilon_1}{\varepsilon_{1,FLC}} (\varepsilon_2)$$

If $D$ is greater than 1, then the simulation predicts a crack.

**Figure 7.** Simulation results with model 1 (shell model)

The experimental results are reproduced correctly. No cracks occur at small blank holder forces, and cup base fractures occur at high blankholder forces.

In figure 8 the simulation results with modelling strategy 2 (implicit, solid) are displayed. To save computation time only a half-model has been calculated (use of symmetry).

**Figure 8.** Simulation results with model 2 (solid model)

The simulations were again evaluated with the rupture risk. Since an FLC should only be used for the middle fiber of a sheet, top and bottom of the sheet were displayed. A crack is only present if both top and bottom show a crack. Modelling strategy 2 shows also a good accuracy. No cracks occur at small blank holder forces, and cup base fractures occur at high blankholder forces.

But when the results of modeling strategy 1 and 2 are compared, there are clear differences.
Further an evaluation was carried out on the strains (thickness changes). Figure 9 shows the sheet thickness along the cup height along the rolling direction. The sheet thicknesses were both experimentally determined and numerical simulated.

Figure 9. Thickness prediction (longitudinal to rolling direction)

After deep drawing, the cups were cut along rolling direction and thickness measurements were performed at different cup heights. The cup height $h$ corresponds to the vertical position with respect to the bottom of the cup and the last measurements were performed on the cup edge.

The sheet thickness increases with increasing cup height. Thinning occurs near the bottom and thickening occurs near the cup edge. An increase in the blank holder force leads to an increase in thinning. With both modeling strategies, this behavior is correctly predicted. However, both modeling strategists predict too much thickening and modeling strategy 1 predicts a slightly too low thinning.

3.2. Flanging and springback
In addition to the prediction of cracks, a sheet metal forming simulation is expected to predict springbacks as well. A simple forming process in which springback can occur is flanging. The principle of flanging is shown in Figure 10.

Figure 10. Tools Setup for flanging

To create a flange, a strip is bent around a straight edge by simple translatory movement of a punch. The strip is clamped between a die and a pad. Parameters of the process are the fillet radius $R$ of the die edge, the clearance $u$ between punch and die and the length $f$ of the unsupported strip. The details of the applied parameter settings are shown in figure 11a.

The flange angle is increasing with increasing radius, clearance and flange length. The numerical modeling is done by both modelling strategies. It should be noted that modeling strategy 1 uses implicit time integration for springback prediction and the explicit time integration is used only for the forming. The simulation results are displayed in figure 11.
Figure 11. Simulation results for flanging and comparison to experiments

Both modeling strategies predict an increase in the flange angle. Qualitatively, both models predict the springback behavior correctly. But quantitatively, strategy 1 (explicit time integration) shows clear deviations from the experimental results. The prediction accuracy of strategy 2 (implicit time integration) is significantly better. The deviations from model 1 are probably due to the time scaling in the explicit forming simulation.

4. Conclusion
In this paper the mechanical behaviour of TWIP-steels and the prediction accuracy of forming simulations for TWIP steel were investigated. Although the material sometimes behaves differently than conventional steels, good results can be achieved using conventional modelling techniques.

In addition, the following results from the material characterization should be emphasized:

- The ratio of the yield stresses in different directions to the rolling direction does not remain constant.
- The hardening exponent does also not remain constant.
- The simple Voce approach is suitable for describing the flow curve.

The main goal of the forming simulation is to predict cracks and springback. This goal is achieved for the TWIP steel. However, deviations exist in the prediction of the stamping force and the thickness distribution. It should also be noted that the forming processes considered here were very simple. Therefore, these studies should be extended to other loading conditions and more complex forming processes.

References
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