Prediction of mechanical properties on large diameter welded pipes through advanced constitutive modelling

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Abstract. Large diameter welded pipes are amongst the most cost effective transportation means for oil and gas. In general, one can differentiate between longitudinally (LSAW) and spirally welded (HSAW) pipes, whereby LSAW pipes are produced from plate and HSAW pipes from coil. Pipe forming involves several cold forming steps, such as (cyclic) bending and (mechanical) expansion. Obviously, the mechanical properties on pipe differ from those of the base material. Detailed understanding of how the mechanical properties evolve during pipe forming would help steel mills to target specific base material properties to ensure the final pipe strength. Therefore, an FE (Finite Element) model, capable of simulating different pipe forming processes, was developed using the commercial FE software Abaqus. Thereby, an advanced constitutive model, accounting for isotropic, kinematic and distortional hardening was implemented via a UMAT user subroutine. A reverse engineering strategy was applied to calibrate the constitutive model. The model was then used to simulate spiral pipe forming of a 28” x 16mm HSAW pipe.

1. Introduction

Large diameter welded pipes are amongst the most cost effective transportation means for oil and gas. In general, one can differentiate between longitudinally (LSAW) and spirally welded (HSAW) pipes, whereby LSAW pipes are produced from plate and HSAW pipes from coil. Pipe forming involves several cold forming steps, such as (cyclic) bending and (mechanical) expansion, as indicated in Figure 1. Obviously, the mechanical properties on pipe differ from those of the base material [1, 2, 3, 4]. The steel manufacturer can control the production of the steel within well-defined process limits. Consequently, he can guarantee the properties of his product. However, the pipe manufacturer only has limited possibilities to control the mechanical properties but eventually he is responsible for the properties of his product, i.e. the pipe.

Detailed understanding of how the mechanical properties evolve during pipe forming would help steel mills to target specific base material properties to ensure the final pipe strength. Therefore, an FE (Finite Element) model, capable of simulating different pipe forming processes, was developed using the commercial FE software Abaqus. Thereby it was assumed that the different steps, except for (mechanical) expansion, can be simulated as pure bending [5]. The mechanical material behaviour was described by von Mises’ yield criterion and a combined nonlinear kinematic-isotropic hardening model, which is readily available in Abaqus and which allows capturing the well-known Bauschinger effect. When validating this FE model against experimental data, it was observed that it provides accurate...
predictions for the transverse direction (i.e. circumferential direction) on pipe, but significantly underestimates the properties in the axial direction [5, 6].

To overcome the shortcomings of the kinematic-isotropic hardening model, it was decided to implement a more advanced constitutive model, capable of describing distortional hardening, in Abaqus/Implicit via a UMAT user subroutine. The concept of distortional hardening was developed to capture the effect of orthogonal strain path changes: some metals show an increase of the yield stress after an orthogonal strain path change [8]. This phenomenon is also referred to as cross hardening. Well-known models, capable of describing distortional hardening are the Teodosiu-Hu model [9], the HAH model proposed by Barlat [10] and the Levkovich-Svendsen model [11]. The Teodosiu-Hu model and the Levkovich-Svendsen model seem to be more general than the HAH model, as they consider isotropic, kinematic and distortional hardening, while the HAH model only accounts for isotropic and distortional hardening. Nevertheless the HAH model also allows predicting the Bauschinger phenomenon. The difference between the Levkovich-Svendsen model and the Teodosiu-Hu model is the way in which they handle distortional hardening: in the Levkovich-Svendsen model distortional hardening is accounted for by changing the shape of the yield surface. However, in the Teodosiu-Hu model distortional hardening is accounted for by changing the size of the yield surface and the saturation parameter of the kinematic hardening component after a strain path change. As shown in [12], both models provide similar results in terms of predicted stress-strain behaviour. As the Levkovich-Svendsen model is less complex than the Teodosiu-Hu model, it was decided to implement the Levkovich-Svendsen model in Abaqus/Implicit.

The mathematical framework of Levkovich-Svendsen is described in Section 2, while Section 3 discusses the material parameter calibration strategy. The model was then used to simulate spiral pipe forming of a 28” x 16mm HSAW pipe, as described in Section 4.

Figure 1. Spiral pipe forming line [7]
2. Constitutive model

In the Levkovitch-Svendsen model, the yield criterion takes the following form [11]:

\[ \Phi = \sigma_{eq} + a \sigma_{ii} - \sigma_y \leq 0 \]  

(1)

With \( \sigma_{eq} \) the equivalent stress, \( a \) a material parameter governing the yield stress pressure sensitivity (assumed to be zero in the present study), \( \sigma_{ii} \) the trace of the Cauchy stress tensor \( \sigma \) and \( \sigma_y \) the size of the yield surface, which is assumed to be a function of the equivalent plastic strain. The equivalent stress \( \sigma_{eq} \) is defined as:

\[ \sigma_{eq} = \sqrt{(\sigma^{dev} - \alpha^{dev}) : (M + H) : (\sigma^{dev} - \alpha^{dev})} \]  

(2)

With \( \sigma^{dev} \) the deviatoric part of the Cauchy stress tensor \( \sigma \), \( \alpha^{dev} \) the deviatoric part of the backstress tensor \( \alpha \), \( M \) a fourth order tensor of constants expressing the initial anisotropy of the material and \( H \) a fourth order tensor which evolves with plastic deformation and describes the evolution of the material’s anisotropy.

The evolution of the backstress is described by the model proposed by Armstrong and Frederick [13]:

\[ \dot{\alpha} = C_x (X_{sat} D^{pl} - \alpha \dot{\lambda}) = \dot{\lambda} C_x (X_{sat} \frac{\partial \phi}{\partial \sigma^{dev}} - \alpha) \]  

(3)

With \( C_x \) and \( X_{sat} \) two material parameters which need to be calibrated based on mechanical tests, \( D^{pl} \) the plastic strain rate tensor and \( \dot{\lambda} \) the plastic multiplier. The evolution of the distortional hardening tensor \( H \) is described by the following equation:

\[ \dot{H} = \dot{\lambda} C_D (D_{sat} - H_D) N \otimes N + \dot{\lambda} C_L [L_{sat} (I^{dev} - N \otimes N) - H_L] \]  

(4)

With \( C_D, L_{sat}, C_L, D_{sat} \) 4 material parameters which need to be calibrated based on mechanical tests, \( N \) a second order tensor parallel to \( D^{pl} \), \( N \otimes N \) a fourth order tensor, \( H_D \) the projection of \( H \) on \( N \otimes N \), \( H_L = H - H_D N \otimes N \) and \( L^{dev} \) the deviatoric fourth order unit tensor. The term “\( \dot{\lambda} C_D (D_{sat} - H_D) N \otimes N \)” is referred to as the directional hardening part, as it results in hardening along the plastic strain rate direction \( N \), while the term “\( \dot{\lambda} C_L [L_{sat} (I^{dev} - N \otimes N) - H_L] \)” is called the latent hardening part as it generates hardening on the directions orthogonal to \( N \).

The model was implemented in Abaqus/Implicit using a fully implicit backward Euler return mapping scheme [14].

3. Material parameter calibration

As it concerns a quite complex material model, in which different types of hardening are considered, an extensive set of mechanical tests, involving non-proportional tests, had to be performed to calibrate the model:

- Uni-axial tensile tests in the rolling direction, the transverse direction and the 45°-direction.
- Uni-axial cyclic tension-compression tests in the transverse direction, whereby tests with different strain amplitudes were applied.
- Mechanical tests in which the strain path was changed. To do so, large samples were prestrained in the transverse direction. Afterwards, small samples were machined from the prestrained samples (see Figure 2) and were loaded in tension and compression.
The uni-axial tensile tests and cyclic tension-compression tests were used to determine the material’s initial anisotropy and to calibrate the isotropic and kinematic hardening behaviour (the isotropic hardening behaviour was described by a Voce equation). Thereby it was assumed that the parameter $D_{sat}$ equals zero. Next the mechanical tests involving strain path changes were used to calibrate the parameters $C_D$, $L_{sat}$ and $C_L$, which determine the distortional hardening behaviour. It should be mentioned that all other parameters were kept constant when identifying these parameters.

As it was not possible to determine the parameter values from the measured data through simple analytical formulas, a reverse engineering approach was applied to calibrate the constitutive model, whereby different optimization algorithms were considered: simulated annealing, the Nelder-Mead algorithm and the Levenberg-Marquardt algorithm.

Figure 2. Mechanical tests with changing strain path

Figure 3 compares the measured stress-strain curves to the ones predicted by the model. Figure 3a shows the engineering stress-strain curve from a tensile test on a 16mm X70 grade, while Figure 3b shows the stress-strain curve from a cyclic tension-compression test on the same material. This material was also considered in the case study presented in Section 4. As can be seen from these figures, the material exhibits a yield plateau and a pronounced Bauschinger effect. Both phenomena can be captured by the applied constitutive model.

Figure 3. Experiment vs constitutive model: a) Tensile test, b) Cyclic tension-compression test
4. Results
The FE model was then used to simulate spiral pipe forming of a pipe with an outer diameter of 28” and a wall thickness of 16mm. The pipe forming angle was 58°. Furthermore, tensile tests were simulated at different stages of the forming process, namely along the rolling (RD) and transverse (TD) direction on coil after levelling and along the transverse (TD_{pipe}) and axial (LD_{pipe}) direction on pipe after pipe forming. The relation between the different directions is shown in Figure 4. Two different material models were applied, namely a combined non-linear kinematic isotropic hardening model and the Levkovitch-Svendsen model.
Table 1 reports the evolution of the yield strength $R_{0.5}$ during spiral pipe forming and compares the numerical predictions to experimental results from lab scale pipe forming simulations [5]. Both material models provide accurate predictions for RD after levelling and for TD_{pipe} after pipe forming. However, the combined kinematic-isotropic hardening model significantly underestimates the yield strength in TD after levelling and the yield strength in LD_{pipe} after pipe forming, while the predictions made with the Levkovitch-Svendsen model are much closer to the experimental values.

![Figure 4. Spiral pipe forming: relation between pipe forming angle α, coil width B and outer pipe diameter D and indication of RD and TD, the rolling and transverse direction on coil, and LD_{pipe} and TD_{pipe}, the longitudinal and transverse direction on pipe.](image)

| Forming step | Direction | Experiment | Combined kinematic-isotropic hardening model | Levkovitch-Svendsen model |
|-------------|-----------|------------|---------------------------------------------|----------------------------|
|             | RD        | 465 MPa    | 475 MPa                                     | 481 MPa                    |
|             | TD        | 538 MPa    | 488 MPa                                     | 532 MPa                    |
| After levelling | LD_{pipe} | 539 MPa    | 477 MPa                                     | 529 MPa                    |
|             | TD_{pipe} | 499 MPa    | 492 MPa                                     | 501 MPa                    |

5. Conclusions
The present paper discusses the implementation and calibration of an advanced constitutive model which accounts for isotropic, kinematic and distortional hardening. An extensive set of experimental tests, involving uni-axial tensile tests, cyclic tension-compression tests and tests with strain path changes, were used to calibrate the model, whereby a reverse engineering strategy was applied.
The model was then used to simulate spiral pipe forming of a 28” x 16mm HSAW pipe with a spiral pipe forming angle of 58°. The predictions made with the Levkovitch-Svendsen model were compared to experimental results and to predictions made with a kinematic-isotropic hardening model, from which it can be concluded that the Levkovitch-Svendsen model provides more complete results: it allows predicting the pipe strength along different directions, while the kinematic-isotropic hardening model only provides accurate predictions for the circumferential direction.
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