# DEVELOPMENT OF A THROUGH-PROCESS SIMULATION WORKFLOW FOR SPIRAL PIPE FORMING INCLUDING EVOLUTION OF TEXTURE AND DISLOCATION SUBSTRUCTURE

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**Abstract.** Spiral forming is a widely used industrial method for the manufacture of large-diameter welded pipes from levelled steel strip. However, the multi-step helical forming process and post-treatment of the pipe influence the material behavior and alter the final mechanical anisotropy of the product. In addition, the complex microstructures of modern pipeline steels contain various sources of anisotropy including residual stresses, crystallographic and morphologic textures, and directional dislocation substructures. They do not only affect the local and global pipe strength, ductility and toughness during monotonic loading but also cause strong strain path change effects, e.g. a pronounced Bauschinger effect. Anisotropy thus poses a true challenge to pipeline designers making it difficult to accurately predict the final pipe behavior from the known properties of the hot-rolled high-strength coil, the starting point of the forming process. Still, such predictive power is vital to guarantee the structural integrity of pipelines without failure in case of in-service loads beyond the elastic range. The pipe manufacturing process can be simplified into two steps: decoiling (incl. levelling) and spiral forming. For subsequent quality control, samples are extracted from the pipe, per standard flattened and tensile tested in hoop direction. With regard to developing a computational twin of the complete manufacturing and testing process, we represent each step by a separate finite element (FE) model. The full through-process simulation workflow thus necessitates tools to transfer the material state between individual FE models. Here, we present such a workflow for the dislocation substructural hardening model by [Peeters et al., Acta Mater. (2001) 49:1607-1619]. For each material point, macroscopic and microscopic state variables, including residual stress, crystallographic texture and dislocation densities, are first interpolated and then transferred to the next model. In this way, the evolution of different anisotropy sources can be studied starting from coil via pipe and ending with tensile testing.

# 1   INTRODUCTION

Pipelines for transport and distribution of liquids and gases (e.g. hydrocarbons, water) are widely spread throughout the world. Due to their relatively low cost and high safety compared with rail, truck, and ship [1] the worldwide network of pipelines and the total volumes transmitted through them are foreseen to keep increasing in future [2]. Still, large ground deformations due to seismic activity and soil settlement may pose serious dangers to the public and environmental safety if not appropriately accounted for in the pipeline design process [3]. Motivated by the need to safeguard pipeline integrity and resource supply in less stable natural environments [4], mitigation of risk inflicted by geohazards is therefore of growing importance.

To this end, limit states and safety margins related to pipeline failure are to be defined and guidance needs to be given on how to apply calculation models that provide reliable predictions of the pipe deformation capacity. Ultimately, the pipe behavior post yielding must be analyzed and safe limits for ultimate plastic strain specified. Central to these efforts are the correct description of the pipe material properties leading to mechanical anisotropy, both in terms of yield strength and strain capacity.

The widely used pipe manufacturing processes (UOE forming, spiral or helical forming [5]) introduce substantial anisotropy and residual stresses into the pipe wall [4, 6-10]. These have been recognized as major factors for pipe mechanical behavior [11], critical bending curvature and sensitivity to buckling [4]. Effects of the manufacturing process on the pipe material properties must therefore be carefully considered when assessing pipe performance.

Because spiral-welded pipes are produced from hot-rolled coil in a continuous process, they can be manufactured at lower cost compared to UOE pipes, which are produced from plate [10]. Therefore, spiral-welded pipes are an economic alternative to UOE pipes for onshore resource transmission. However, due to the lack of adequate fundamental knowledge about their stress and strain capacity, spiral-welded pipes have seen limited implementation in challenging environments [4].

Spiral pipe forming consists of a series of cold forming steps, altering the material properties of the coil. After decoiling and levelling, the coil tail is welded to the coil head of the previous
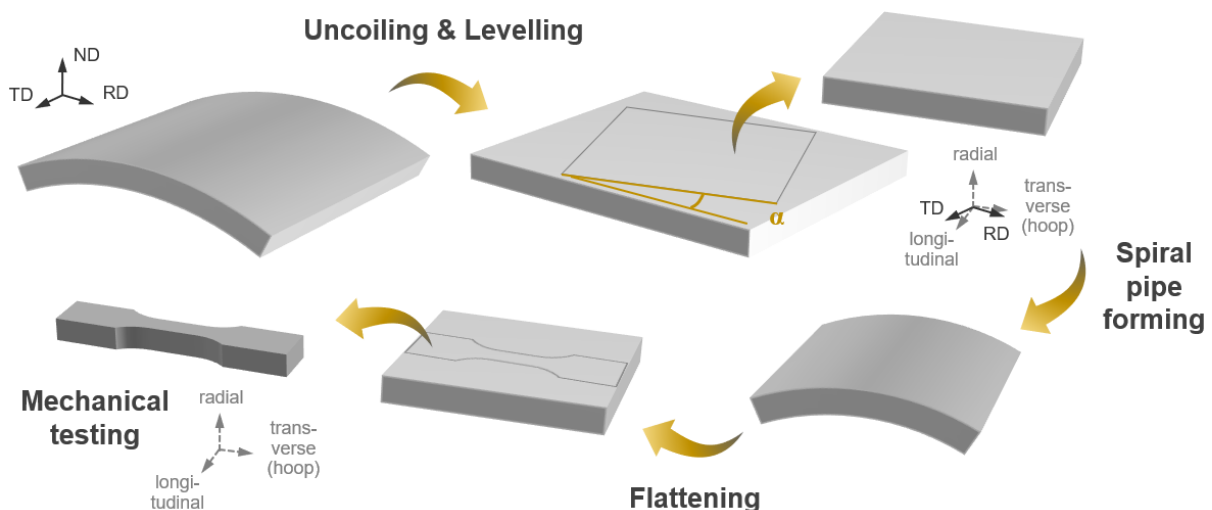


**Figure 1**: Spiral forming a steel coil into a large-diameter pipe and subsequent mechanical testing.

coil to make it a continuous process. The strip is then fed at an appropriate angle into a precision 3-roll stand to obtain a continuous tube of desired diameter, which is closed by welding. The forming process can be largely simplified by 2 major bending operations, as illustrated in Fig. 1: Decoiling (including levelling) and spiral (3-roll) forming. The bending axis for spiral forming is oriented at an angle $\alpha$ relative to the coil axis. For subsequent quality control, samples are extracted from the pipe, per standard flattened and tensile tested in hoop direction, where the yield strength is employed to indicate pipe quality. For each of the 3 bending operations (decoiling, spiral forming, flattening) the bending sense is inverted, resulting in strain reversals leading to the Bauschinger effect. In addition, the rotation of the bending axis by $\alpha$ leads to combined reverse and cross-loading during spiral forming, corresponding to a sign change and rotation of the strain mode.

To characterize a strain path change, Schmitt et al. [12] proposed the scalar parameter $\theta \in$ [-1,1] calculated as the double-dot product between the plastic strain rate modes:

$$\theta = \mathbf{D}_1 : \mathbf{D}_2 \tag{1}$$

$\mathbf{D}_1$ and $\mathbf{D}_2$ are the normalized strain rate tensors of the previous and the next strain path segment, i.e.

$$\sqrt{\mathbf{D}_i : \mathbf{D}_i} = 1 \tag{2}$$

$\theta = 1$ corresponds to a monotonic strain path, $\theta = 0$ to a cross-test, and $\theta = -1$ to a reverted strain path (Bauschinger test).

The bending operations give rise to either plane strain tension or plane strain compression depending on the material location relative to the neutral fiber. Material layers inside the neutral fiber experience plane strain compression, while those outside the neutral fiber are subjected to plane strain tension. For uniaxial tension, assuming isotropic material properties and thus isotropic transversal contraction (corresponding to a Lankford r-value of $r = 1$) is sufficiently accurate in the present context: Assuming no thickness contraction (i.e. a very large $r \gg 1$) decreases $\theta$ in magnitude by 0.11. Table 1 lists $\theta$ for the 3 strain path changes depicted in Fig. 1 on the coil in- and outside for the spiral forming angle $\alpha = 45°$. Obviously, the strain path changes in Fig. 1 are dominated by reverse loadings. Only the coil inside experiences a rather monotonic loading during flattening and tension testing along transverse (hoop) direction (HD) of the flattened pipe.

Table 1: Schmitt parameter on the coil in- and outside for strain path changes during spiral pipe forming ($\alpha = 45°$) and mechanical testing.

| | Coil inside | Coil outside |
|---|---|---|
| Decoiling → Spiral forming | -0.75 | -0.75 |
| Spiral forming → Flattening | -1 | -1 |
| Flattening → Uniaxial tension HD pipe | 0.87 | -0.87 |

## 2   RECENT ADVANCES IN MODELLING PIPE FORMING

Predicting pipe behavior could strongly benefit from taking the complex strain history imposed by forming operations into account, albeit requiring a through-process modelling approach. While through-process modelling has matured significantly in case of UOE forming [11, 13-18], comparably few complete implementations of spiral forming and mechanical testing have been realized to this date, inhibiting the needed optimization of spiral formed pipes.

In an extensive study from 2014 [8], combining FE simulations and experiments on 3 different steel varieties (X65, X70, X80), a von Mises yield criterion coupled to a nonlinear kinematic-isotropic hardening model was employed to simulate spiral pipe forming including mechanical testing starting from coil. While that multi-step model allowed capturing the pronounced Bauschinger effect and gave accurate strength predictions for the pipe transverse direction (i.e. along its circumference), it significantly underestimated the properties along the axial pipe direction. An advanced constitutive model accounting for isotropic, kinematic and distortional hardening (Levkovitch-Svendsen model [19]) gave improved results [7]. However, it still showed significant discrepancies between experiment and simulation.

A detailed study from 2019 examined the effects of the spiral manufacturing process on the bending response of pipes by FE simulations of decoiling, straightening and spiral bending [10]. Using an extended Frederick-Armstrong model [20, 21] for the materials' constitutive behavior, the influence of pipe processing parameters (coil diameter, unloading after 3-roll forming, hydrotesting) was numerically studied. Correct description of material behavior under reverse (cyclic) loading was identified as major factor for reliable modelling of the ultimate deformation capacity of pipe.

These studies have demonstrated that while the general pipe strength levels can be predicted with good accuracy along selected pipe directions using phenomenological constitutive laws, the numerical reproduction of pipe mechanical anisotropy in terms of strength and hardening is yet to be achieved.

## 3   HIERARCHICAL MULTISCALE MODELLING OF PIPE FORMING

A remedy approach for improved prediction of pipe mechanical anisotropy could be to inform the continuum level yield and hardening behavior by lower-level crystal plasticity models. In this way, different sources for anisotropy could be included in a more bottom-up way, potentially yielding more lifelike simulation results. This approach drives the present work: we derive the continuum level yield surface from virtual experiments which are controlled by 2 anisotropy sources, namely crystallographic texture and the intragranular dislocation substructure. In addition, macroscopic residual stresses present in the coil are included on the continuum level. The yield surface is represented by the Facet expression [22]. The Facet is calibrated using the ALAMEL crystal plasticity model [23], which relaxes the iso-strain Taylor assumption for grain pairs. Furthermore, the evolution of the critical resolved shear stresses (CRSSs) on individual slip systems is described by the model by Peeters et al. [24]. The crystal plasticity material model is implemented in Abaqus Explicit as a user subroutine (VUMAT) within the hierarchical multi-scale simulation framework (HMS) developed at KU Leuven [25].

## 4   WORKFLOW DEVELOPMENT

The model set-up can be strongly simplified by dividing the forming process and the subsequent mechanical testing (see Fig. 1) into several process steps, where for each step a separate FE model is created. The process shown in  Figure 1 is then represented by 4 FE models corresponding to the process steps decoiling & levelling, spiral pipe forming, flattening, and mechanical testing [8]. Depending on the desired mechanical test, additional or other test geometries different from the depicted tension sample along HD of pipe can be relevant as well. For bending operations (decoiling & levelling, spiral pipe forming, flattening), the main assumption is that they can be modelled as pure bending deformations under plane strain conditions. The plane strain condition is realized by using a single element wide (along the bending axis) model and keeping the element width constant. Bending with constant radius along the entire model is imposed by applying a moment on one side (see also Fig. 4a) while enforcing a symmetry plane on the other end. For each model 3D brick elements with reduced integration (C3D8R) are used.
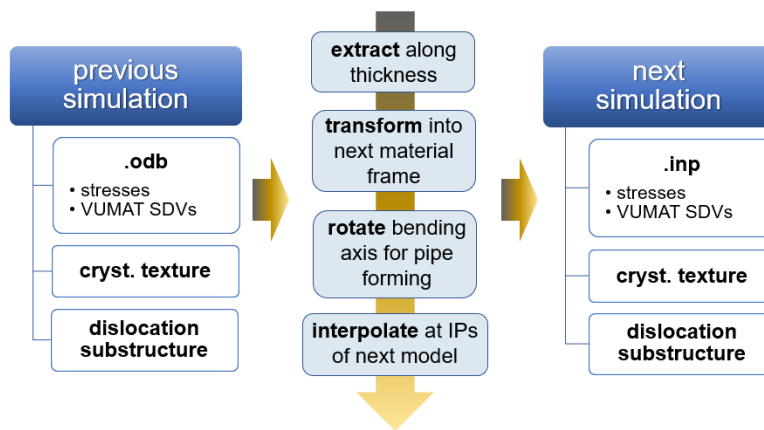


**Figure 2**: General workflow to transfer the material state between simulations.

At the end of each simulation, the final material state needs to be transferred to the model of the next processing step, as illustrated in Fig. 2. This entails the following steps: the relevant state variables are to be made available and are to be extracted from the Abaqus output database (.odb) as well as from the state files created by the VUMAT. While among the former are the macroscopic stress state and VUMAT variables stored inside the output database,  the latter describe the crystallographic texture and the dislocation substructure.

Since the material properties are assumed to be uniform in the plane of the (bent) strip, property gradients exist only along the plate thickness. It is therefore sufficient to extract the material state from a representative column of elements along the thickness, as illustrated in Fig. 3a. Each model has its own material frame. In case they are not identical in different models, the complete material state needs to be transformed into the new material frame (Fig. 3b). Furthermore, to correctly orient the material state for spiral pipe forming the rotation of the bending axis relative to the coil axis needs to be correctly considered (Fig. 3c). In the present approach we chose to orient the material frames such that transformations are avoided, including the transfer from levelling to spiral pipe forming. Then, based on the element
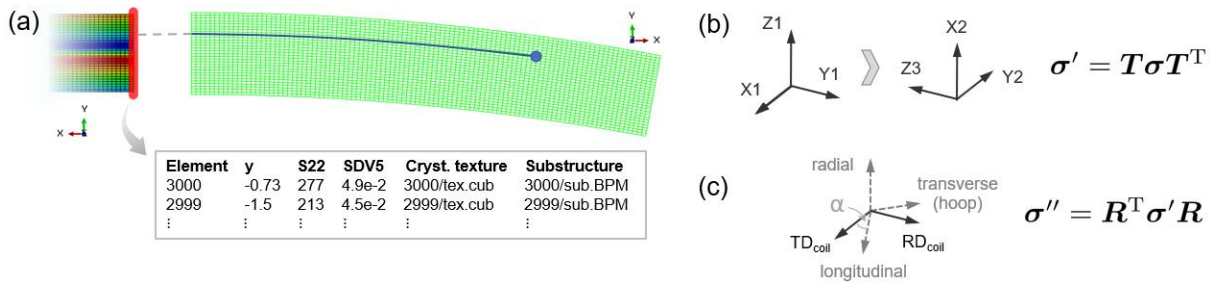
**Figure 3**: Transferring the material state. (a) Interpolation of the material state of the new model along the representative element column of the previous model. (b) In general, differently oriented material frames need to be taken into account by performing coordinate transformations on the material state. (c) In case of spiral pipe forming the rotation of the bending axis needs to be considered as well.

thickness position in the new model the material state is interpolated along the representative column of the previous model (Fig. 3a). The resulting interpolated material state is then used to define the initial state of the next simulation. This is achieved through external include files what concerns Abaqus, and by preparing the relevant state files related to the VUMAT.

## 4.1 Interpolating texture and dislocation substructure

To describe the crystallographic texture a statistical approach [25] is employed, where the texture at each FE integration point is represented by a discrete ODF consisting of 5000 crystal orientations given by Euler angles. In general, the textures of neighboring elements will be different from each other after some deformation, necessitating an interpolation procedure in case if the elements in the subsequent models are not located at the same thickness positions. Due to the discrete representation of texture, crystal orientations are statistically selected from neighboring elements according to weights describing the distance of interpolation location to the neighboring elements. The interpolated ODF then again consists of 5000 crystal orientations.

An equivalent approach is followed for interpolating the state variables of the dislocation substructure. Each grain (crystal orientation) has a set of state variables attached to it describing (i) the dislocation densities of the Peeters model (dislocation cells, cell block boundaries, pile-ups), (ii) the accumulated shear per slip system, (iii) the current CRSS per slip system and slip direction. As the development of the dislocation substructure is distinctly sensitive to the grain orientation [26], grain (substructural) state and grain orientation are best transferred together. The statistical selection procedure employed for transferring grain orientations thus transfers in parallel the grain substructural state.

## 4.2 Material state evolution

The developed workflow consisting of separate FE models and state transfer scripts allows tracking the evolution of material properties from coil to pipe mechanical testing, as demonstrated in Fig. 4-6. The material used for this example is a 22.7mm thick X70 steel. Fig. 4a shows the evolution of residual (von Mises) stress, where the coil residual stress has been measured by high-energy X-ray diffraction [27]. Fig. 4b shows the number of material property updates as the forming process progressed. Each update is triggered by a user-defined plastic

strain threshold. Micro-state properties (crystallographic texture and dislocation substructure) are updated and subsequently the effective macro-scale properties (Facet yield surface and macro-hardening) are re-calibrated. Elements directly at the coil in- or outside received most updates, as to be expected. The resulting texture evolution is depicted in Fig. 5a and 5b, at hand of two elements lying on the coil in- and the coil outside, respectively. Changes in (crystallographic) texture are weak as previously suggested in reverse bending trials using a simple von Mises yield surface without kinematic hardening [27].

On the other hand, the dislocation densities evolve clearly, as Figure 5c and 5d demonstrate. The displayed values are averages for material points consisting of 5000 grains. The density of randomly distributed and oriented dislocations ($\rho_{CB}$) leading to isotropic hardening increases with every forming step (Fig. 5c). The sign of polarizing dislocations ($\rho_{WP}$) depends on the position of the element (material point), i.e. coil in- or outside, after the first two forming operations. Note that the sign of $\rho_{WP}$ indicates on which side of the cell block boundaries (acting as obstacles for slip and thus facilitating pile-up formation) the net dislocation pile-up forms. Since in- and outside of coil are strained in opposite directions during bending, the sign of $\rho_{WP}$ is positive on one side and negative on the other. That difference wears down by spiral forming and flattening so that after flattening pile-ups have the same sign on either coil side (in or out).
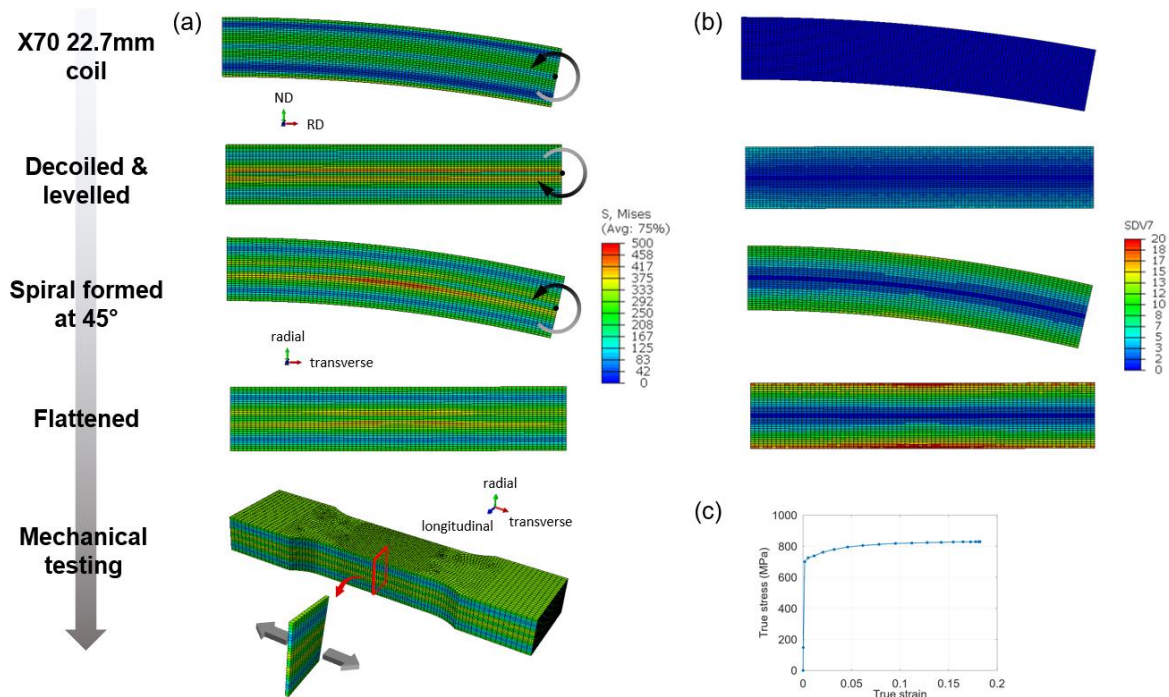


**Figure 4**: (a) Evolution of residual stress (in terms of von Mises stress) for 22.7mm thick X70 from coil to mechanical testing of flattened pipe samples. (b) Number of accumulated material property updates. Arrows in (a) indicate the imposed bending moments. On the left side of the bending models a symmetry plane parallel to the bending axis and to ND is inserted to ensure a constant bending radius. (c) Simulated stress-strain curve for uniaxial tension along TD of flattened pipe. That simulation was performed on a single slice covering half the cross section of the gauge section to reduce the simulation time.
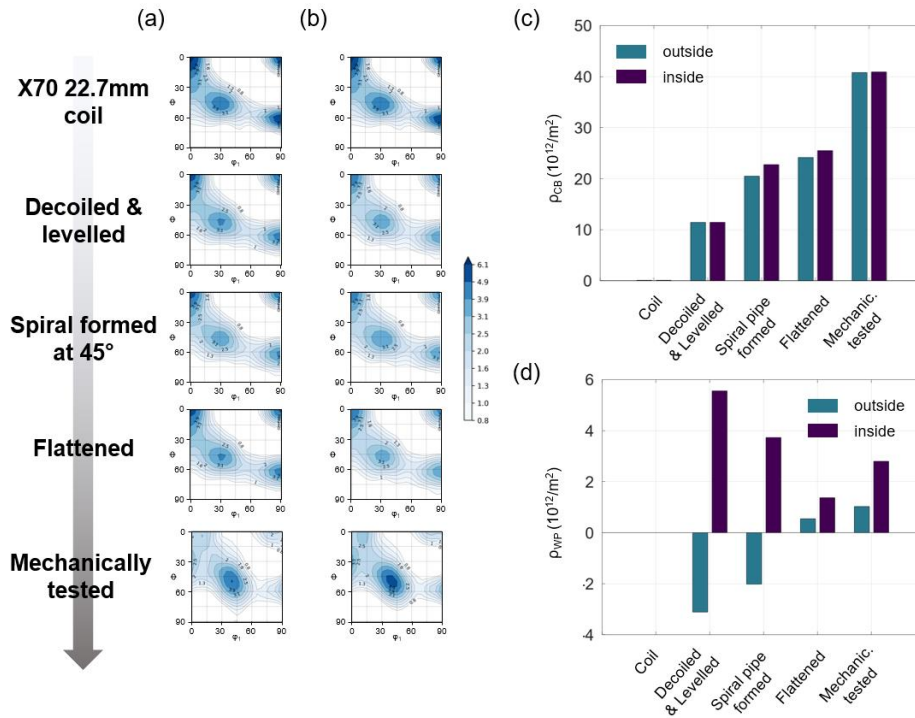
**Figure 5**: Evolution of crystallographic texture and dislocation density during pipe forming and mechanical testing. $\varphi_2 = 45°$ ODF sections for (a) coil inside and (b) coil outside. Because of the nearly orthorhombic material property symmetry ODF sections focus on $\varphi_1 \leq 90°$. Evolution of density of (c) randomly oriented dislocations ($\rho_{CB}$) associated with isotropic hardening and of (d) polarizing dislocations leading to Bauschinger effect.

## 5 CONCLUSIONS

The presented work developed a workflow to simulate, starting from coil, spiral pipe forming and mechanical testing of pipe. To facilitate the material state transfer, tools (scripts) were developed, which interpolate the material state for the next simulation based on the final material state of the previous simulation. For each material point, macroscopic and microscopic state variables, including residual stress, crystallographic texture and dislocation densities, are first interpolated and then transferred to the next model in the process chain. In that way, the evolution and role of different anisotropy sources can be investigated during pipe manufacture and testing. While detailed analyses of the residual stress profiles, textural changes and mechanical anisotropy in terms of yield surface sections are beyond the scope of this work, a continuous material state evolution can be well appreciated from the data presented. Future work will use the developed workflow to investigate the influence of different anisotropy sources [27, 28] on the pipe mechanical response.

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