# COUPLED FEM CALCULATIONS – A CAE TOOL TO IMPROVE CRASH-RELEVANT AUTOMOTIVE BODY COMPONENTS BY LOCAL HARDENING

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## Summary:

In the automotive industry, there is an increasing demand for weight reduction as well as safety requirements. These demands have motivated the use of locally optimized components. This study shows how local rigidity of crash-relevant side rails made of multi-phase steels can be improved by local hardening and thus avoiding an increase of the cross section. At the same time simulation process chains were completed and results validated by experiments. A dedicated software tool for the coupling of a wide range of commercially available FEM software products was developed. Codes for metal forming, heat treatment and crash simulations can now be used in one serial workflow. One major aspect here was the transfer of tensor-like values such as stress or strain states.

## Keywords:

Coupled process chains, stamping simulation, crash analysis, mapping tools

## 1 Introduction

In automotive manufacturing there is an increasing request for lightweight construction and safety which leads to an intensified use of high-strength multi-phase steel such as DP or TRIP. The required stiffness of crash relevant body parts can differ locally. Nowadays such components are realised with place-dependent cross sections („tailored blanks"), by combination of several sections, with reinforcement, or by using different materials.

Another possibility for the design of locally adapted parts with further weight reduction could be the partial hardening. The local strength can be increased without increasing the cross section. This method could be named as „tailored microstructure "[1]. In order to protect particularly areas like the passenger cabin against deformation the energy absorption potential of modern multi-phase steel has to be combined with the strength and rigidity of hardened steel. Such local hardening can be achieved by partial austenitisation and quench hardening in water. In the other zones the typical ductility of multi-phase steel is maintained.

In earlier publications it was already shown that by local hardening of multi-phase steel a doubling of the tensile strength is possible - without getting an unwanted weakening in the transition area between hardened and unhardened zone [2, 3]. In that work the effect of local hardening of a generic part (S-Rail) for crash was examined.

In order to reduce complex experiments more and more virtual simulations with finite element method (FEM) are used to design and test new components. For selected parts of the car body the manufacturing history of the stamping process is incorporated by mapping metal thickness and equivalent plastic strains [4, 5]. Residual stresses and micro-structural transformations so far are only considered partially. In some cases this may limit the accuracy of a simulation. This is especially true for those cases where a heat treatment is one step of the whole manufacturing process.

A dedicated software – the SCAIMapper – was developed to solve this problem. The SCAIMapper enables the coupling of such commercial FEM-codes which are used for the different manufacturing and development steps: stamping, local heat treatment, and crash analysis. Various approaches for the mapping of tensor values and a dedicated module to validate the mapping quality were implemented. With the help of this software a complete simulation process chain – from stamping over heat treatment to crash - could be set up and used successfully for the first time.

The investigations presented in this paper are based on a generic S-shaped test unit (S-Rail) which was already used in earlier comparison studies on stamping effects [6, 7].

## 2 Experimental Studies

### 2.1 Material Characteristics

As base material a DP 600 dual phase steel from the ThyssenKrupp Steel AG with a thickness of 1 mm and a chemical composition as represented in table 1 was used. The basic micro-structure consists of approximately 83% of a ferritic matrix with small martensitic inclusions (fig. 1). The ferrite grains have a diameter of 15 µm in lateral direction and 5 µm vertical to the sheet rolling direction. The martensite zones have a size of approximately 2-4 µm. The majority of the dissolved carbon is concentrated in those martensite areas (determined by micro probe measurements). The average carbon concentration is 0.128 Ma- %.

*Table 1: Chemical composition of DP600 (OES measurement)*

| *Element* | *C* | *Mn* | *Al* | *Cr* | *Si* | *Ni* | *Cu* | *P* | *Sn* |
|---|---|---|---|---|---|---|---|---|---|
| *Ma.-%* | *0.128* | *1.442* | *1.220* | *0.435* | *0.039* | *0.023* | *0.015* | *0.014* | *0.013* |

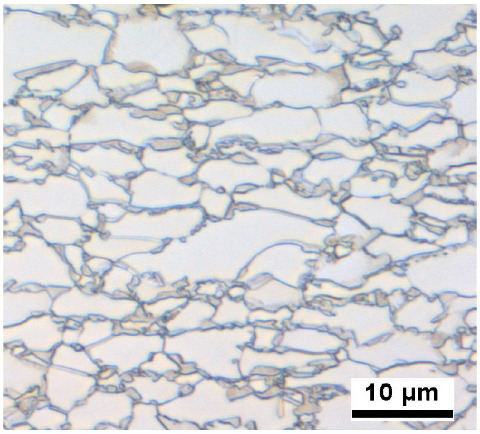

*Figure 1: Nital etching of raw material - Martensite in a ferrite matrix*

### 2.2 Production of S-Rails

The used test component („S-Rails “) consists of two laser-welded S-shaped sheet metal parts. The total size is approximately 270 mm by 70 mm. The upper part is an U-shaped hat profile, the lower part is a flat sheet metal part (fig. 2, left).

The upper hat profiles were punched from rhombic plates with edge lengths of 224 mm by 294 mm. The drawing depth was 40 mm. A blank holder force of 1300 kN was used. After the stamping process and still being in the die tool the hat profiles were laser-cut to the final shape. Finally the cover plate was applied by a laser welded seam (fig. 2, right).

To prepare a photogrammetry with GOM ARGUS three sheets were marked with a point grid in each direction of rolling by an electrolytic process (center distance of the circles: 2 mm, diameters of the circles: 1 mm). GOM ARGUS measurements can be used to compare major, minor and equivalent plastic strains with the results of the stamping simulation.

Following to the heat treatment two circular triggers of up to 7 mm depth were milled into each side and within the unhardened area. These triggers cut through the welded seams in their thickest place. These triggers were applied as an outcome of previous simulations and should initiate a folding within the unhardened area (fig. 2, left).

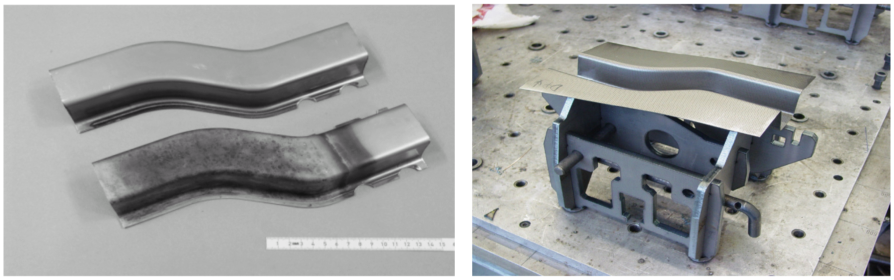

*Figure 2: Left: S-Rails without (top) and with partial hardening (bottom);*
*Right: Device for the laser finished trimming of the hat profile*

### 2.3 Heat treatment of S-Rails

Two third of the S-Rail body was immersed into a BaCl salt bath with a temperature of 950 °C for 30 seconds. An equilibrium with a two-phase mixture ferrit-austenit can be achieved at this temperature. This equilibrium however will not yet be reached after 30 seconds since first a carbon compensation from the former martensite areas must take place. Subsequently, the S-Rails were quenched in water in order to prevent them from bainitic transformation. By using this thermal treatment the hardness within the immersed area could be increased from 200 to approximately 273 HV 1. Figure 3 shows an example of this hardness spreading. The transition to the unhardened zone can be described well by a Sigmoide [3]. As a result of parameter adjustments the transition zone could be settled to 9 mm. The transition zone is defined by the area (oder: length, distance) between a change of the fit function from 1% to 99%.

The measured hardness spreading is quite smooth and runs proportionally to the rise of the martensite portion from 17 to 39%. Figure 3 shows micro-structure etchings at characteristic places of the transient area (Klemm). In area A the nearly unchanged initial micro-structure can be seen. The small bright inclusions are martensitic, the blue and brown grains are ferritic. In area B the martensite inclusions have partially been dissolved. However the annealing phase was too short to enrich larger areas of the former ferrite with carbon. The hardness remains at its initial value. In area C austenitisation and carbon balance continued and larger areas with medium carbon content could evolve. During the cooling process those regions convert martensitically and the hardness rises. The formation of Carbides is suppressed by the aluminum content.

Locally hardness respectively strength can be increased by this partial heat treatment, without producing weak points in the transition zone. This is important for the employment as crash components. In preliminary investigations on sheet metal samples a hardness increase of up to 340 HV 1 was reached. Due to the short time for austentisation tempering effects and grain coarsening could be avoided. Also the measured hardness of the S-Rails was bigger than the hardness of the raw material.

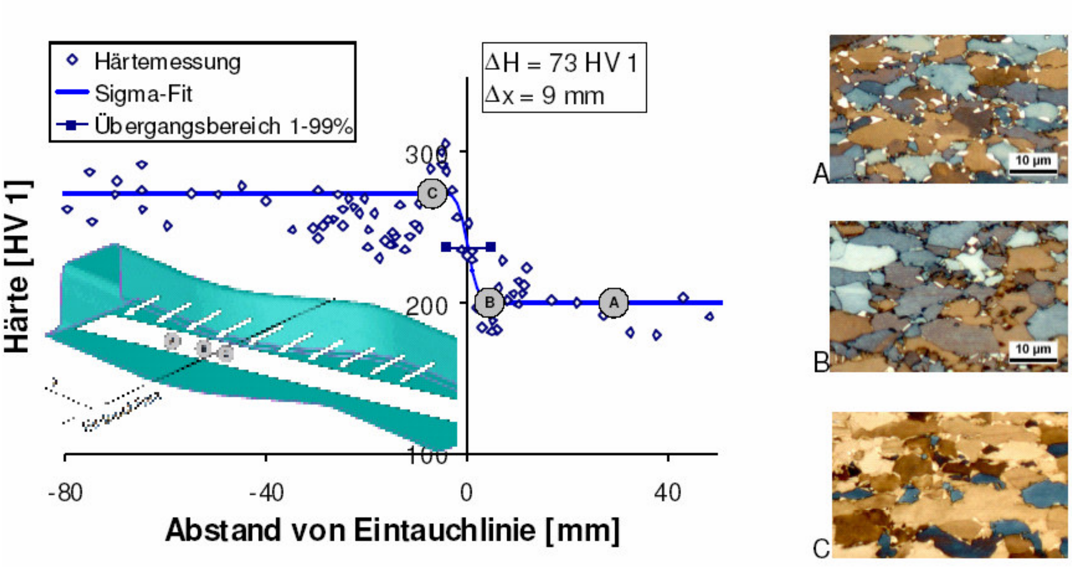

*Figure 3: Hardness process at a strip of a partially hardened S-Rails (left), cut out from the cover, and associated micrographs (right/after corrosion wedge); the martensite portion lies between 17% (A) and 39% (C)*

### 2.4 Crash Experiments

The real crash experiments were done in a drop tower at the Forschungs-gesellschaft Kraftfahrwesen mbH Aachen (fka). The S-Rail was equipped with a impact plate in order to lead the kinetic energy into the construction unit. After the first two attempts a stabilizing core was added in the lower sample area. An impactor with 125 kg mass falls down from a height of 0.46 m with approximately 3 m/s onto the receiving plate. This introduces an energy of approximately 564 J into the component.

## 3 Using SCAIMapper to Couple FEM Calculations

The Crash behavior of the S-Rails does not only depend on design geometry and material properties, but is also influenced by manufacturing history. A failure can be caused by local thickness reduction or residual stress peaks which are a result of the stamping process. This failure can limit the functionality of the entire component. In particular the local hardening step can induce gradients in the phase proportions or influence residual stresses – and thus influence the dynamic behaviour of the crash part.

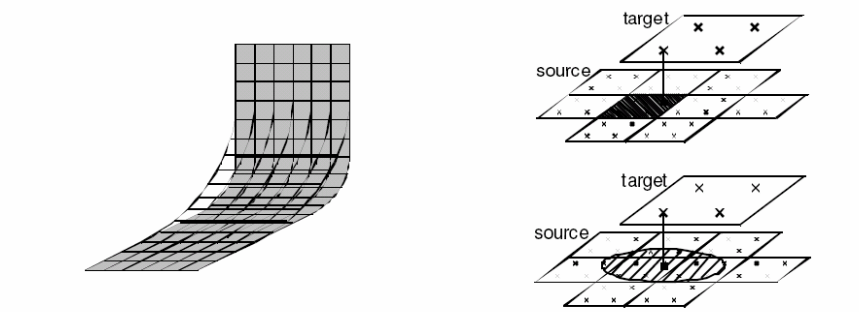

*Figure 4: Left: Mapping between non-overlapping structures.*
*Right: Element selection for the interpolation basis - modified Shepard algorithm [8] (down) in relation to element-based interpolation (top)*

The individual manufacturing and development steps are usually done with different programs from independent software providers, each of them optimized for its application area. To create a complete simulation chain which considers also the manufacturing history, the programs must be able to take into account the final state of the preceding simulation step as a starting condition. In most cases the FEM codes do not use compatible discretised models (meshes). Especially for meshes based on shell elements the corresponding areas have to be assigned to each other (fig. 4, left). If the size of elements of the coupled meshes differs strongly simple interpolation methods may lead to a loss of information and an increasing "blurring" (fig. 4, right). Further challenges arise from different internal representations of characteristics like e.g. absolute or relative displacements. A major goal of this project therefore was a general solution to couple different FEM codes in a manufacturing process chain.

### 3.1 Mapping of Tensors

The SCAIMapper tool is an extension of the MpCCI coupling software from Fraunhofer SCAI [6]. Before this project was started only scalar values could be transferred. One major extension now is the interpolation of tensor quantities like strains and stresses. During the project it was evaluated which of these tensor values needed to be interpolated in a conservative way. The simplest and fastest method is the interpolation of the individual tensor components. This method however does not conserve the main tensor components, particularly, if these do not vary in size but in the direction. Other procedures aim to be conservative for the important physical values like e.g. the Von-Mises equivalent stress. These methods however use under-determined systems of equations or even provide ambiguous signs. Better results can be achieved if one considers the tensor nature of these conditions, which is ensured by the separate interpolation of the main components and their directions in space. However this method generates higher computational loads. Usually it is not necessary to do a computation of the local equilibrium, as the transferred condition already is in equilibrium and the interpolation only creates small deviations. These deviations will be balanced in the later computation steps.

### 3.2 Validation of Mapping Results

In order to validate the quality of interpolation, a method to visualize inaccuracies of the mapping process was implemented. Differences can occur for example with large deviations between the element sizes of source and target mesh.

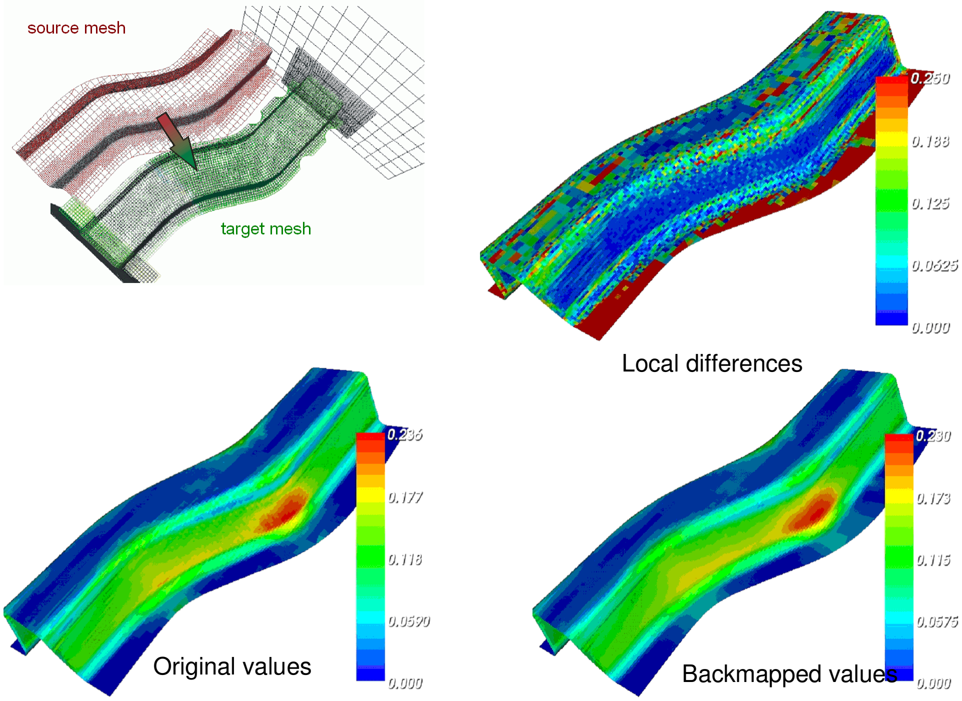

*Figure 5: Example for the validation of the interpolation (transmission of plastic strains): The original values (lower left) are compared with values, which are a result of the backmapping (lower right). Large local differences (right top) can be seen, where the meshes (top left) differ locally*

The concept of validation is to compare the original values from the source mesh with those values which were mapped from source to target mesh and back again onto the source mesh. Then the local differences can be calculated and visualised. The disadvantage of this method is that the largest deviations are in those model areas where there is no matching part on the other side e.g. with supernatant edges or in the case of notches. In practice these deviations do not have an actual relevance, since no values from these areas are used in the next simulation step (if the source model is larger than the target model) or if they cannot be visualized at all (if the target model is bigger than the source model). Thus the validation module provides an outstanding possibility to examine the quality of mappings (fig. 5).

### 3.3 Simulation Results

Simulations with several combinations of software packages were run for the two manufacturing steps stamping and heat treatment as well as for the crash analysis. The results of the stamping simulation shown in this paper were received with the programs LS-Dyna (v. ls971d R2 rev. 7600.1116) and INDEED. The blank was modelled with fully integrated thin shell elements with five Gauss points in normal direction (LS-Dyna) respectively thick shell elements (INDEED). The element size of 5 mm was locally refined in two steps. The friction coefficient was set to 0.03 to describe the contact between the sheet metals (treated with lubricating oil) and the punch. The punch was modelled as rigid body, which affects the forecast of the flange move-in.

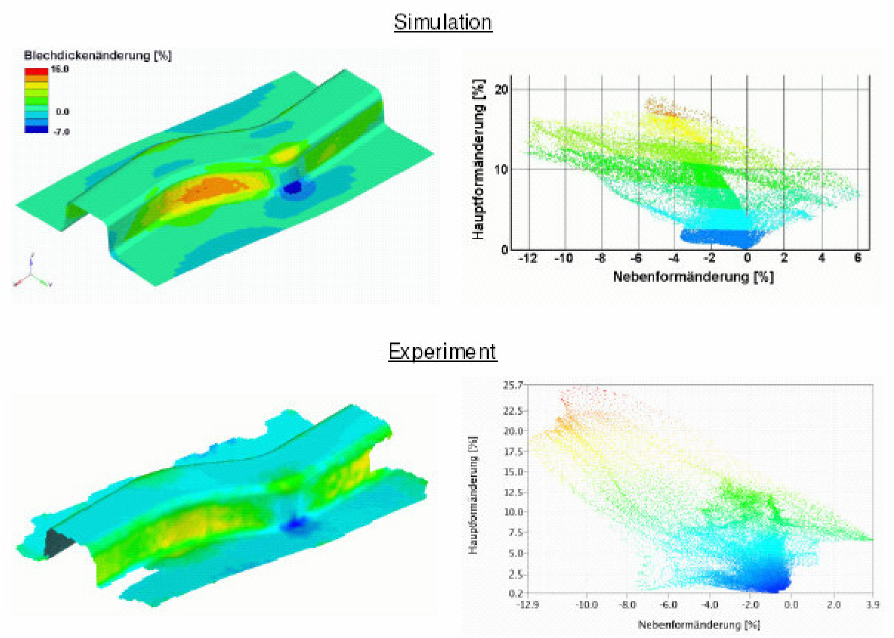

*Figure 6: Comparison of the stamping simulation with experiment.*
*Left: Thickness distribution after the stamping; Simulation with LS-Dyna;*
*Right: Related forming diagrams for the forming limit analysis*

Fig. 6 shows the comparison between simulation and measurement for the thickness distribution on the blank as well as the forming diagrams. The experimental data originate from a measurement with GOM ARGUS. The behaviour of the blank was computed properly in simulation. Differences are mainly due to potential deviations of the friction coefficient as well as the rigid body modelling of the stamping tool.

Figure 7 (left) shows the mapping of the stamping results onto the heat treatment simulation, which was done with the software Sysweld™ V. 2007. For this simulation step thin volume elements were used, in order to compute the phase transition of the dual phase steel with a particularly developed material model [2]. Boundary conditions such as heat transition coefficients as well as material properties such as tensile stress-strain curves were determined in preliminary investigations [3]. In order to reach an equilibrium after the mapping and the spring-back calculation some calculation steps without thermal loads were run initially (fig 7, right). In this case the model shows a slight torsion, which effects a tilt of the front edge of approximately 1 mm. This distortion fits in amount and direction well with the experimentally observed tendencies.

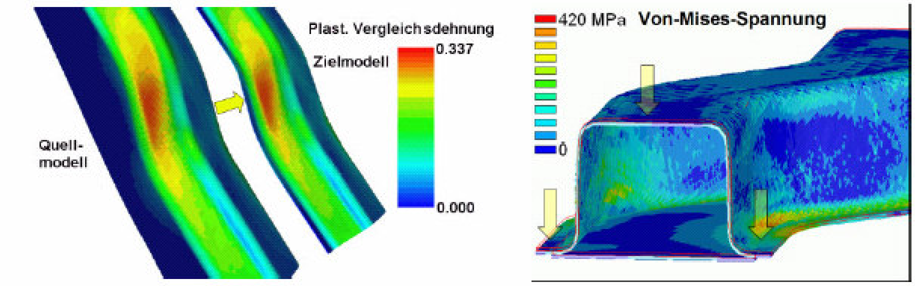

*Figure 7: Mapping of the plastic strains from the stamping to the heat treatment model (left);*
*Von-Mises stresses and displacements according to the spring-back calculation*
*(right, increased by factor 1)*

The conditions of the partial immersing in salt bath were emulated by applying a place-dependent heat transition coefficient. After the thermal treatment the immersed areas showed an increased martensite portion. A small transition area with a size of 10mm evolves, which matches well with the experimental data (figure 3).

The effect of the partial heating up can be described quite good by simulation. Below the immersing line the S-Rail expands much. At the same time the structure is partly austenitised. In the consequence the apparent yielding point decreases. Also directly above the immersing line there is still a heating up, but no austenitisation. Due to the temperature gradient in the upper area a local stress field with compression stresses results directly above the immersing line (fig. 8, left). In the austenite the stress cannot be kept. Directly below the immersing line a plastic deformation in the order of magnitude of 1% can be observed. During the cooling these plastic deformations result into strong residual tensile stresses (fig. 8, right).

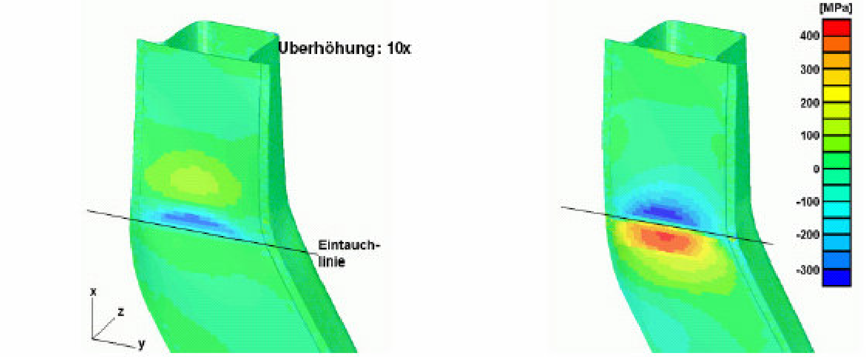

*Figure 8: Simulation of the residual stress component σyy shortly before (left) and after quenching (right); the thermally caused deformation is represented with a factor of 10.*

In a second mapping step the final state of the heat treatment simulation was transferred to the crash model. On base of the phase proportions a stress curve was assigned to each element, which had been measured in preliminary tests at different temperatures. Further boundary conditions were given by the experimental setup.

In figure 9 the final state of crash simulation is compared to the appropriate picture from the real crash experiment. The figure shows one simulation result without mapping (left) and one result with mapping (center). The simulation without mapping was prepared with a mechanical behavior of the hardened material onto the lower 2/3 parts of the model while the upper third was modelled as unhardened material. Thus a smooth transition like in the mapped models is missing in this model. Moreover the strain and stress conditions from manufacturing were not transferred into this crash-model.

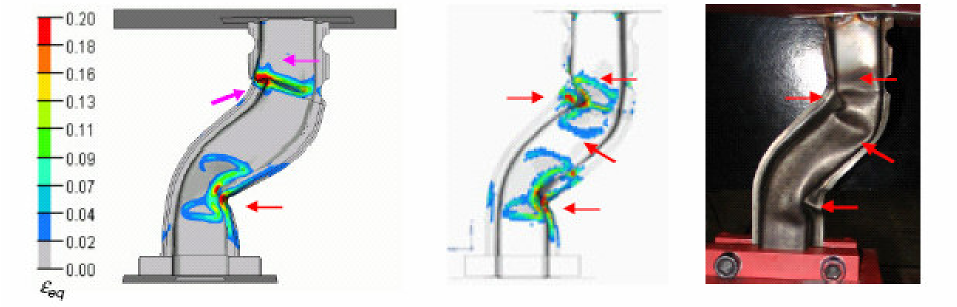

*Figure 9: Comparison of mapped and non-mapped simulations with experiment*

The comparison with a typical experiment shows a more realistic shape of the deformation compared to simulation without mapping. A drape near by the transition area of the hardened zone is computed in the run without mapping, while in the model with mapped initial conditions this drape is calculated more accurately.

In general it could be shown that by partial hardening the deformation way could be reduced by 40% compared to standard components - even if the same kinetic energy was absorbed. This improvement was reached without an increase of the component's cross section.

## 4 Conclusion

The improvement potential of crash relevant automobile components by local hardening was proven by investigations with generic punched side rails (DP 600 S-Rails). By partial immersing the parts into a 950°C hot salt bath a smooth structural change could be achieved. This graded martensite portion causes a higher stiffness in this zone, without generating weak points in the transient area. Parts

treated in such a way could absorb the same mechanical energy in the crash test, but proved a reduced deformation way (40%) compared with other standard components.
The SCAIMapper software was developed and extended. This tool is able to map results between most of the available FEM codes for stamping, heat treatment, and crash analysis. The SCAIMapper transfers a most data of the final state of a simulation step including the tensor variables to the following model. A new module allows to validate the mapping quality by a fast graphic control. By using this software it was for the first time possible to run a complete simulation chain from stamping through heat treatment to crash analysis. This mapped simulation chain showed a more realistic deformation in the crash simulation

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## 6 Literature

[1] Lütjens, J.; Hunkel, M.; Scholl, U.; Wallmersperger, T.; Schilling, R.; Sihling, D.; Wiegand, K.: Using coupled FEM simulations for improvement of crash-relevant automotive parts by local hardening. SCT 2008, International Conference on Steels in Cars and Trucks, June 1 – 5, 2008, Wiesbaden
[2] Lütjens J., Hunkel M., Hoffmann F., Zoch H.-W.: FEM simulation of carbon diffusion and phase transformations in dual phase and TRIP steels, Proc. 15th IFHTSE Congress and the 20th Surface Modification Technology Conference (2006)
[3] Lütjens J., Hunkel M., Hoffmann F., Zoch H.-W.: FEM simulation of local heat treatment on dual phase and TRIP steel parts, HTM 61 (2006) 5, S. 249-253
[4] Schilling, R.; Lanzerath, H.; Paas, M.; Wesemann, J.: Numerische Analysen zum Einsatzpotential neuer Werkstoffe in der passiven Sicherheit. VDI Berichte Nr. 1559, Würzburg, September 2000
[5] Schilling, R.; Lanzerath, H.; Ghouati, O.: Coupled Stamping-Crash-Analysis. In: E. Dehning & K. Wolf (Ed.): Why do Multi-Physics Analysis? NAFEMS 2006
[6] Fraunhofer SCAI, ISD Uni Stuttgart, FAT AK 27: Verbesserung der Prognosefähigkeit der Crashsimulation aus höherfesten Mehrphasenstählen durch Berücksichtigung von Ergebnissen vorangestellter Umformsimulationen, Umform-Crash-Kopplung, FAT-Schriftenreihe, 2005
[7] Stiftung Institut für Werkstofftechnik Bremen (IWT), Institut für Statik und Dynamik der Luft- und Raumfahrtkonstruktionen (ISD), Fraunhofer-Institut für Algorithmen und Wissenschaftliches Rechnen (SCAI), FAT AK 27: Untersuchungen zum Einsatz von Wärmebehandlungsverfahren zur gezielten Beeinflussung des Crashverhaltens von hochfesten Karosseriekomponenten, Schlussbericht zum AiF-Vorhaben 171 / ZN, 2007
[8] Shepard, D.: Two-Dimensional Interpolation Function for Irregularly-spaced Data. Proc. ACM National Conference (1968), S. 517-524.