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Numerical Determination of Optimal Interphase Thickness in Dual-Phase Steels

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Abstract

Micromechanical behavior of two dual-phase steels is investigated using experimental and numerical methods. Experimental data for 2 dual phase steel specimens (SP1 and SP2) is obtained from the literature and is used to create 2D representative volume elements (RVEs) based on the continuum mechanics framework. Interphase of the specimens is incorporated in the RVEs using digital image processing and flow curves are modeled based on a linear interpolation between flow curves of the two phase. The effect of interphase thickness is investigated to determine an optimal thickness of the interphase region for each steel specimen, based on the average error between experimental and numerical stress-strain curves. It was concluded that for SP1 and SP2, models with interphase thickness of less than 1.4 µm and 0.45 µm can predict stress-strain response better than the model without interphase. Also, optimal interphase thickness values of 0.90 µm and 0.24 µm have been obtained for the two specimens respectively. Also, it was demonstrated that failure initiates at the interphase and then propagates to the ferrite phase.

Keywords: Dual-Phase Steel, Mechanical Behavior, Micromechanical Modeling, Interphase

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Introduction

Dual-Phase (DP) steels are a family of high-strength low-alloy steels that exhibit high strength and good formability and therefore have found extensive use in the automotive industry [1]. Their desirable properties can be attributed to their microstructure, mainly consisting of hard martensite islands and a soft ferrite matrix. This dissimilarity causes strain localizations which is the first stage of the failure process in DP steels, warranting exhaustive research to enable safer and more economic engineering decisions.

Methods used for micromechanical modeling of DP steels using can generally be divided based on dimensionality into 2D and 3D methods and geometrically into idealized and real microstructures [2]. Two-Dimensional models offer simpler modeling and are computationally cheaper, but fail to accurately capture the effect of phase morphology in strain localization [3,4]. Al-Abbasi and Nemes [3] investigated the performance of plane strain and axisymmetric geometrical models in predicting the effect of martensite phase fraction (MPF) on strength and uniform strain. Sun et al. [5] created realistic RVEs of DP980 steel from scanning electron microscopy images and predicted ductile failure of DP steels in the form of plastic strain localizations. Sodjit and Uthaisangsuk [6] modeled the microstructure of DP steel sheets with different MPFs and found that 2D plane strain RVEs consistently underestimate stress-strain curves and this phenomenon increases with an increase in MPF.

Realistic 3D models require very expensive experiments [7–9], making improvement of 2D models a very important task.

Although there has been various studies on properties and structure of DP steels, so far limited attention has been paid to the effect of the interphase between ferrite and martensite phases. Kadkhodapour et al. [10] observed differences in hardness of the ferrite phase at different distances from the ferrite/martensite phase boundary and attributed this difference to geometrically necessary dislocations created during grain refinement. They modelled this phenomenon by enhancing a geometrically ideal axisymmetric model with multi-layered phase boundaries of constant thickness and reported improvements in accuracy of stress-strain response. Khoshbin et al. [11] proposed a linear variation of flow curve in the interphase to improve results of 2D FEA, but did not calculate the effect of interphase thickness on the accuracy of the model.

In this paper we propose a method for optimizing thickness of the interphase in DP steels and compare the results with realistic 2D RVEs and experimental results.

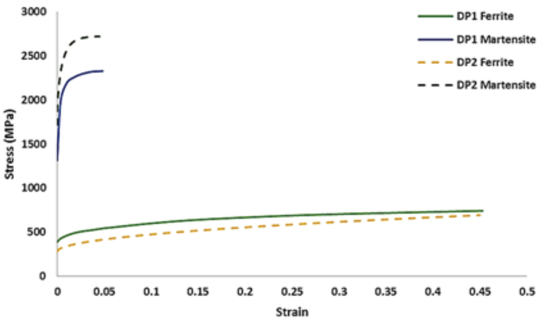

Figure 1. Calculated flow curves of the specimens used in this study.

Table 1. Chemical composition of the specimens used in this study.

Specimen	C	Mn	Si	Al	N	P	S	Cr	Ni	Mo	V	Cu	Co
SP1	0.2	1.1	0.22	0.011	-	0.004	0.02	0.157	0.083	0.046	0.008	0.121	0.019
SP2	0.17	1.49	0.22	0.033	0.0033	0.0017	0.0031	-	-	-	-	-	-

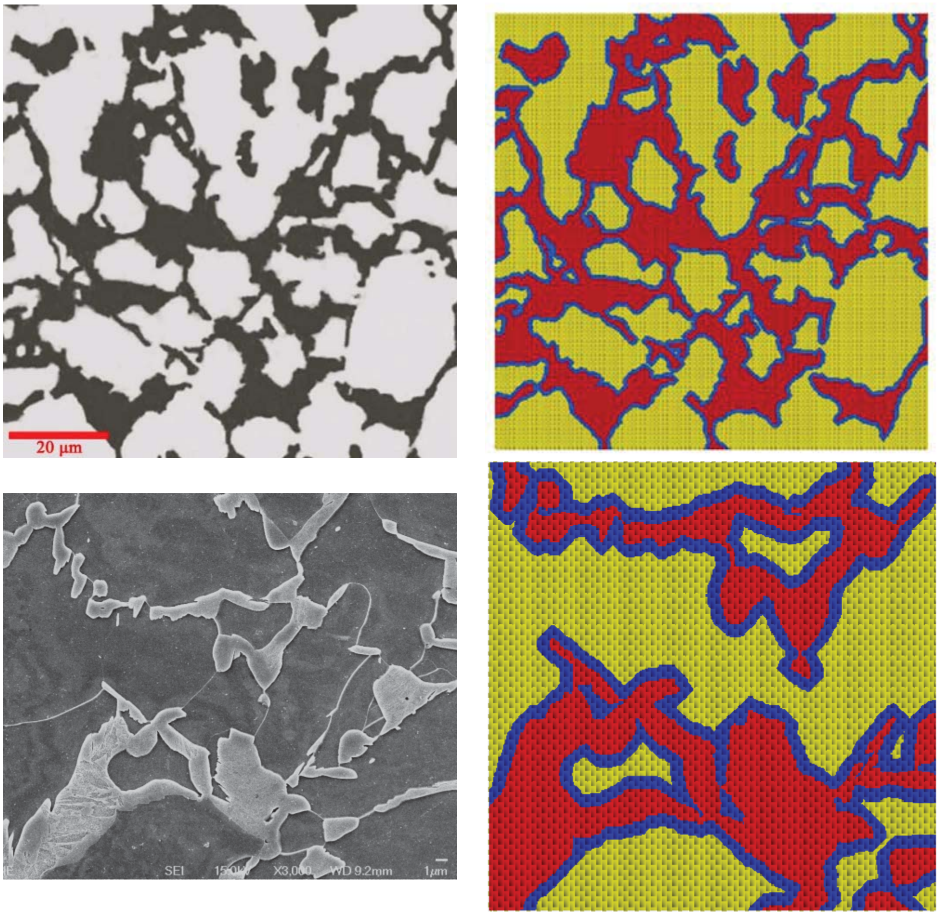

Figure 2. Optical microscopy images of the microstructures and resulting RVEs with the interphase colored blue.

Materials and Methods

Experimental data for two dual-phase steel specimens were extracted from the literature. The specimens are named SP1 and SP2, and have a martensite phase fraction (MPF) of 33% and 31.3% respectively. Chemical composition, optical microscopy images, and uniaxial tensile test data of the specimens, is shown in Table 1 and Figures 2 and 3 respectively.

Matlab's image processing toolbox was used to convert the grayscale optical microscopy images to binary images. Binarization threshold was set so as to ensure that MPF of the resulting image would match that of the original microstructure. The resulting images were used for creating the RVEs without interphase.

Afterwards, morphological operations were used to repeatedly erode the ferrite phase in the binary image and create a third region between the two phases. This was done based on nano-hardness results of [10], in which martensitic values were observed at the phase boundary which changed gradually to ferritic inside the ferrite phase. Binary erosion was performed using a disk shaped structuring element with a radius of 1 pixel, ensuring that each erosion results in a one-element thick layer of empty space which can be used as an interpolation point. In Figure 2, RVEs created using this method is shown with the resulting interphase colored blue.

For both specimens, flow curves of martensite and ferrite were determined based on their microstructure and chemical composition using a dislocation density-based approach proposed by Rodriguez and Gutiérrez [12]. The result is illustrated in Figure 1.

Following our previous study [11], Properties of elements in the interphase region were determined using a linear interpolation between fully ferritic and fully martensitic values. This interpolation was used for all parameters describing the elastic and plastic behaviors of the material. Eq. (1) was used to interpolate the material parameters for each element in the interphase region.

$$P_{element} = \left((P_1 - P_2) \times \left(\frac{d_2}{d_1 + d_2} \right) \right) + P_2 \qquad (1)$$

In this equation, $P_{element}$ is the value of the parameter in question for the element, d_1 and d_2 are the closest distance between the element and the first and second phases, and P_1 and P_2 are constants referring to values of the parameter in their respective phases.

The goal of this study was to numerically determine the optimal thickness to be used for each steel. Therefore, for each specimen RVEs were modeled with different values of interphase thickness. For each model, care was taken to use enough material property interpolation points so as to eliminate its effect on the results. For each analysis, stress-strain curve was calculated and then the average relative error between this curve and the experiment was calculated as it provides a suitable measure of accuracy.

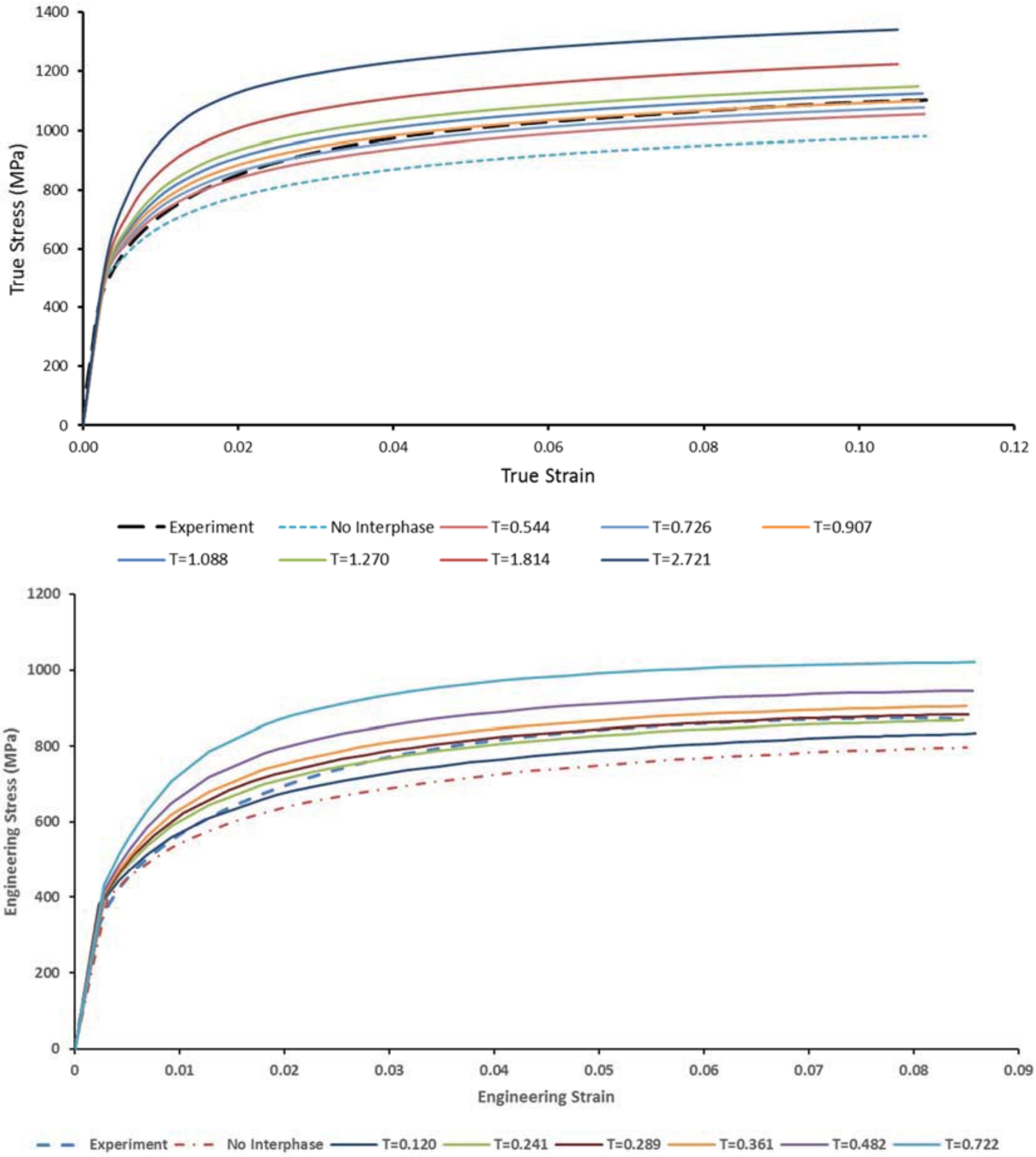

Figure 3. Experimental and numerical stress-strain curves of SP1 (top) and SP2 (bottom).

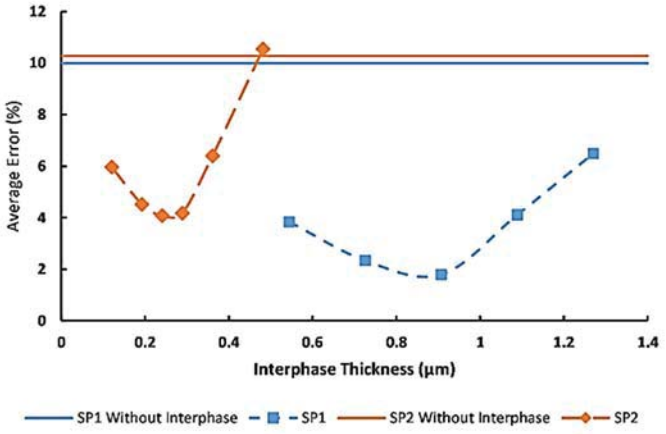

Figure 4. Average error between simulated and experimental stress-strain curve as a function of interphase thickness for the two specimens.

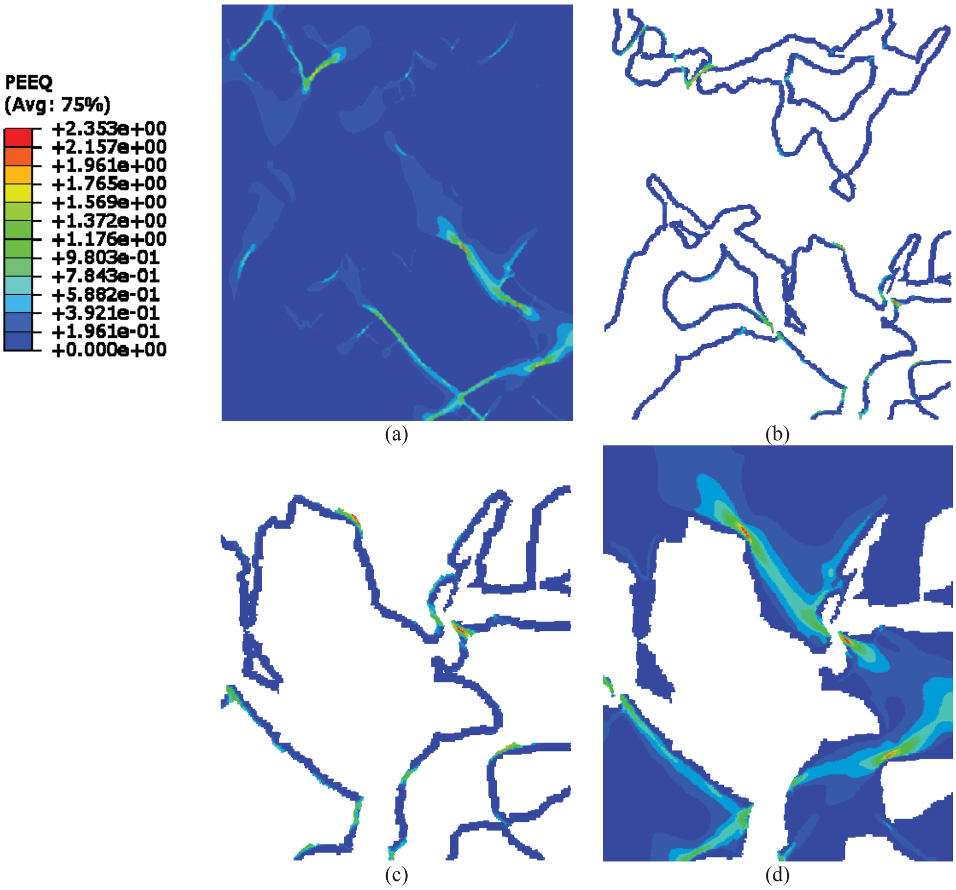

Figure 5. Distribution of equivalent plastic strain in the RVE in SP2 at ε=0.089; (a) whole model, (b) the interphase, (c) part of the interphase and (d) part of the ferrite phase

Results and Discussion

Figure 3 compares stress-strain response of RVEs with different values of interphase thickness. Note that for SP1 true stress-strain and for SP2 engineering stress-strain values are reported. This is done to preserve the format of the original experimental values.

As with all 2D models created from real microstructure, it is evident that the models without interphase underestimates the experimental curve. It can also be observed that as long as a reasonable thickness is chosen, more accurate results can be obtained which reduces the need for computationally expensive 3D models

Figure 4 shows average error between simulated and experimental stress-strain curve as a function of interphase thickness for the two specimens. It can be observed that as thickness changes, there is a smooth change in average error and that this function has a minimum.

For SP1 and SP2, models with interphase thickness of less than 1.4 μm and 0.45 μm can predict stress-strain response better than the model without interphase. Also, optimal values of 0.90 μm and 0.24 μm have been obtained for the two specimens respectively.

Figure 5 shows distribution of equivalent plastic strain in the RVE of SP2 with interphase thickness of 0.24 μm at ultimate tensile strength of the experimental specimen (ε=0.088). Shear bands seen in the figure mark the failure paths in the RVE. Figure (c) and (d) show that most of these shear bands begin to form in the interphase and then propagate to the ferrite phase. This can be attributed to martensite grains undergoing much less deformation than the ferrite grains, and the mismatch between the values of deformation in two phases causing deformed bands at the interphase and ultimately, in the softer ferrite phase.

Conclusions

In this study, the micromechanical behavior of two dual-phase steels was investigated using experimental and numerical methods. Interphase of the two steels was modeled based on experimental results of Kadkhodapour et al. [10] and the model proposed by Khoshbin et al. [11] and an optimal thickness was determined for their interphase region, resulting in better prediction of stress-strain response of 2D RVEs. Also, it was demonstrated that failure initiates at the interphase.

References

[1] N. Fonstein, Dual-phase steels, 2016. doi:10.1016/B978-0-08-100638-2.00007-9.

[2] C.C. Tasan, M. Diehl, D. Yan, M. Bechtold, F. Roters, L. Schemmann, C. Zheng, N. Peranio, D. Ponge, M. Koyama, K. Tsuzaki, D. Raabe, An Overview of Dual-Phase Steels: Advances in Microstructure-Oriented Processing and Micromechanically Guided Design, Annu. Rev. Mater. Res. (2015). doi:10.1146/annurev-matsci-070214-021103.

[3] F.M. Al-Abbasi, J.A. Nemes, Micromechanical modeling of dual phase steels, Int. J. Mech. Sci.

45 (2003) 1449–1465. doi:10.1016/j.ijmecsci.2003.10.007.

[4] T. Iung, M. Grange, Mechanical behaviour of two-phase materials investigated by the finite element method: necessity of three-dimensional modeling, Mater. Sci. Eng. A. 201 (1995) 1–4. doi:10.1016/0921-5093(95)09891-7.

[5] X. Sun, K.S. Choi, W.N. Liu, M.A. Khaleel, Predicting failure modes and ductility of dual phase steels using plastic strain localization, Int. J. Plast. 25 (2009) 1888–1909. doi:10.1016/j.ijplas.2008.12.012.

[6] S. Sodjit, V. Uthaisangsuk, Microstructure based prediction of strain hardening behavior of DP steels.pdf, Mater. Des. 41 (2012) 370–379. doi:http://dx.doi.org/10.1016/j.matdes.2012.05.010.

[7] M.R. Ayatollahi, A.C. Darabi, H.R. Chamani, J. Kadkhodapour, 3D Micromechanical Modeling of Failure and Damage Evolution in Dual Phase Steel Based on a Real 2D Microstructure, Acta Mech. Solida Sin. 29 (2016) 95–110. doi:10.1016/S0894-9166(16)60009-5.

[8] D. Brands, D. Balzani, L. Scheunemann, J. Schröder, H. Richter, D. Raabe, Computational modeling of dual-phase steels based on representative three-dimensional microstructures obtained from EBSD data, Arch. Appl. Mech. 86 (2016) 575–598. doi:10.1007/s00419-015-1044-1.

[9] J. Ha, J. Lee, J.H. Kim, M.G. Lee, F. Barlat, Investigation of plastic strain rate under strain path changes in dual-phase steel using microstructure-based modeling, Int. J. Plast. 93 (2017) 89–111. doi:10.1016/j.ijplas.2017.02.005.

[10] J. Kadkhodapour, S. Schmauder, D. Raabe, S. Ziaei-Rad, U. Weber, M. Calcagnotto, Experimental and numerical study on geometrically necessary dislocations and non-homogeneous mechanical properties of the ferrite phase in dual phase steels, Acta Mater. (2011). doi:10.1016/j.actamat.2011.03.062.

[11] M. Khoshbin, A. Cheloee Darabi, S. Rastgordani, J. Kadkhodapour, A. Pourkamali Anaraki, S. Schmauder, The Effect of Interphase in Micromechanical Modeling of Dual-Phase Steel, in: G.H. Liaghat, A. Alibeigloo, H. Ahmadi (Eds.), 25th Annu. Int. Conf. Mech. Eng., Tarbiat Modares University, Tehran, 2017: pp. 121–122.

[12] R.-M. Rodriguez, I. Gutiérrez, Unified Formulation to Predict the Tensile Curves of Steels with Different Microstructures, Mater. Sci. Forum. 426–432 (2003) 4525–4530. doi:10.4028/www.scientific.net/MSF.426-432.4525.