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Extension of a Simulation Model of the Freeform Bending Process as Part of a Soft Sensor for a Property Control

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Abstract. This work introduces an Abaqus CAE simulation model and its validation for freeform bending with movable die, which is extended in the simulation of a weld seam for the longitudinally welded tube. The superordinate goal is the development of a soft sensor, that can derive mechanical properties of a freeform bent tube as a basis for a closed-loop control. To guarantee a close monitoring of the mechanical properties, the soft sensor needs to be able to extrapolate the mechanical properties spatially. Because the investigated steel tubes are longitudinally welded, the weld depicts a disturbance regarding the rotational symmetry. In developing and validating a numerical simulation of the process, that quantitatively describes the influences the weld has on the mechanical properties, a significant improvement of the qualitative and quantitative prediction of the soft sensor can be achieved. The numerical modelling is done based on tensile tests on material taken from the weld seam, where hardness measurements are then used for the local validation of the model. The validated model now provides a time as well as cost efficient way of a primary investigation of the mechanical properties, especially regarding the local strength of the steel tube for a soft sensor and as input data for a feed forward control in the machine. Therefore, this work represents an important addition to the superordinate goal of developing a closed-loop property-control based on a soft sensor for freeform bending with movable die.

Introduction

Recent trends in manufacturing engineering show that as part of continuous improvement the modelling of processes and their limits is necessary. Closer product tolerances lead to the necessity of designing the processes to be more robust as well as controllable [1]. Thus, manufacturing processes are usually intensely equipped with sensors used to monitor and control the process. Dependent upon the monitored and controlled process, the equipped sensors might have scanning frequencies that are too low for adequate process control or the parameter of interest can only be determined through downstream offline analyses. The development of predictive mathematical models from the physically measured data sets, so-called soft sensors, offer a solution for the continuous monitoring of relevant process parameters [2,3].

The freeform bending process with movable die provides a bending solution that can bend complex geometries without changing the bending die. Currently, a pre-defined geometry can be bent, yet the mechanical properties of the component are not controllable. Due to the bending process, the mechanical properties of the steel tubes are influenced – namely due to strain hardening and a change in residual stress state. Yet, both of these mechanical characteristics not only influence further manufacturing steps but also determine the service application of the tube [4,5]. Thus, inline monitoring of the mechanical properties is essential, as this will allow the implementation of a closed-loop property control.

The authors in [4] introduce a soft sensor based on an Extended Kalman Filter for freeform bending of circular steel tubes that can infer residual hoop stresses, local strength and plasticity level based on Ultrasonic Contact Impedance (UCI-) hardness measurements. UCI-hardness measurements are taken on the steel tubes and saved within a .csv file. The data can then be read into the soft sensor were based on the hardness measurements a prediction of residual hoop stresses, local strength and plasticity level is generated. The predictions are based on offline analyses determining how residual hoop stresses and local strength influence hardness. The prediction of the plasticity level is based on the prediction of the local strength utilizing tensile test data. For further information on the soft sensor, the authors refer to [4]. This soft sensor now enables component evaluation already during the forming process. Furthermore, component failure due to unfavorable residual stress distribution, varying degrees of plastic deformation or excessive hardening of the material can be avoided. Finally, based on the soft sensor, a closed-loop property-control for the freeform bending process based on [6] will be designed.

However, effects of the weld seam on mechanical properties have so far been neglected. It is commonly known that the weld seam in a tube, especially the heat affected zone (HAZ), tends to differ in the mechanical characteristics compared to, for example, the base material as well as the weld metal due to thermal influences during welding [7]. Especially with regard to the disturbances on rotational symmetry due to the weld, the influences of the weld on the mechanical properties must be investigated. Furthermore, the current predictions of the soft sensor are limited to local values. Yet, the soft sensors qualitative and quantitative predictions can be significantly enhanced in the spatial extrapolation of mechanical properties across the tube.

Thus, this work will introduce an FEM model of the freeform bending process that models both the base material as well as the weld seam. This FEM model helps to provide additional data on the materials properties for the soft sensor in terms of spatial extrapolation of mechanical properties and the disturbances due to the weld seam. Furthermore, it offers a solution for a time-efficient and economically advantageous tool for data acquisition for a feed forward ensuring a higher quality product [8].

Experiments

Material. The investigated material is a P235 TR1, which is a low-alloyed steel grade for pressure purposes [9,10]. The circular steel tubes are longitudinally welded with an even finish along the inner and outer side of the tube, as is required for freeform bending. The tubes have an outer diameter of 42.4 ± 0.5 mm, a thickness of 2.6 ± 0.3 mm and a length of 800 ± 2 mm. The chemical composition was determined by optical emission spectrometer (OES) and can be seen in Table 1.

Table 1: Chemical Composition of P235 TR1 determined by OES

Element	C	Si	Al	Mn	P	S	Cr	Cu	Mo	Ni
P235TR1	0.037	0.027	0.025	0.11	0.0048	0.0016	0.041	0.244	0.011	0.081

Fig. 1 shows the optical micrographs of the base material, heat affected zone and weld metal. Both the base material and HAZ have a ferritic matrix with a slight amount of perlite towards the grain boundaries. It can be seen that the microstructure in the HAZ exhibits a coarser-grained microstructure. The weld metal has a bainitic microstructure.

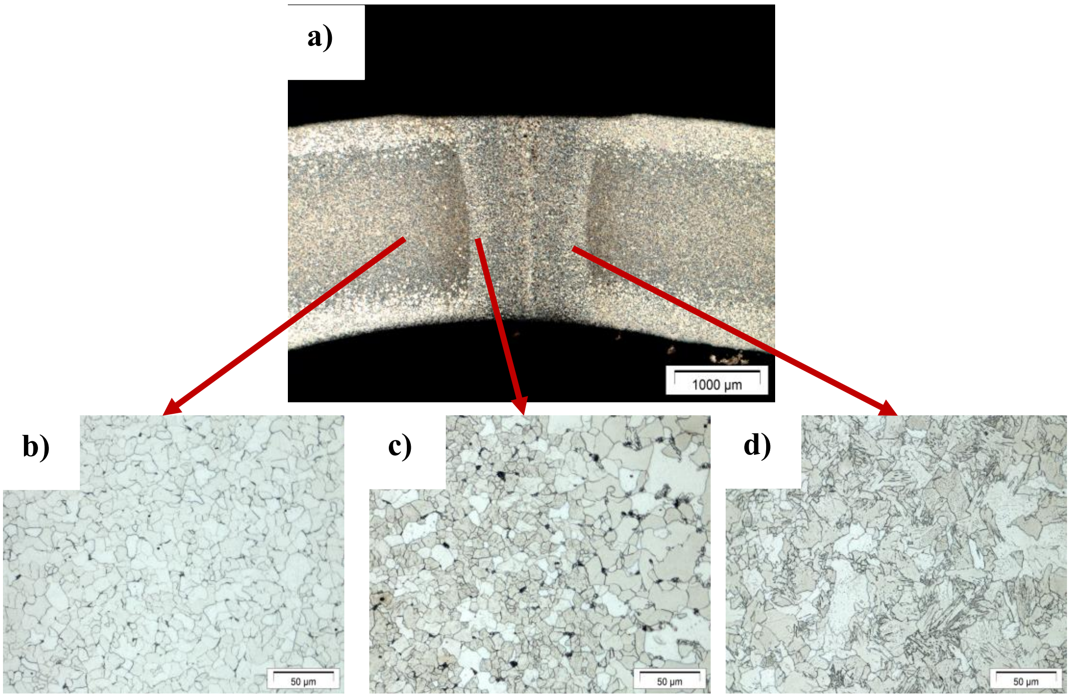

Figure 1: Optical micrographs of investigated material; (a) Cross-Section of P235 TR1 (magnification x25) (b) Base Material (x500), (c) Heat Affected Zone (x500), (d) Weld Metal (x500)

Tensile Tests. To investigate the materials properties of both the weld seam and the base material, quasistatic tensile tests were performed according to DIN EN ISO 6892-1 [11]. The test specimens were miniature tensile test specimens taken from the steel tubes. In taking miniature tensile test samples, the effects of curvature due to the forming of the tube could be minimized, thus allowing tensile testing in uniaxial stress state. The specimens were taken both from the base material opposite the weld seam as well as from the weld seam, hence, enabling the investigation of the potentially different mechanical properties. For the samples taken from the weld seam the reduced section lay right in the weld seam, as the weld seam also has a width of 2 mm. This allows a complete testing of the weld seam and the investigation of varying mechanical properties thereof. This automatically implies that HAZ properties will be neglected.

The tensile tests were conducted at room temperature with a strain rate of 0.00025 1/s with a uniaxial tensile test machine of type Zwick/Roell Z4204.

Model. To model the base material and the weld seam material, the tensile tests were used for a fitting of flow curves. A Ludwik-Voce Fitting was conducted for both materials, according to Eq. 1, and used to simulate the tensile tests in Abaqus CAE. The fitting was done using the least squares method to find the best fitting curve. The determined flow curves were then implemented into the Abaqus model of the freeform bending process using a partition in the Abaqus CAE part module.

$$\bar{\sigma}(\bar{\varepsilon}_p)=\alpha_L\left(b_L+A_L\times \bar{\varepsilon}_p^{\,n_L}\right) + (1-\alpha_L)\,(k_{0,V}+Q_v\times \left[1-e^{-\beta_V \times \bar{\varepsilon}_p}\right]). \quad (1)$$

The exact fitting parameters can be taken from Table 2.

Table 2: Fitting Parameters for the extrapolated flow curve of base material and weld seam for simulation model of tensile tests

Parameter	α_L	b_L	A_L	n_L	$k_{0,V}$	Q_v	β_V
Base Material	0.225	425	1200	0.7	420	65	62.92
Weld Seam	0.25	470	1000	0.4	488.814	0.1	0.1

Fig. 2 shows the conventional stress – strain curves in relation to the fitted simulation of the tensile test simulation model. It can be observed that the tensile test results scatter. This is due to two facts; miniature tensile test samples were used, which tend to have a higher scatter. Yet, the scatter is primarily because the materials characteristics scatter strongly, which has been shown in [4], and can be seen in the outlier posed by sample 10 in Fig.2a. Thus, the strain-stress curve of sample 4 was taken for the fitting of the flow curve for the base material and sample 5 for the weld seam material, as these samples lie well within the range of resulting stress-strain curves. To further investigate the scatter due to the sample shape, additional tensile tests will be conducted. The fitted flow curves were subsequently utilized as input for the weld seam material and base material in the simulation of the freeform bending process with movable die.

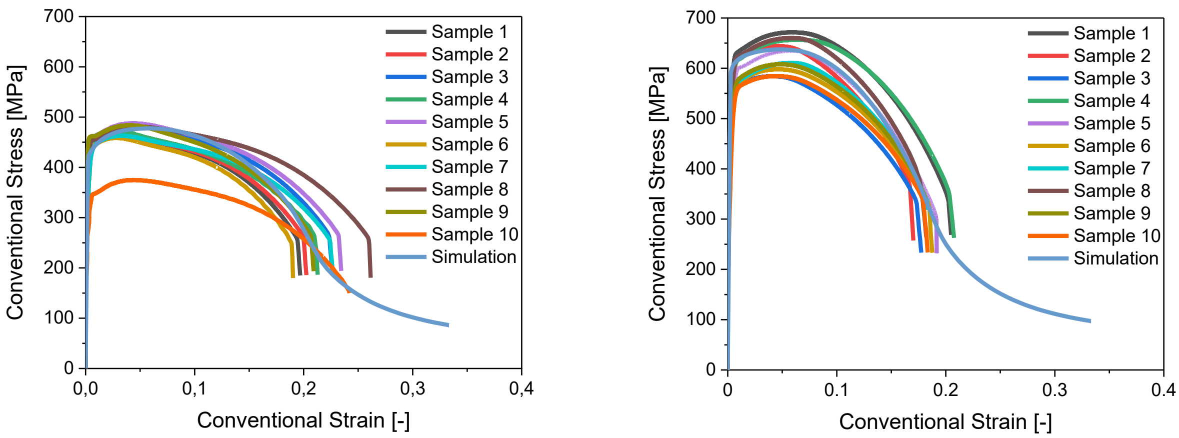

Figure 2: Left: Conventional Stress-Strain curves of base material and simulated tensile test (Adapted from [4]), Right: Conventional Stress-Strain Curves of weld seam material and simulated tensile test

The extended FEM model of the bending process itself is based on the results of [12] and [5], who already have investigated numerical simulation models for freeform bending with movable die but without considering the weld seam. The standard FEM-model for freeform bending with movable die consists of the bending die, the guider and the mandrel, that are all modeled as rigid elements. The tube is modeled as 3D deformable shell element and is meshed with the element type S4R with five integration points in thickness. The authors chose the element type S4R, as this simulation model poses the most time efficient calculation method taking thirty minutes on four cores. In comparison, simulations running on four cores modelled with solid elements of type C3D8R take a minimum of six hours, simulations with element type C3DR run eight hours, simulations with element type C3D8R_3 run twenty hours, simulations with shell elements of type S4 run two hours and with SC8R elements 5 hours. Furthermore, the simulated bending strategy is a pressurized process. Thus, no classical bending conditions are present, which is why the authors chose element types of S4R to be used. To implement the weld seam a section is defined with an arc length of 2 mm, across which the material properties of the weld seam are averaged. In the assembly module the position of the mandrel is chosen in such a way that it still provides support from the inside even when the bending die is deflected, thus preventing folds, and buckling. The elements of the mandrel are coupled by using pins as multi-point constraint types. For pushing the tube forward through the guider and the bending die, a displacement boundary condition is set at the end of the tube. The movement of the bending die is also done by using boundary conditions. Therefore, in the center of rotation of the die, both a displacement and a rotation are applied. The exact values for displacement and rotation are set over different amplitudes. During the bending process, the position of the mandrel as well as the position of the guider is fixed. For the whole model a general contact is defined with a friction coefficient of 0.1. [13] have already proven that this friction coefficient leads to good results. Fig. 3 shows the assembly of the Abaqus model. The weld seam, guider and bending die are marked accordingly.

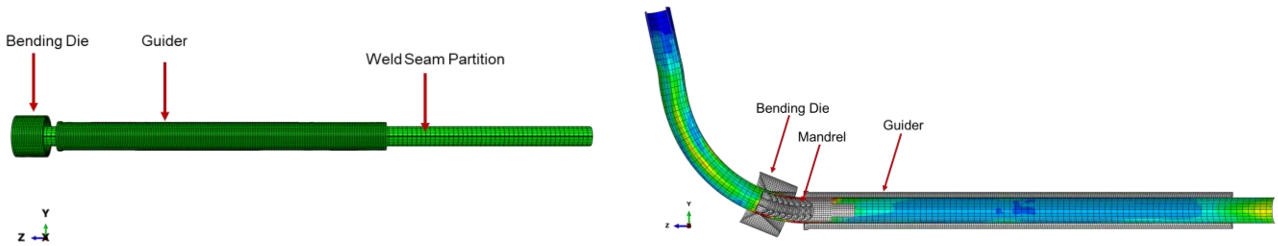

Figure 3: Design of the Abaqus model of freeform bending with movable die; Left: Assembly of model with parts marked; Right: Running simulation of bending process with marked parts

All simulations were done using J_2 plasticity theory, as is default in Abaqus solver. As the Abaqus solver does not have a predefined output variable for hardness and the strength cannot be taken directly from the bent tube, the conversion was done according to the findings of the authors in [4]. They proposed that hardness up to necking can be converted into strength in multiplying the hardness by 2.88, see eq. 2.

$$\sigma_{\mathrm{Mises,Local}} = \mathrm{HV}_1 * 2{,}88. \tag{2}$$

Thus, the hardness converted into strength was used for the validation of the Abaqus simulation results. The hardness was measured using an UCI-measurement equipment. The equipment uses a longitudinally oscillating rod, where a Vickers diamond is attached at the end. During the measurement, the Vickers diamond is pushed into the material which leads to a damping of the rod, and, thus, to a change in the frequency of the oscillating rod. Due to the known applied load and calibration values defined in the device, hardness can be determined. To reconfirm the stability of the measurement signal of the UCI-measurement equipment and thus proving that hardness converted to strength is a adequate tool for validation of the simulation model, cross-sections of the tube cut from the tube were investigated regarding their UCI hardness. The cross-sections were cut from the tube, embedded into epoxy resin, and carried out by a customized guider for the UCI-hardness measurement tool. The measurements were set to be taken 0.3 mm apart. All measurements for measuring equipment validation were taken on unbent material with prepared surfaces both on the cross-section and the tubes.

Final comparison was done using the converted hardness from the bent tubes and the von Mises stresses from the Abaqus CAE model.

Results and Discussion

Fig. 1 depicts that the microstructures of the base material and, especially, the critical heat affected zone both have a ferritic matrix with embedded perlite towards the grain boundaries, whereas the weld metal shows a bainitic microstructure. For a primary numerical investigation of the weld seam, taking tensile test samples from the entire weld seam is appropriate. Fig. 2 shows the tensile tests of both the weld seam and the base material. It can be observed that in the weld seam the tensile strength is reached at uniform elongations levels but also reaches higher values than in the base material. Furthermore, overall ductility in the weld seam material is lower than in the base material. Both observations are expected, as the HAZ exhibits a coarser microstructure compared to the base material, which entails lower strength and ductility levels. Furthermore, sample ten in the tensile tests of the base material poses an outlier. This is due to a strong scatter in the investigated material [4].
Fig. 4 shows the UCI-hardness measurements in HV 1 for both (a) along the surface of three different tubes and a (c) cross-section of the material. This was done to reconfirm that the hardness measurements taken along the tube surface can be used as a validation parameter. In comparing the hardness measurements taken on the surface of the tube to the hardness across the thickness, see Fig. 4 (b), of the tube, it can be confirmed that surface hardness measurements are suitable as a comparative parameter if the hardness measurements are in concordance. It can be seen that the

hardness of the cross-section increases towards the outer and inner edges of the tube. This is due to the embedding in epoxy resin that can influence the UCI measurement results. The measurements on the surface of the unbent tube, were taken by hand thus yield a higher scatter in measurements. However, when comparing the two, the hardness intervals measured are corresponding. Thus, the hardness values taken along the tube's surface can be taken as validation parameter and the conversion of hardness into strength is a suitable validation parameter for the simulation model.

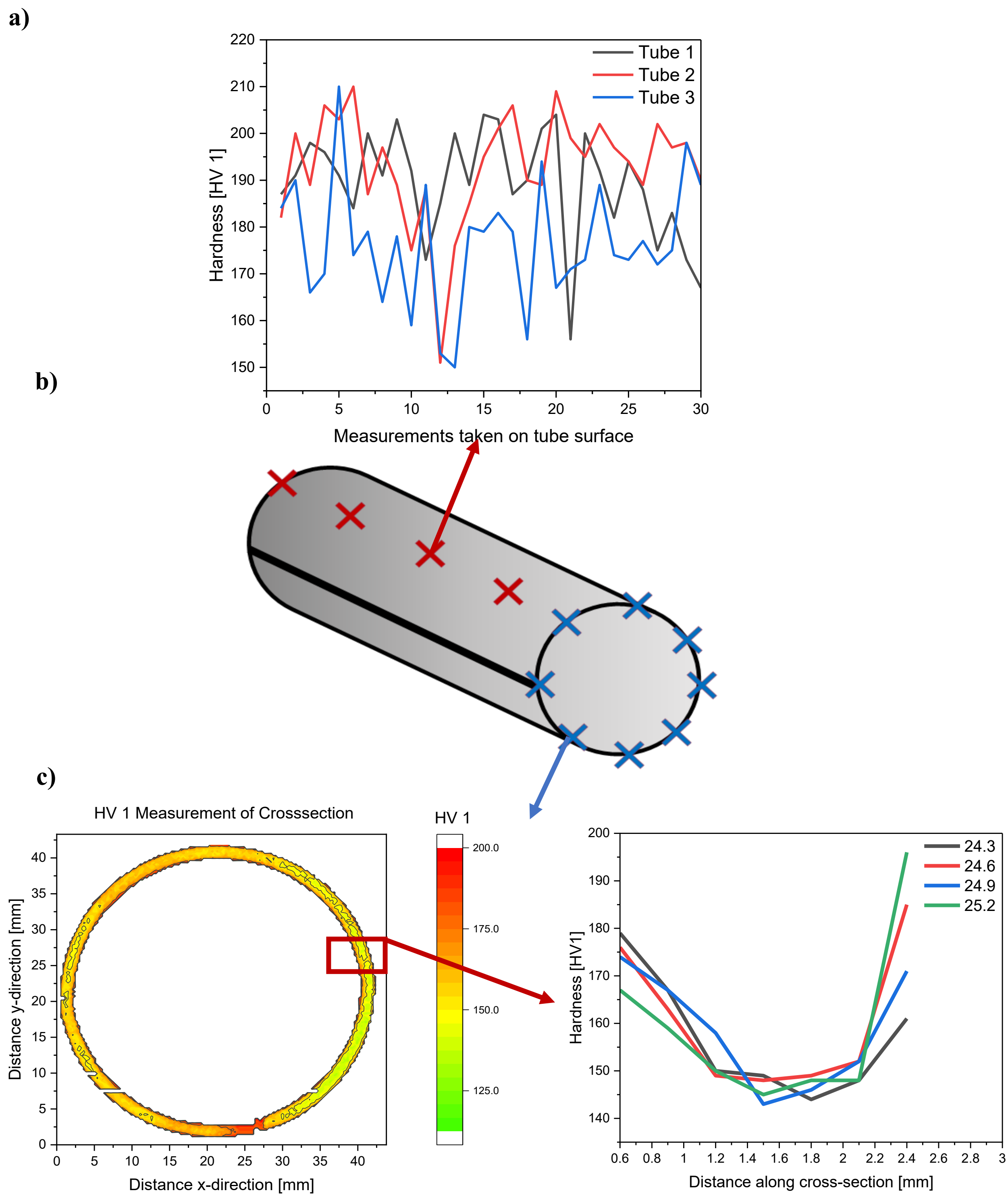

Figure 4: (a) Hardness development on tube surfaces (b) schematic depiction of measurement position on tube (c) hardness development across cross-section

For validation of the simulation model, the hardness measurements converted into the strength values are based on the results in [4]. Further hardness measurements of the weld seam were conducted according to [4].

In this work, the maximum von Mises stresses obtained from the simulation and the converted hardness from the tubes were compared to each other, see Fig. 5. The measurements were taken inside, meaning along the inner bending radius, where the material was compressed, outside, meaning along the outer radius, where the material was elongated as well as along the weld seam. It can be observed that the strength values along the weld seam tend towards higher values which can be expected due to the varied cooling parameters through welding which lead to the formation of the HAZ [7]. As the hardness measurements were taken post bending and offline, the investigated simulation parameters also rely on the fully bent tube. It can be seen that the Abaqus Simulation is overall in good agreement with the maximum values in strengths along the tube. The largest deviation is between the simulation and the measurements on tube 11mm14deg outside, where the simulation underestimates the real measurements by 106 MPa. Nonetheless, for an initial evaluation of bending parameters for a feed forward control the model is suitable. Discrepancies between the real measurements and the simulation can be explained by the neglect of modelling residual stresses. As the authors in [4,5] describe, residual stresses have a strong influence on the hardness. The higher the residual stresses in a tube, the higher the measured hardness, thus, also the local strength. Further improvements can, hence, be made in taking the residual stresses into account. Additionally, it must be noted that the comparative parameter for the simulation model was calculated based upon a mathematical relationship between hardness and strength; deviations may therefore also derive thereof. Furthermore, process disturbances as well as batch fluctuations of the material influence the real measurements and are not modelled in the simulation.

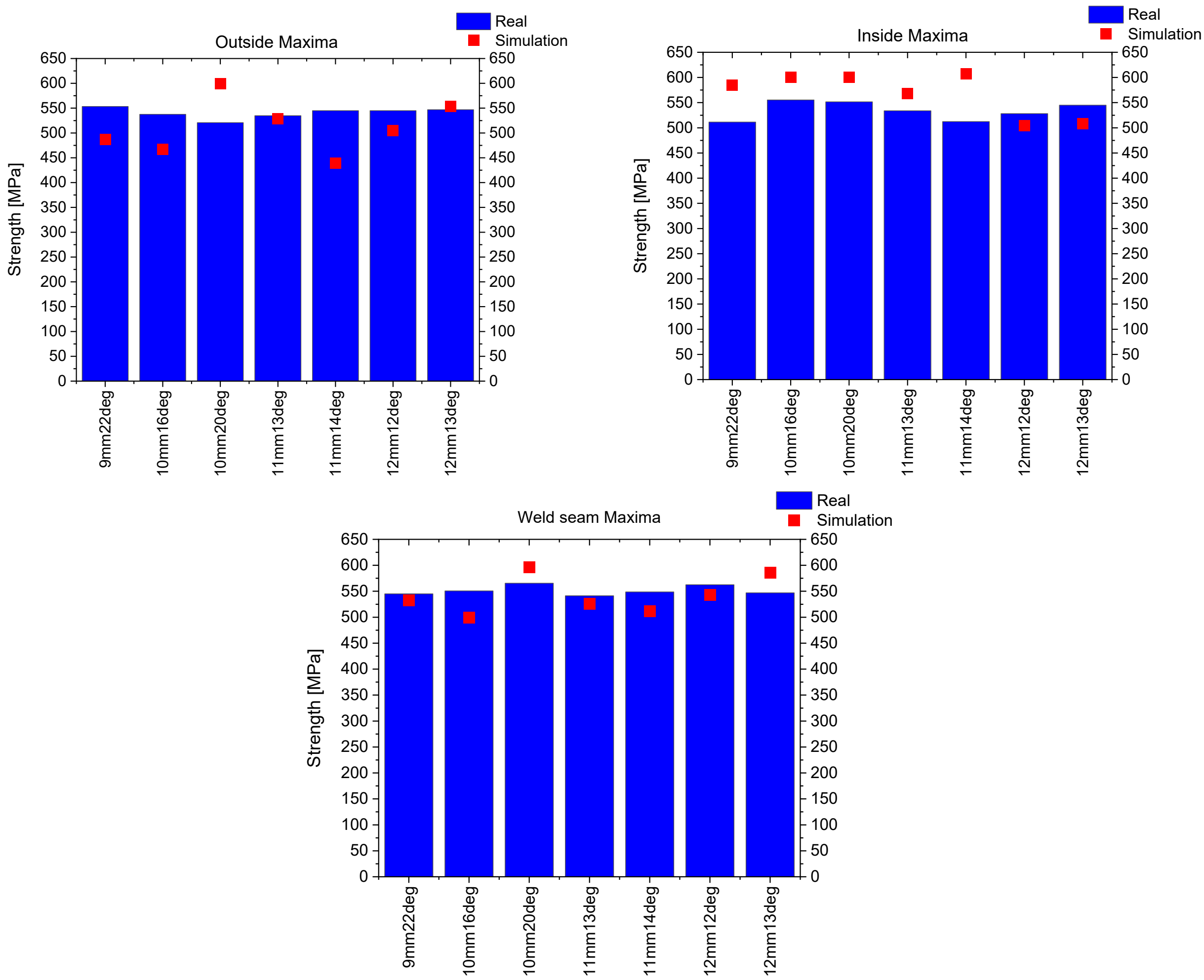

Figure 5: Comparison of simulation von Mises stress results, and real strength measurements based on hardness for outside and inside of bending radius as well as the weld seam

Conclusion and Outlook

In conclusion, this work introduces a validated implementation of a weld seam into a simulation model for freeform bending with movable die. This allows a cost as well as time efficient way of obtaining additional data for both the soft sensor and a feed forward control for freeform bending with movable die. Thus, providing an important part in the superordinate goal of designing a closed-loop property-control for the process. The following insights can be gleaned:

- The results show that the simulation model is in good accordance with the maximum measured hardness values converted into local strength values, thus proving the investigation of the weld seam as a whole to be a good way of implementing the weld seam into the FEM model.
- Upcoming studies will need to take the residual stress state of the pipe into account as previous studies have shown, that residual stresses strongly influence the hardness, thus also the strength of the material.
- The simulation model provides an important basis for the spatial extrapolation of the mechanical properties in the soft sensor for freeform bending, while taking the weld seam as a disturbance especially on the rotational symmetry into account. This will ultimately increase the quality of the soft sensor's prediction.

It shall be noted that further investigations of the weld seam of the tubes will be conducted in the forms of nanoindentations in the weld seam. Implementation into Abaqus is planned in conducting RVE simulations utilizing the approach of [14].

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