Re: Response letter for the review of: **Modeling the Deformation Response of High Strength Steel Pipelines, Part I: Material Characterization to Model the Plastic Anisotropy**

Dear Editor,

We thank the reviewer for the detailed and careful observations and recommendations for our paper. We have modified the manuscript and have taken the observations and notes into consideration. We have provided two versions for Revision 1; One version after incorporating the changes and one version at the end of this file with the changed highlighted. Below is a detailed response to the reviewer's comments. The reviewer comments are listed in **boldface**.

1- **The authors have to make a more extensive literature review on the subject, e.g., reference [1] and corresponding papers cited in this reference. Also, they should add some references in section 1.1.**
**[1] Shinohara, Y., Madi, Y., and Besson, J., "A combined phenomenological model for the representation of anisotropic hardening behavior in high strength steel line pipes," European Journal of Mechanics A/Solids, 29 (2010) 917-927.**

We thank the reviewer for his guidance in pointing us to this important reference. We have added the following paragraph at the end of section 1.2:

*"There are other more recent successful approaches that utilize an anistropic yield surface for modeling HSS pipes. Shinohara et al. [12] conducted various experiments on HSS pipelines and formulated a comprehensive anisotropic-kinematic plasticity model that is capable of capturing the required response given the required material data. Shinohara's models present a modification to previous attempts that are only able to model the anisotropic plasticity without a kinematic hardening component and thus are not able to capture Bauschinger effect [13],[14]. Recent approaches also utilize the microstructure behavior (dislocations and grain sizes and orientation) to predict the stress-strain behavior of the material[15]. All these models are perfect candidates for the modeling of the anisotropic behavior of the HSS pipes. However, in this paper we present a simple approach that relies on a material model that is already implemented in most commercial finite element analysis software and is able to accurately model HSS pipes with a different behavior in the circumferential and the longitudinal directions."*

2- **The authors should clarify what they mean with the word "intrinsic anisotropy". Does it mean microstructure-induced anisotropy due to the presence/morphology of defects (inclusions, precipitates, grain shape / grain orientation, dislocation sub-structures) in the stock material before processing? Note that many of these initially microstructure features typically change /**

**evolve during the TMCP, and hence, any anisotropy in the mechanical response is mainly related to the manufacturing process.**

We thank the reviewer for his detailed explanation of the intrinsic anisotropy which we have included in our manuscript:

"The initial intrinsic anisotropy in due to the microstructure of the plate which is due to the presence and the morphology of dislocations, inclusions and precipitates in addition to the different shapes, sizes and orientations of the grains."

3- **Before presenting the kinematic hardening models (section 1.2), the authors should describe how these models can capture the directionality in the mechanical response (e.g. Figures 1 and 2), and which are the limitations of this approach as compared to the use of anisotropic yield surfaces.**

The following paragraph was added in section 1.2 along with an appropriate reference:

*"While the use of the kinematic hardening plasticity model is designed to capture the Bauschinger effect, previous attempts were successful in implementing it for simulating the anistropic behavior of pipelines. Adeeb et al.[10] showed that the kinematic hardening plasticity model, can be calibrated to model the anisotropic plasticity of HSS pipelines by assuming that the plate material is originally isotropic and that the "apparent" anisotropy is due to the manufacturing process. This approach cannot model the plate material if the behavior of the plate, before manufacturing the pipe, is initially anisotropic. In addition, if the anisotropic behavior is due to factors other than Bauschinger effect introduced during the manufacturing process then this approach would not be appropriate; the kinematic hardening model assumes that the yield surface is always isotropic (von-Mises cylinder) but its centre moves in the stress space. In our current work, however, we use the kinematic hardening plasticity model to simulate the "apparent" anisotropic behavior of HSS pipelines since it is fully cable of correctly capturing the stress-strain behavior in both the circumferential and the longitudinal directions. In addition, we will be utilizing this material model to simulate the pipe under a monotonic longitudinal loading condition and under monotonic bending loading that initiates local buckling."*

4- **A related item to above, the authors keep emphasizing how important is to capture cyclic loading and the corresponding Bauschinger effect to be able to model the directional anisotropy of HSS (sections 1.2, 1.3, 2.1). From the text, it is not clear how they are related. Is this because of the pre-straining imposed in the pipes? The paper needs to add some explanation in one of these sections. Note that, in general, both phenomena are modeled using different approaches (cyclic loading versus anisotropy).**

An extensive modification was applied to section 1.2. In particular, the following sentence was also added to clarify the difference between modelling cyclic loading and anisotropy:

*"The use of the kinematic hardening plasticity models are well suited for capturing the apparent "anisotropic" response that is induced by cyclic loading applied on materials with an initially isotropic yield surface. However, for materials that have other sources of anisotropy, another approach is to use an anisotropic yield surface for the material model instead of using a "kinematic" or a "moving" yield surface centre."*

5- **In section 2.1, there is some emphasis on pointing out that the deformation history of the pipe does not affect the performance response. This is not true, as it is very well known that material history effects have a strong influence on the mechanical response (processing-structureproperty relationship). The authors should modify their comments in this section accordingly.**

We thank the reviewer for his comments. We have added the following at the end of section 2.1 to explain the intended use of our model:

*"It should be noted that the choice of the 2% plastic strain and the shape of the curve prior to this plastic strain is arbitrary and does not affect the results of the simulations post manufacturing of the pipe. It has to be emphasized here that this approach is not intended to model the behavior of the pipe prior or during the manufacturing process but rather it is intended to come up with a suitable model that is able to capture the behavior of the pipe post manufacturing."*

6- **The description of the calibration procedure presented in section 2.2 is very confusing and nonconventional. How the L-direction experimental data is used as input for the fitting of the parameters based on the C-direction experimental stress-strain curve? How the optimum Ldirection stress-strain curve is found by calibrating the C-direction curve? The sentences used in this paragraph do not convey this concept clearly. The authors could add a flow chart and / or equations that clarify this methodology which seems to be an important part of the approach presented in the paper.**

We apologize for the very confusing paragraph that we initially used. We have modified the explanation to make it clear.

*"The first step is to assume an initial stress-strain curve for the plate material by utilizing the experimental circumferential stress-strain curve as the portion of the initial stress-strain curve for the values of plastic strains higher than 2%. This was conducted by shifting the experimental circumferential stress-strain curve by 2% plastic strain. The portion of the initial stress-strain curve before the 2% plastic strain is interpolated to produce an initial smooth portion. Then, an arbitrary set of material parameters $C$ and $\gamma$ are assumed. Given this initial set of material parameters, the conditions of loading up to the level of 2% plastic strain in the circumferential direction is applied to the yield surface and to the yield surface centre. Afterwards, the longitudinal stress-strain curve is obtained using incremental plasticity and the appropriate evolution law of the yield surface and the yield center starting from the initial conditions of the 2% plastic strain level in the circumferential direction. This "calculated" longitudinal stress-strain curve is then compared with the experimental longitudinal stress-strain curve at 14 different plastic strain levels throughout the longitudinal stress-strain curve. Finally, the values of $C$ and $\gamma$ are changed to minimize the sum of the squares of the difference between the "calculated" longitudinal stress and the experimental longitudinal stress at the various different plastic strain levels. The procedure is repeated a few times until the material parameters obtained stabilize and the longitudinal experimental versus model stress-strain curve have the best match. Note that the same optimization scheme was used for the Chaboche model except that the backstress is decomposed into two components. So, there are two sets of material parameters $C$ and $\gamma$ to be obtained."*

**7- As aspect related to the above concerns the results from the fitting procedure and the use of ABAQUS. It seems that the authors have implemented the plasticity equation in their own code (a material point simulator, MPS) for the fitting, and then used ABAQUS for verification of the model using the computed material parameters. For this purpose they used three different types of elements. Here the paper must present the stress-strain response computed using their MPS, and the results from ABAQUS using the three elements they referred to. One should expect some differences in the response due to the type of element used. This request is also related to what is described in section 2.3.**

Our computed manual results and the finite element analysis results were identical for all the elements. This is perhaps due to the fact that ABAQUS separates the notion of "element" from the "Material". The fact that our manual calculations exactly matched the ABAQUS calculations is perhaps due to the fact that we were able to input the exact material parameters we used into ABAQUS. This point has been clarified in section 2.3 with the following clarification:

"*When conducting FEA modeling in ABAQUS, the calculations based on our implementation of the incremental plasticity theory exactly matched the calculations using the finite element analysis software. In addition, the results using the different elements utilized in ABAQUS were identical as ABAQUS uses the same material behavior for the different elements. In addition, the implementation in ABAQUS of the evolution laws exactly matched our numerical implementation as was evident in the fact that both analyses produced exactly the same results. It should be noted that a cylindrical coordinate system had to be used for the pipe elements implemented in ABAQUS to properly define the material orientation. In the figures shown henceforth, the FEA results using the pipe elements are reported.*"

**8- What kind of ABAQUS element was used to compute the stress-strain response presented in Figures 3-5?**

The results of the finite element analysis were identical for all the elements. As per the previous comment, we have clarified which elements were used for reporting the results.

**9- Since the authors are investigating the use of two kinematic hardening models, they should present the computed results from both models. Hence, the predictions using Chaboche model should also be added to the paper (to Figures 3-5?).**

Figure 7 (which was missing in revision 0) has been added. Figure 7 shows how the Chaboche model using two terms is able to capture the behaviour in both the longitudinal and the circumferential directions. We have clarified this in section 3.2 by adding the following:

*"Figure 7 shows the comparison between the Armstrong-Frederick and the Chaboche models applied to the material with the highest observed level of anisotropy; The Armstrong-Frederick law over-predicts the stress in the longitudinal direction while the Chaboche model exactly replicates both the longitudinal and the circumferential responses."*

**10- Based on the results obtained from the calibration of the model, it seems that there are cases (materials) where the approach does not capture accurately the anisotropy exhibited by the material. This is clear from Figure 5 that shows a bigger difference in the mechanical response between L and C directions (material pattern III). In other words, the higher the anisotropy, the less accurate is the prediction of the kinematic hardening models. This points out to the limitations of the approach, as the referred plastic anisotropy may mainly be induced by texture, on top of the pre-straining induced anisotropy. In this case, the use of an anisotropic yield surface may be the way to go [1]. Note that increasing the number of back-stress variables (Chaboche model), one can improve the fitting of the experimental data as more degrees of freedom are used in the calibration procedure (supposedly shown in Figure 7?). The question here is then how many more variables are needed? Does it make any physical sense to add many back-stress components? In this respect, the authors should add a paragraph in section 4 (discussions/conclusions) discussing all these issues.**

We thank the reviewer for his comment. We apologize for having missed Figure 7 in Revision 0. We have added figure 7 and it clearly shows that the Chaboche model is able to capture the high level of anisotropy. Our response to the previous comment applies here as well.

**11- The classification presented by the authors in Figure 6 is somewhat artificial and should be considered for removal from the paper. The fact is that, as the anisotropy of the material increases due to the TMCP-induced changes in the material microstructure (e.g. sharper texture, higher pre-straining), the difference in the stress response of the material strained along different directions will also increase. This is the main root of the "pattern type" behavior seen in Figure 6. Besides, classifying a material response as belonging to pattern II or III is very relative.**

We thank the reviewer for this very important observation. We have modified the definitions of the patterns to be more rigorous. The exact definitions are now given in section 3.3. The exact definitions as per the text now read:

"*Pattern I is defined as that with a difference less than 1% between the longitudinal stress-strain curve and the circumferential stress-strain curve for plastic strains higher than 1.5%. Pattern II is defined as that with a difference less than 5% between the longitudinal stress-strain curve and the circumferential stress-strain curve for plastic strains higher than 1.5%. Pattern II is defined as that with a higher difference.*"

**12- The article "the' is missing in many parts of the manuscript. The authors should consider this while reviewing their paper.**

We appreciate the reviewer's observation. The article was proof read and the grammar and punctuation were corrected throughout. The missing articles were added.

**13- Finally, Figure 7 is missing in the manuscript.**

Figure 7 was added. In addition, better qualify figures and tables are used.