Experimental Investigation and Numerical Characterization of the Bake-Hardening Effect of a Two-Phase Steel

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1 Introduction

Typically, the material characterization for the simulation is performed based on the virgin material, which is used for the preparation of the corresponding component. However, due to the processing of the material, its properties may vary greatly. Exemplarily, in Fig. 1, experimental results are shown based on the same material. The test specimens belonging to the red curve were pre-stretched and heated prior to the experiment, while the test specimens belonging to the black curve were not treated at all. Obviously, a material card adapted to the untreated material would not provide an acceptable match with the material being treated. Therefore, a closer look at the influence of pretreatment as well as the development of methods to take this influence into consideration is of great interest.

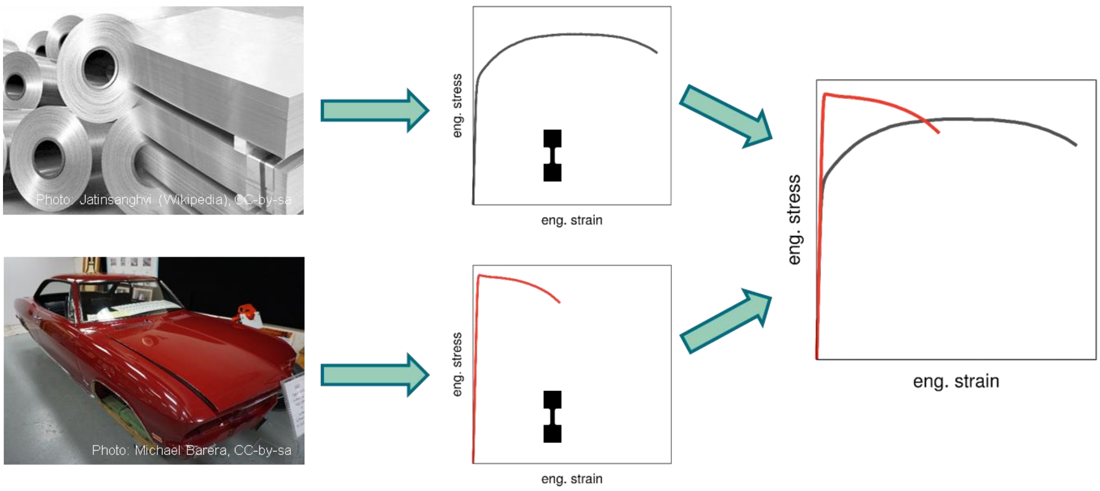

Fig.1: Tensile tests of the same material lead to completely different results when the material is pretreated.

Pretreatment by plastic deformation and subsequent moderate heating results in a work and bake hardening effect on many steels. Typically, this effect can be found, among other things, in bodywork components which are plastically deformed during the forming process and are then subjected to heat treatment during the baking of the paint. Physically speaking, the increase in temperature accelerates the diffusion of the carbon atoms in the steel, which accumulates in the lattice dislocations (cf. Fig. 2 and [1]). The reallocation of the carbon atoms increase the tension that is necessary for further plastic deformations in the steel. Correspondingly, an increased yield stress and ultimate tensile strength (UTS) can be observed in tensile tests. At the same time, a considerable decrease in the uniform elongation and the engineering failure strain can be observed. It is expected that the here used DP1000 shows these bake-hardening effects (cf. [2]). A particular focus of this study is on the anisotropy of the effects.

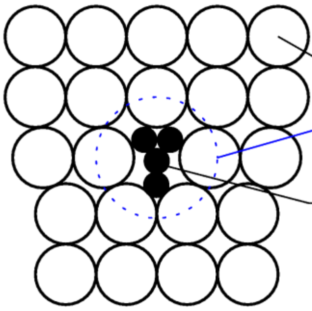

Fig.2: Accumulation of carbon atoms in a lattice dislocation.

2 Experiments

2.1 Pre-treatment

In order to examine the influence of individual parameters on the bake-hardening effect, an extensive test program was carried out. Thereby, the following influencing variables are considered: rolling direction, degree of pre-strain, heat treatment, pre-straining direction. From Fig. 3 can be seen, that this setup finally leads to an overall number of 24 (2*2*2*3) variants.

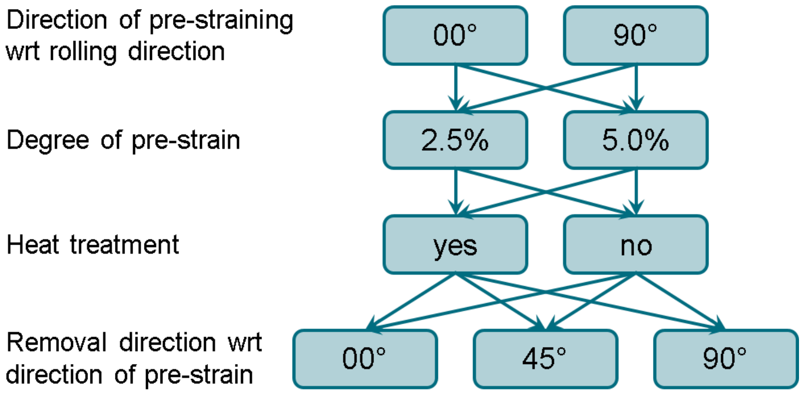

*Fig.3: Test setup with 2*2*2*3=24 variants.*

In order to investigate the influence of the rolling direction, the sheets were cut into strips along the longitudinal direction (0 °) and transversely (90 °) to the rolling direction (Fig. 4).

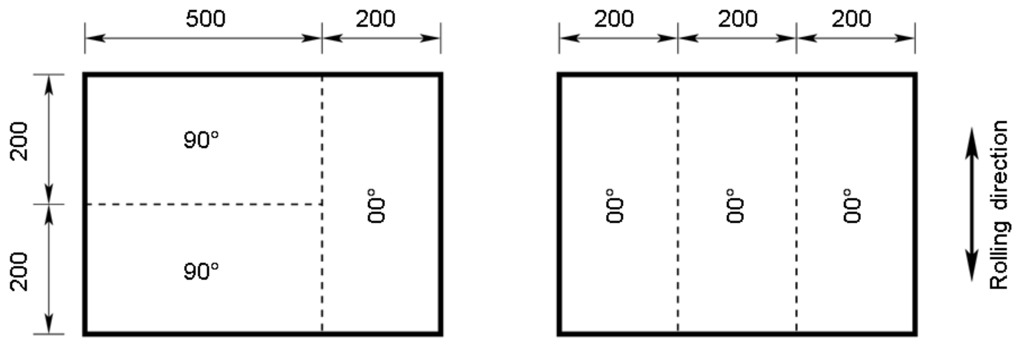

Fig.4: Cutting the plates longitudinally and transversely to the rolling direction.

The pre-straining was carried out by means of a Marciniak tool. In this case, the strip is pulled over a cylindrical punch while the sides do not reach to the edge in order to obtain a state of uniaxial tension in the middle region of the strip. The degree of pre-straining was controlled by optical strain measurement (see Fig. 5).

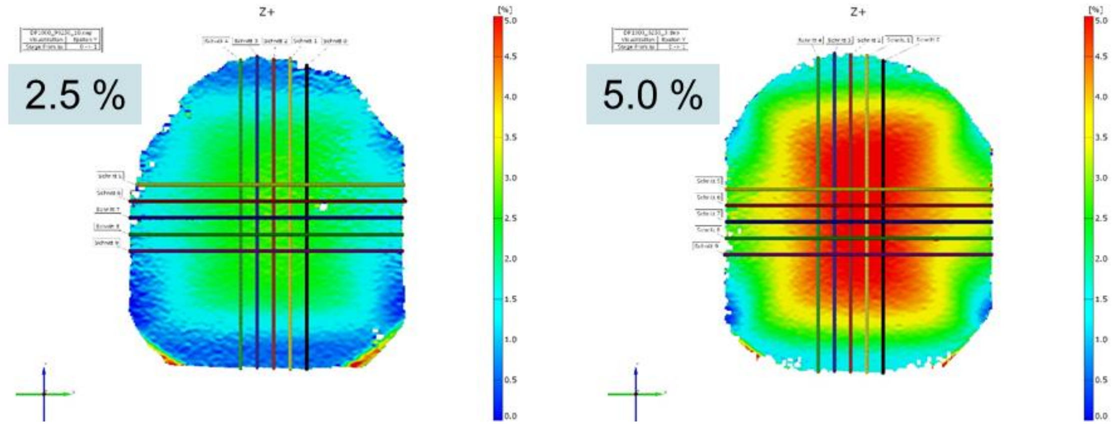

Fig.5: Confirmation of the plastic pre-straining by optical strain measurement.

To reproduce the heat treatment during the paint-baking process, half of the stripes were heated after the pre-staining to about 180 °C for approximately 30 minutes. Fig. 6 shows the applied temperature profile.

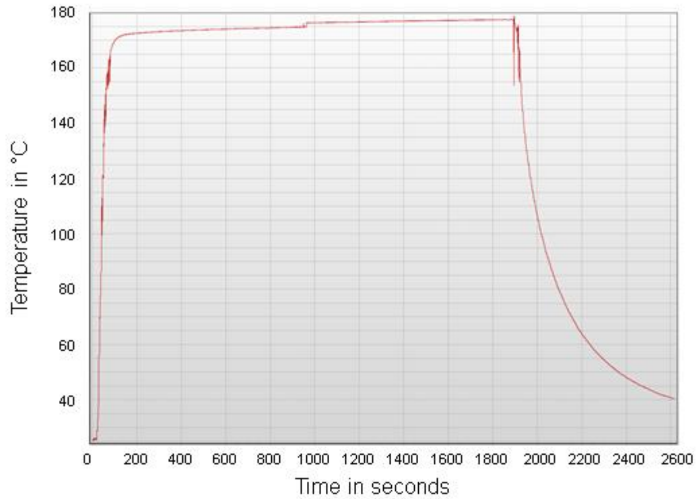

Fig.6: Temperature profile of the heat treatment.

In order to be able to extract tensile specimens in 0 °, 45 ° and 90 ° direction to the pre-straining (see Fig. 7) from the stripes, a comparatively small sample geometry, which is shown in Fig. 8, is used.

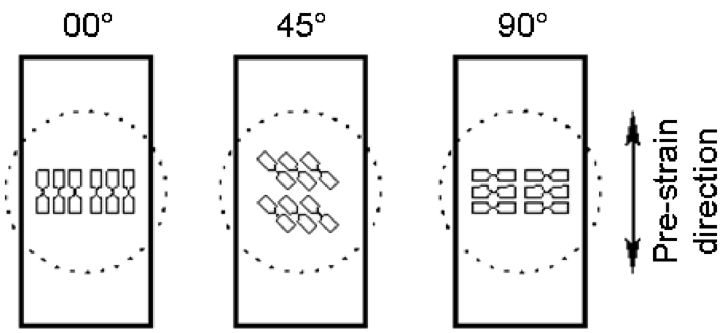

Fig.7: Extraction of tensile specimens in 0 °, 45 ° and 90 ° direction to pre-stretching.

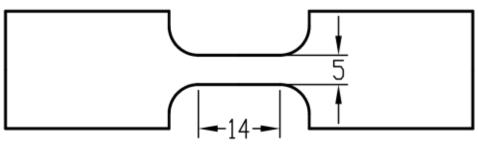

Fig.8: Specimen geometry (dimensions in mm).

2.2 Experimental results

The evaluation of the test results is carried out using the engineering stress-strain curves, where a reference length of 10 mm is used for the engineering strain. The first parameter whose influence is being evaluated is the rolling direction. In Fig. 9, the test results for 5.0 % pre-straining and subsequent heat treatment are shown for all three directions of sampling the specimen with respect to the pre-stretching direction. The results in the rolling direction (longitudinal) are shown in blue, and perpendicular to the rolling direction (transversal) in red. A slight difference may be observed, but it gets clear in the following that the influence of the rolling direction is only of minor importance and is therefore not taken into account in further investigations.

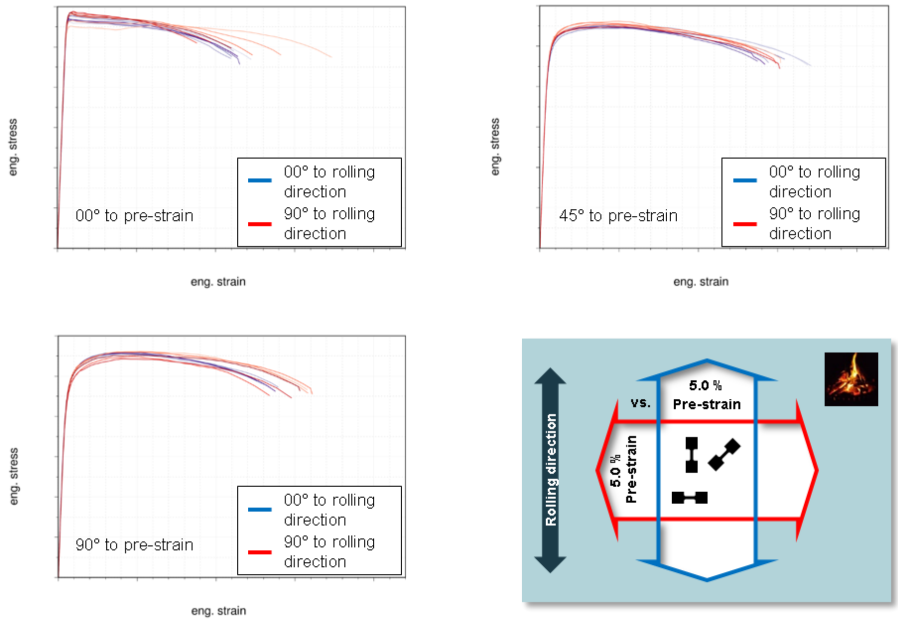

Fig.9: Investigation of the influence of rolling direction.

Next, the degree of pre-strain is examined. As shown in Fig. 10, the degree of pre-strain has a significant influence on the hardening of the material. Moreover, it is found that the direction of the pre-straining influences the effect, such that the shape of the stress-strain curve changes very strongly, in particular in the direction of pre-straining.

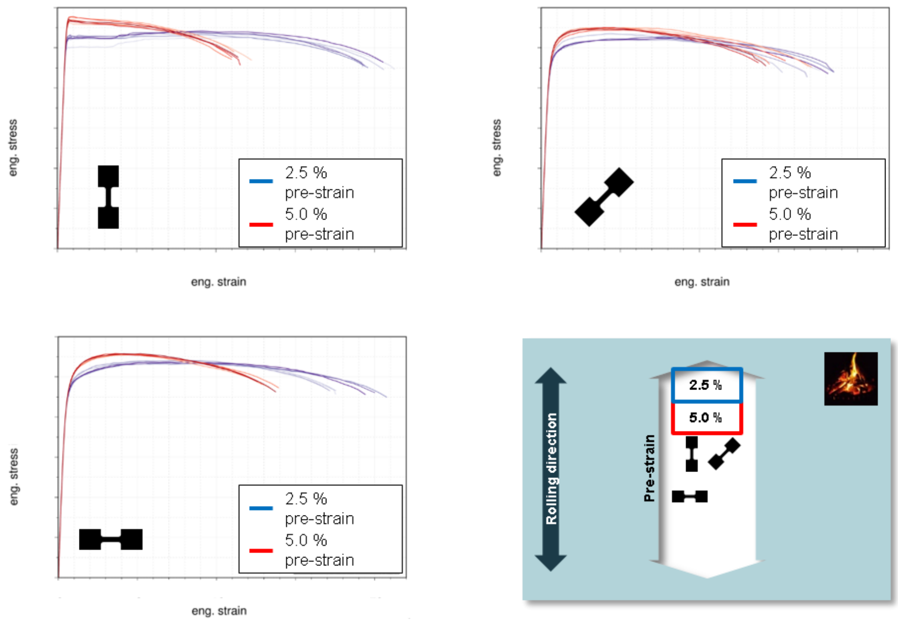

Fig.10: Investigation of the influence of the degree of pre-strain.

In order to determine which portion of the hardening is related to the heat treatment, the test results for specimen with and without heat treatment are shown in Fig. 11. The heat treatment leads, as well as the pre-strain, to a further hardening of the material, whereby the yield stress and the UTS increase and the uniform elongation and engineering failure strain partially decrease strongly. Also for this bake-hardening effects, the direction of pre-straining plays a decisive role and again, whereas in the direction of pre-straining the effect is most affected.

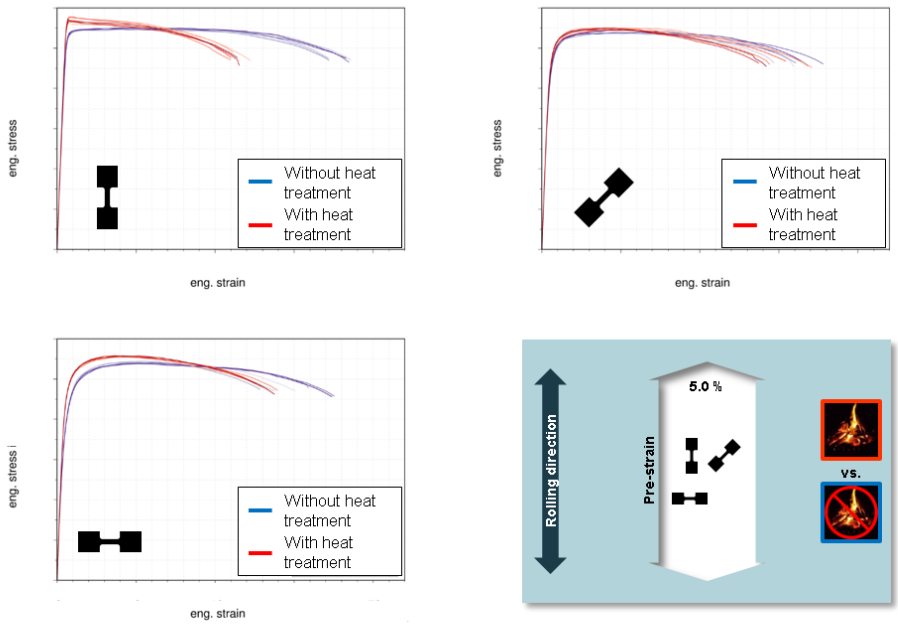

Fig.11: Investigation of the influence of heat treatment.

In summary, due to the pre-treatment, the following effects can be identified: The pre-straining as well as the subsequent heat treatment increase the yield stress and the UTS and decrease the uniform elongation and the engineering failure strain. The effect rises with the degree of pre-strain. In addition, the hardening also strongly depends on the direction of the pre-straining, whereby the effect in the pre-straining direction is most pronounced. The rolling direction plays only a minor role. These hardening effects can also be clearly seen in the overview in Fig. 12. All these findings are likely to be similar for other materials, however, there are certainly exceptions.

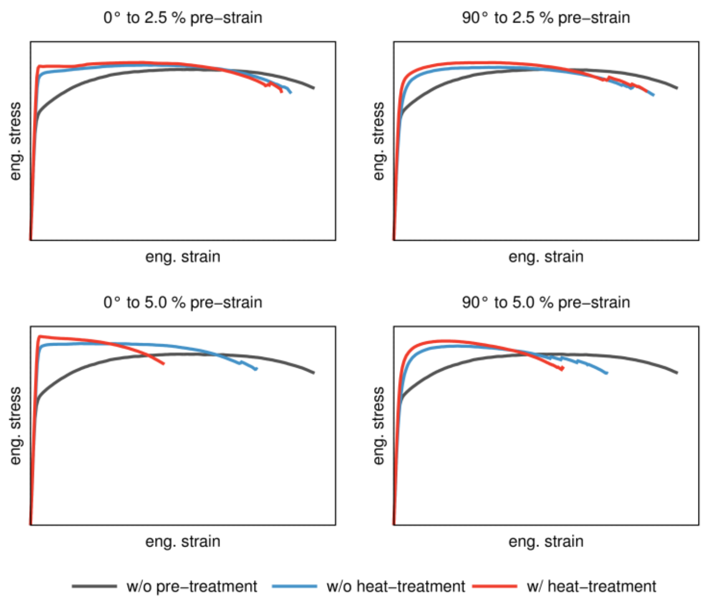

Fig.12: Exemplary comparison of the averaged test results for 2.5% and 5.0 % pre-strain for specimen with (red) and without (blue) heat treatment in different directions to the pre-straining.

3 Simulation

3.1 Phenomenological approach to consider bake-hardening effects

Existing pre-strain is usually taken into account in modeling by shifting the yield curve, which describes the yield stress as a function of the equivalent plastic strain. This shifting allows a good representation of the hardening resulting from the pre-strain, the so-called work hardening.
On the 14th German LS-DYNA forum, a phenomenological approach was introduced by D. Riemensperger [3] to take the bake-hardening effects into account. Since bake hardening usually has a similar effect as work hardening, his proposal was to shift the yield curve again by a certain amount, in analogy to the work hardening. This principle is illustrated in Fig. 13, where WH is the pre-strain and BH may be some sort of “bake-strain”.

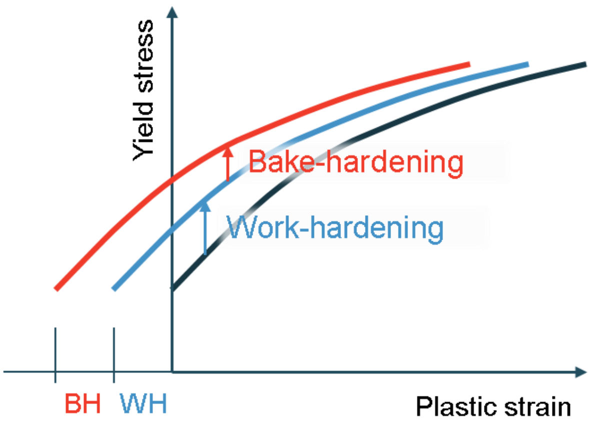

Fig.13: Phenomenological modelling pre-strain and heat treatment by shifting the yield curve.

Based on this approach, the directional dependence of the pre-straining is taken into account in the following. The initial-boundary-value problem is solved using LS-DYNA implicit where the material behavior is described by *MAT_PIECEWISE_LINEAR_PLASTICITY (*MAT_024). Failure is not taken into account for this study since the focus is on the ability to reproduce the stress-strain curves as well as possible. In order to find the optimal shift of the yield curve for each tested variant except for the differentiation of the rolling direction, LS-OPT is used.

3.2 Simulation results

The results are depicted in Fig. 14. Generally speaking, this comparatively simple approach of proportional plasticity is capable of delivering greatly improved results, where the corresponding values for the WH and BH shifts are illustrated in Fig. 15. Nevertheless, for some variants it is not possible to find a shift that yield to correct prognosis of the yield stress and the stress level in the post critical area simultaneously. For example, in the simulation of the variant with test in direction of 2.5 % pre-strain and heat treatment, the yield stress is considerably underestimated. A further shift of the yield curve leads to a better agreement with the yield stress, but instead the stress level after the uniform elongation is too low, see Fig. 16.

As expected, it is found that in the pre-straining direction the WH shift of the yield curve coincides exactly with the corresponding pre-straining of 2.5 % and 5.0 %. For the other directions, the optimal WH shifts to match the curves are smaller. It can also be said that the effect of bake hardening apparently increases with the degree of pre-strain. The large differences in the shifts for the individual directions illustrate the strong anisotropy of the bake-hardening effect. Here too, the effect in the direction of pre-stretching is most pronounced.

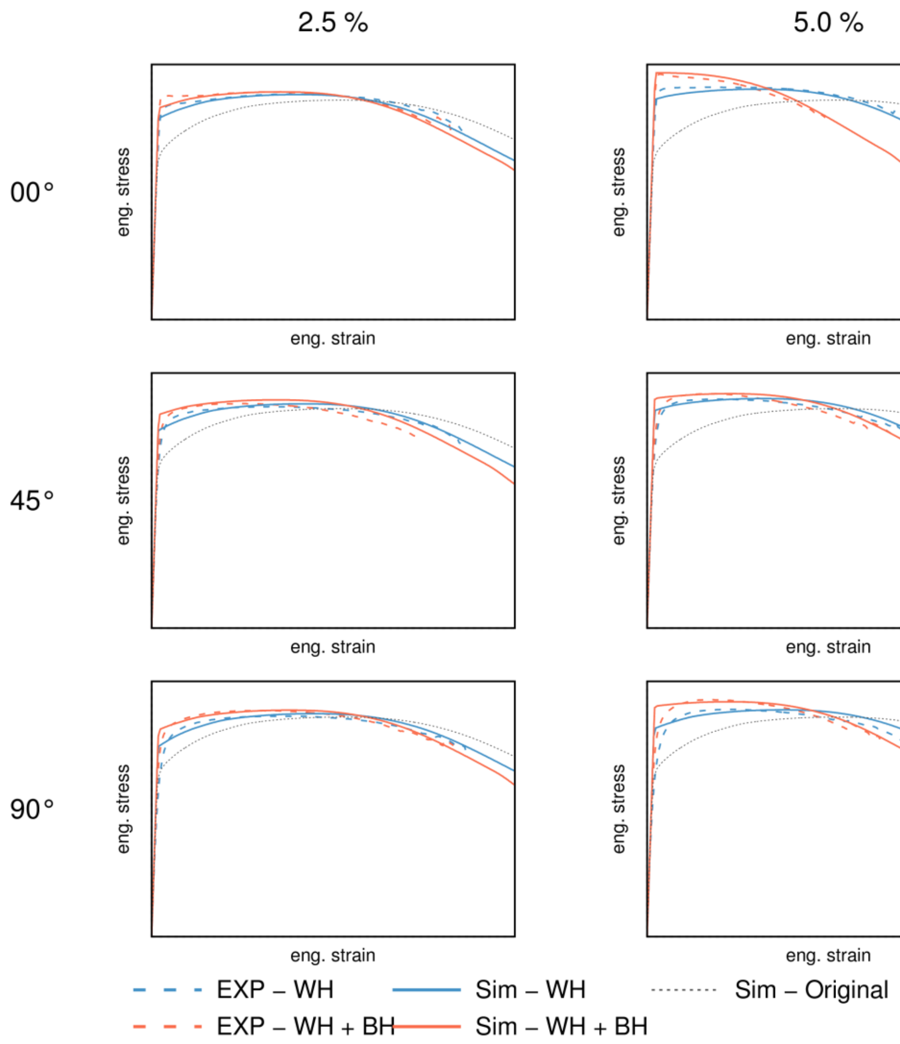

Fig.14: Simulation results with optimized shifts for yield curve for different sampling directions (lines) and different degrees of pre-straining (columns) with (red) and without (blue) heat treatment.

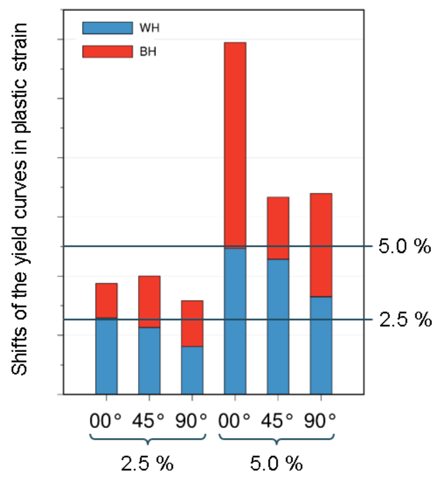

Fig.15: Optimized values for the WH (blue) and BH (red) shifts.

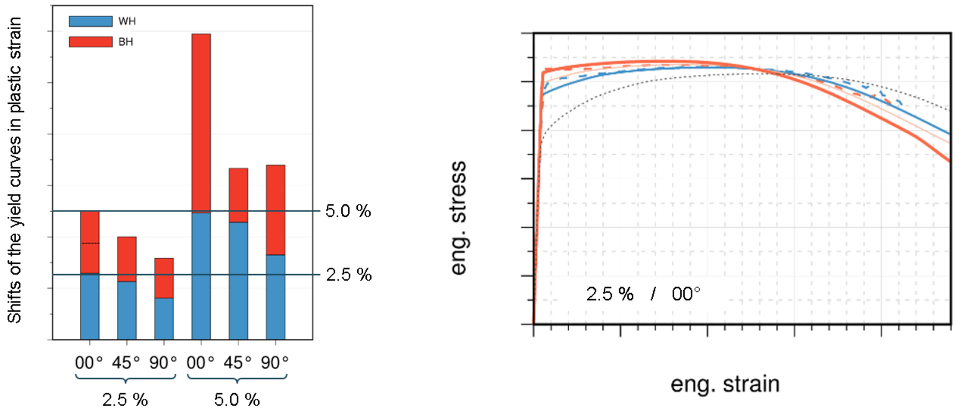

Fig.16: BH shift to agree with the yield stress of the test in the direction of 2.5% pre-stretching and heat treatment.

4 Conclusions

The investigation shows that both the work-hardening and the bake-hardening effect are dependent on the direction of the mechanical preload. As a consequence, in addition to the degree of pre-strain also the direction of pre-straining has to be mapped to subsequent simulations to use this approach. These mapping features are most likely to be available in the mapper ENVYO in the near future. Since only the influence of uniaxial pre-strain has been investigated so far, an open question is how the material reacts to biaxial pre-straining or shearing, or even to strain states somewhere in between. This point will next be considered more closely. There are possibly other factors whose influence could be of decisive importance and which could be worth looking at. For example, the temperature and the exact duration of the heat treatment.

Nevertheless, in order to take account of the presented dependencies in a simulation, not only a corresponding material model must be available, which does not currently exist according to the authors knowledge, but the dependencies for the following parameters must also be determined from tests: degree and direction of pre-straining , Heat treatment and, if appropriate, the state of the pre-straining.

This presented approach of proportional plasticity is capable of significantly improving the description of the pretreated material. However, here too, concessions must be made to the simplicity of the approach in the form of local inaccuracies. The presumably next logical step would mean that the shape of the yield curves must be changed according to the pretreatment. Most likely, this would further increase the effort both in determining the dependencies and in the simulation itself.

5 Literature

[1] Timokhina, I. B.; Pereloma, E. V.; Ringer, S. P.; Zheng, R. K.; Hodgson, P. D.: “Characterization of the Bake-hardening Behavior of Transformation Induced Plasticity and Dual-phase Steels Using Advanced Analytical Techniques”, ISIJ International, Vol. 50, 2010, pp. 574–582

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[3] Riemensperger, D.: “Considering Bake Hardening for Deformed Sheet Steel - A phenomenological approach“, 14th GERMAN LS-DYNA FORUM, 2016