

Improved rule of mixture for determination of mechanical properties of dual phase steel with different martensite fraction

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1 Introduction

Dual phase (DP) steels are widely used materials for sheet metal applications for example in the automotive industry. They combine high strength with good ductility. Their microstructure contains two phases: soft and ductile ferrite as well as hard and brittle martensite. Depending on the heat treatment the martensite content varies. This offers the adjustment of material properties either for the whole sheet during the production process or locally by applying inductive heating and gas cooling before or after the forming process. This local treatment could be used at joints for example.

2 Mechanical properties of Dual Phase Steel

The two phases ferrite and martensite have different properties. While ferrite offers low yield strength and high ductility, martensite has very high yield strength and is rather brittle. A simple approximation for the hardening behavior could be gained by using mixture rules for the two phases, if the single phase properties were known. Simple mixture rules are either the parallel spring model as an upper bound or the series spring model as a lower bound. The results of this models differ significantly [1]. In [1] a mixture with a varying slope depending on the actual values along the hardening curves was proposed. Unfortunately, agreement with experimental data was not very good.

The problem of the simple mixture rules arises from the change of morphology with increasing martensite content: For low martensite fraction, see Fig. 1a), we have a soft ferrite matrix with hard martensitic inclusions. Therefore, the stress of the hard inclusion is approximately equal to the stress in the soft matrix, but strain might differ. This can be described by a serial spring model. For high martensite fraction, see Fig 1b), there is a hard matrix with soft inclusions leading to transfer of the matrix strain into the soft inclusions. These are properties of a parallel spring model. This urges the ability of the mixture rule to account for this change of mechanism.

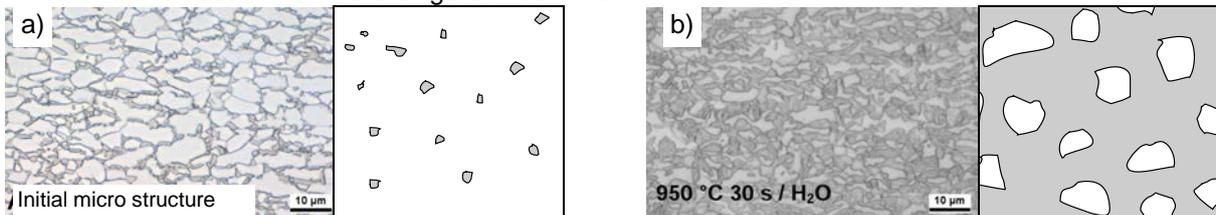


Fig.1: Change of morphology (micrograph and scheme) from a) small martensite islands (darker gray) in a ferritic (light gray) matrix to b) ferrite islands in a martensitic matrix.

3 Modified rule of mixture

Often, averaging either at constant stress σ or constant strain ε is done by

$$\sigma = V_m \sigma_m + (1 - V_m) \sigma_f ; \varepsilon = V_m \varepsilon_m + (1 - V_m) \varepsilon_f \quad (1)$$

where $()_f$ labels ferrite and $()_m$ martensite. Based on the identified change of mechanism, we propose a modified rule of mixture depending on the martensite fraction V_m . For both, ferrite and

martensite, stress and strain are calculated for a given σ_k as follows:

$$\sigma_k = \sigma_{m,f} - m_k \varepsilon_{m,f}, \quad m_k = Ek_k, \quad k_k = 1 - 0.5 \operatorname{erfc}[(V_m - V_{mu})/(\sqrt{2}s_b)], \quad (2)$$

where the slope m_k depends on V_m . The slope m_k can vary from 0 to E for low to high martensite fraction. The connectivity parameter k_k ranges from 0 to 1, E stands for phase independent Young's modulus. The ansatz has two free constants: the transition martensite content V_{mu} and the transition width s_b . Afterwards the overall stress and strain are calculated according to Eq. (1).

3.1 Inverse Identification of single phase properties and of the transition

The single phase properties are identified inversely and approximated by a simple swift law. In order to identify ferrite data from dual phase steel with low martensite fraction, it is assumed that the series spring model ($\sigma = \text{const.}$) holds and the much harder martensite behaves completely elastic. So we obtain from the overall strain $\varepsilon = (1 - V_m)\varepsilon_f + V_m\varepsilon_m$ of the DP steel for the ferrite

$$\varepsilon_f = \varepsilon - V_m(\sigma/E)/(1 - V_m). \quad (2)$$

Here this model is adopted for two steels. The two steels considered here are both DP600 steel grade, their chemical composition is given in Table 1. The data of the DP600-1 is taken from [2].

Element:	C	Si	Al	Mo	Mn	P	S	Cr	Ni	Cu
DP600-1	0.128	0.039	1.220	-	1.442	0.014	0.003	0.435	0.023	0.015
DP600-2	0.106	0.184	0.034	0.183	1.431	0.017	0.005	0.154	0.023	0.020

Table 1: Chemical composition of the two DP600 steel of in ma%.

The inverse identification of the ferrite from a DP600-1 Sample with a martensite content of $V_m = 0.15$ can be seen in Fig 2a).

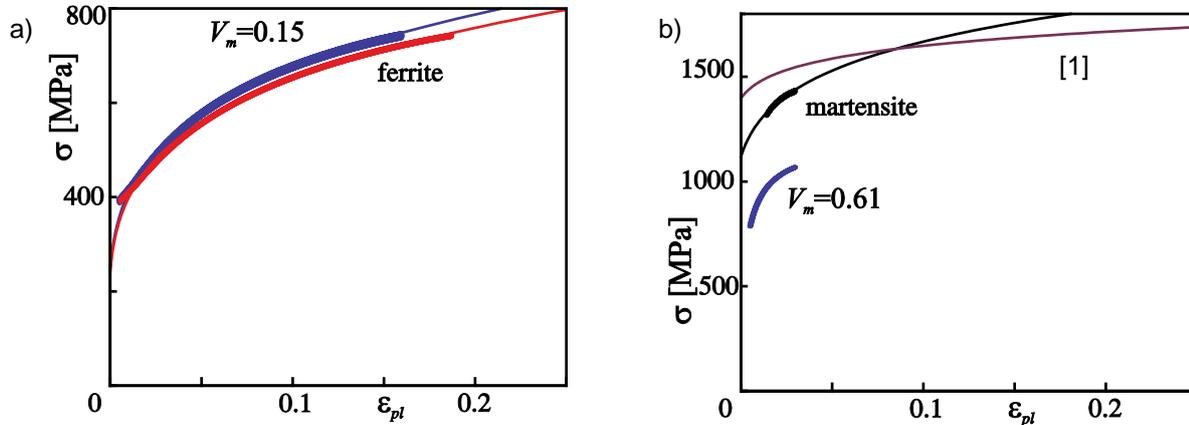


Fig.2: a) Identification of ferrite data from a DP600-1 sample with $V_m = 0.15$. b) Identification of martensite data from from a DP600-1 sample with $V_m = 0.61$ in comparison to data from [1]

Afterwards from the data of a sample with high martensite content under the assumption of a parallel spring model ($\varepsilon = \text{const.}$) the martensite properties can be identified by

$$\sigma_m = [\sigma - \sigma_f(1 - V_m)]/V_m. \quad (3)$$

For this fit data with low strain is omitted, since there the martensite might behave partly elastic. The result is shown Fig 2b).

For the transition the stress at a certain value of strain (here exemplarily chosen to be 0.025) is analyzed by a fit function accounting for a constant value at low martensite content, a linear dependency for high martensite content and a transition in between. This is shown in Fig. 3a).

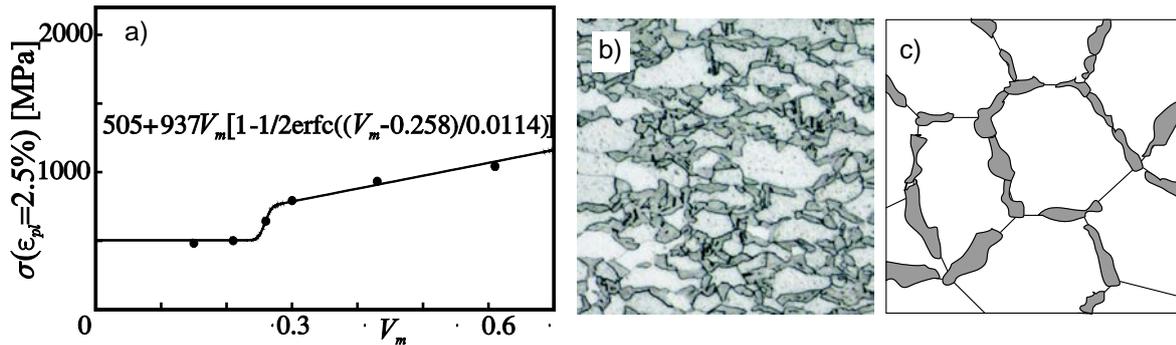


Fig.3: A) Stress at a plastic strain of 0.025 for different martensite content V_m and fitted curve, b) micrograph with $V_m = 0.33$ and c) scheme for martensite formation mainly at the grain boundaries

It is remarkable that the transition occurs at relatively low V_m . But this can be explained again by microstructure: The martensite forms at the grain boundaries of the ferrite grains and therefore builds up a hard network already at relatively low martensite content V_m .

4 Results

The model was tested on experimental data of DP600-1 steel from [2], where a wide range of martensite content was achieved due to thermal treatment. The model input data was obtained from samples with the lowest and the highest martensite content. The parameters retrieved by the inverse identification are:

$$\begin{aligned}
 m_k &= E k_k; \quad k_k = 1-0.5\text{erfc}((V_m - V_{mu})/(\sqrt{2}S_b)); \quad V_{mu} = 0.258; \quad S_b = 0.0114; \\
 \sigma_f &= B_f (\epsilon_{0f} + \epsilon_{pl})^{m_f}; \quad \sigma_m = B_m (\epsilon_{0m} + \epsilon_{pl})^{m_m}; \\
 B_f &= 1086 \text{ MPa}; \quad m_f = 0.2235; \quad \epsilon_{0f} = 0.0011723; \\
 B_m &= 2258 \text{ MPa}; \quad m_m = 0.1348; \quad \epsilon_{0m} = 0.0054564;
 \end{aligned}
 \tag{4}$$

The model is used in the following to calculate hardening curves for different martensite content V_m . The results in Fig. 4 show good agreement between the model and the experimental data if one takes into account that the martensite content is difficult to measure exactly.

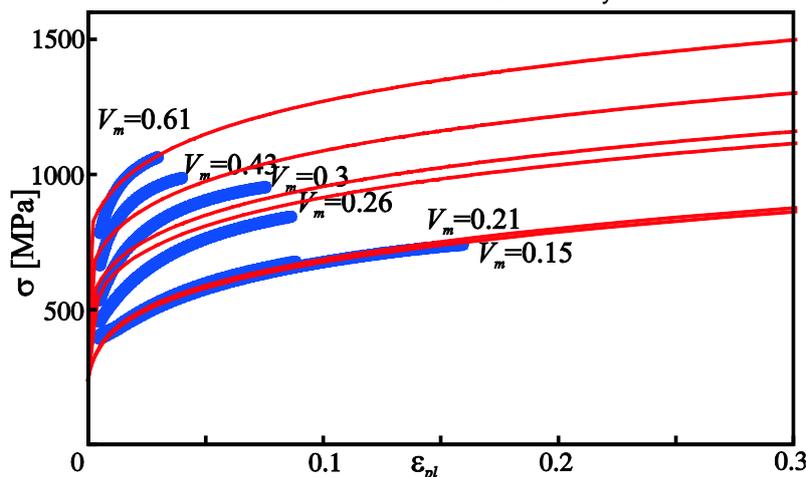


Fig.4: Stress versus plastic strain of the model compared to the experimental data from [2].

Another test of the model was done with data from the DP600-2. Its chemical composition is given in Table 1, too.

Due to the different alloying elements we have to recalibrate the model. But since the grain size of both DP600 is approximately the same, we assume that the ferrite data remains the same as well as the transition. Only the strength of the martensite has to be changed. This is again done by using the sample with the highest martensite content, which can be seen in Fig. 5a). The gained swift fit is

$$\sigma_m = B_m (\varepsilon_{0m} + \varepsilon_{pl})^{m_m} \quad (6)$$

$$B_m = 1583.04 \text{ MPa}; \quad m_m = 0.116751; \quad \varepsilon_{0m} = 0.006814$$

The recalibrated model shows good agreement with the experimental data, see Fig 5b).

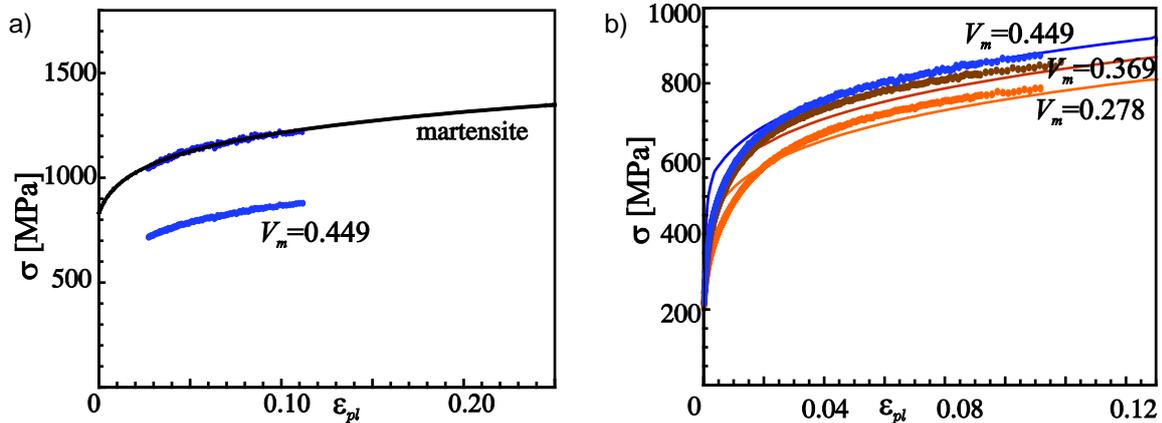


Fig.5: a) Recalibration of martensite data, b) comparison of the results of the model with the second DP600.

5 Summary

The proposed mixture rule is a simple tool to approximate the hardening properties of DP steels with reasonably low effort. It uses a simple inverse identification for the single phase properties. But it is sensitive to the martensite content in the transition range. This is very critical due to the remaining uncertainty of experimental determination of martensite fraction. Furthermore it neglects the influence of the carbon content within martensite, alloying elements and grain size. So, for a new material with different chemical composition the calibration has to be done partly or completely anew. The model could be improved further by including the grain size via the Petch-Hall relation or a dependency with respect to the content of carbon. The simulation of parts with varying martensite content and hardening behavior could be included via `mat_251` in LS-Dyna.

6 Acknowledgements

The financial support by the AiF within the project AiF 379 ZN/1 "UmCra - Werkstoffmodelle und Kennwertermittlung für die industrielle Anwendung der Umform- und Crash-Simulation unter Berücksichtigung der mechanischen und thermischen Vorgeschichte bei hochfesten Stählen" is greatly acknowledged.

7 Literature

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