Bending behavior of a hot stamped complex phase steel with tailored properties by local carburization

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Abstract. Concerning lightweight design, hot stamping of boron-manganese steels has developed to a state-of-the-art process for manufacturing safety-relevant car body parts in the last two decades. To further improve passenger safety, the idea of components with tailored properties has become even more important. Normally, these process variants aim to bring in so-called soft zones, where a fully martensitic microstructure is prevented to significantly improve ductility. The growing importance of battery electric vehicles and their special requirements call for alternative processes. Especially the battery and its housing are often referred to as a no deformation zone. Concerning this matter, the new process of tailored carburization can be advantageous, since it aims to locally improve strength rather than ductility. Regarding the field of application as a safety-relevant component, the crash behavior is of high interest. In recent years, the three-point bending test has prevailed as a suitable comparative test to estimate crash performance. Within this work, the influence of various carburization parameters on the bending behavior is analyzed. The results reveal that the additional carburization improves punch force at the cost of the bending angle. By analyzing locally carburized samples it is shown, that especially the carburization of the tensile loaded side within the deformation zone is crucial for local strengthening under bending load.

1. Introduction

Hot stamping of ultra-high-strength steel is a well-established process for manufacturing safety-relevant components in the automotive industry. To extend the limits of the conventional hot stamping process, the research focus lies on the qualification of new materials and further development of existing alloy concepts. In this context, new steel grades with a tensile strength of up to 2000 MPa are now utilized. The higher strength can be traced back to an increased carbon content compared to the conventional 22MnB5 [1]. Besides new materials, tailoring of the material properties is of the highest interest. These process variants aim to bring in soft zones locally, with a phase composition consisting of bainite, ferrite and pearlite instead of martensite [2]. Due to the increased ductility in these areas, energy absorbance can be improved during crashes. The most spread process variants in this context are tailor welded blanks, partial austenitization and partial hardening. Apart from various disadvantages like the formation of heat transfer-induced transition zones, limited flexibility, or elaborate system engineering, none of these processes enables local strengthening of the material. While tailor rolled blanks or tailor patchwork blanks do allow for local strengthening, these processes require additional material, which is disadvantageous in terms of lightweight design. Regarding
battery electric vehicles and their special safety requirements for the battery housing, processes to locally improve strength are necessary [3].

Therefore, the new process variant of tailored carburization aims to combine the trend of higher strength materials with increased carbon content and tailored properties [4]. In this process, a localized carburization process is applied to increase the carbon content of the semi-finished parts before hot stamping. With this process combination, components with a wide range of mechanical properties can be manufactured. Depending on the carburization parameters, a variable gradient in strength can be achieved between the carburized and the non-carburized areas. Furthermore, due to the nature of the diffusion process during carburization, the sheets exhibit a hardness gradient along the sheet thickness after hot stamping [4]. Considering the potential application as a safety-relevant car body part, the crash behavior is of the highest interest. In this context, the three-point-bending test is established as a model experiment for the evaluation of the crash behavior. Therefore, within this work, the influence of various carburization parameters on the bending behavior will be investigated and the tailoring potential of this process combination will be assessed.

2. Experimental procedure

2.1. Material
As a base material, the complex phase steel CP-W®800 with a sheet thickness of 1.6 mm will be utilized. Compared to the conventional hot stamping steel 22MnB5 [1], the CP-W®800 exhibits a significantly lower carbon content of only 0.14 mass contents in % [5], which enables further strengthening by carburization. In as-delivered condition, the sheets have a pickled surface without any residues from mill scale or additional coatings to prevent any impact on the carburization process.

2.2. Process combination of carburization and hot stamping
The sheets of the complex phase steel are locally coated with carbonic material such as graphite. If necessary, the additional boron-nitride coating is used as a barrier to localize the carburization. After preparation, the semi-finished parts are carburized above $A_c3$ temperature for several hours. Due to the process design with two independent steps, the sheets are first cooled to room temperature after carburization and then reheated for actual hot stamping with subsequent water quenching. The austenitization temperature is aligned to the carburization temperature and the dwell time amounts to 4 min. While the samples are wrapped in stainless steel foil during carburization to prevent oxidation, the austenitization process is done in an oxidative atmosphere, so decarburization takes place.

2.3. Experimental setup
The three-point bending test is done at room temperature and the dimension of the samples is 20 x 58 mm$^2$. The radius of the bending punch is 1 mm and the traverse speed amounts to 1 mm/s. A more detailed description of the test rig can be found in [6]. Within the bending of the sheets, no stop criterion is applied. The evaluation of the three-point-bending test is based on the maximum force $F_{\text{max}}$ and the bending angle at maximum force $\alpha_{F_{\text{max}}}$. The respective bending angle is calculated according to the standard DIN EN ISO 7438 [7].

Regarding the sheets with tailored properties, additional hardness measurements are carried out. For this purpose, a Fischerscope HM2000 is utilized to determine the hardness distribution in the cross-section of the bending line. The evaluation of the hardness is done with samples after hot stamping without bending deformation.

2.4. Experimental design
In the first part of this investigation, the sheets have homogeneous mechanical properties. Previous studies [4] analyzed carburization temperatures of 900 °C and 950 °C as well as carburization times of one to six hours. Within this work, the holding times of 1 h, 3 h and 6 h at 900 °C and 3 h and 6 h at 950 °C are investigated. To enable a holistic assessment of the bendability, uncoated sheets as well as
conventionally hot stamped sheets and sheets in as-delivered condition, are tested as well. The uncoated sheets have run through the same heat treatment cycle as the carburized ones but without graphite coating. With the idea of tailored carburization, both material conditions of the graded sheets are considered with this approach. The conventionally hot stamped sheets are only heat-treated for austenitization, which means 4 min at 900 °C or 950 °C. An overview of the different treatments of respective material conditions is shown in Table 1.

| Condition                   | Heat treatment 1 | Austenitization |
|-----------------------------|------------------|-----------------|
|                             | Temperature in °C| Time in min      |
| As-Delivered                | --               | --              |
| Conventionally hot stamped  | --               | 900             |
|                             | --               | 950             |
| Uncoated                    | 900              | 1, 3, 6         |
|                             | 950              | 3, 6            |
| Carburized                  | 900              | 1, 3, 6         |
|                             | 950              | 3, 6            |

The second part of this study focuses on sheets with tailored properties. Therefore, the semi-finished parts will undergo local carburization before hot stamping. As will be derived from the preceding results, especially carburization of the deformation zone is of interest. In this context, the four different tailoring strategies presented in Figure 1 are deducible. Number one to three limits the carburization on the area along the bending line. The carburization process can be done from both sides (Nr. 1), as well as solely on the tensile loaded (Nr. 2) or compressive loaded side (Nr. 3). The fourth strategy aims to carburize half of the specimen perpendicular to the bending line rather than parallel to it. The carburization parameters for this part are specified as 3 h for holding time and 900 °C for temperature.

3. Results and Discussion

3.1. Bending behavior of sheets with homogeneous properties
The estimation of the crash behavior is one crucial aspect during the design of safety-relevant components. One of the most suitable test setups to simulate crash-like load cases is the drop tower test [8]. However, tests like this often require extensive experimental effort. In this context, the three-point bending test turned out to be a suitable alternative for the estimation of the potential crash behavior [9]. Though, due to the quasistatic load during the bending test compared to highly dynamic loads during a crash, the results cannot be directly transferred. They are rather an indicator that could help to estimate the potential.

Within the first part of this investigation, it must be distinguished between parts with and without carburization. The results of the bending test of the last-named samples are shown in Figure 2. This relates to specimens in as-delivered condition, specimens after conventional hot stamping and
specimens that have undergone the same heat treatment as the carburized samples but without graphite coating. The figure shows the maximum punch force $F_{\text{max}}$ as a function of the bending angle at $F_{\text{max}}$. In as-delivered condition, bending angles of around 111° are achieved at a punch force of 20 kN. This overall good bendability can be traced back to the good local formability due to the homogeneous microstructure [10]. After conventional hot stamping, the bendability even tends to improve, since the angle at $F_{\text{max}}$ increases to around 116°. Simultaneously, the punch force goes up to almost 28 kN. Regarding the influence of the austenitization temperature, no significant effect is observable. The same applies to the two-step heat treatment cycle of the uncoated samples. In this context, neither the heat treatment temperature nor the several hours of holding affect the bending results. While the rise in punch force can be traced back to the increase in strength after hot stamping, the improved bendability is unexpected. In this context, it is noteworthy, that the three-point-bending tests suffer from one uncertainty factor when testing high-strength materials with up to 1200 MPa [11]. At high bending angles, the bending punch might lift off from the sample and force transmission changes from three-point bending to four-point bending. Regardless of this uncertainty, after hot stamping, a significant reduction of bendability was expected. The present opposite material behavior can be explained by two factors. After conventional hot stamping as well as after the two-step heat treatment of uncoated specimens, the increase in strength from the as-delivered condition amounts to less than 300 MPa and not more than 70 HV0.2 [4]. Furthermore, the microstructure does not change significantly since martensite is also present in the as-delivered condition and the fine grain size can be maintained. Therefore, the additional heat treatment has only a minor influence on the local bendability. As explained in section 2.2, decarburization takes place during austenitization. Furthermore, Maikranz-Valentin [12] and Choi and De Cooman [13] reported, that a decarburized surface has a positive effect on bendability after hot stamping. Due to these two factors, the bendability of the complex phase steel tends to increase after hot stamping compared to the as-delivered condition. Within the conducted experiments, most of the samples presented in Figure 2 only showed initial signs of damage such as roughening or microcracks but no complete failure. The initial damage was more pronounced in the case of the uncoated samples. Solely one uncoated sample after heat treatment of six hours at 900 °C exhibited a macroscopic crack in the surface. The maximum bending angle achievable with the testing setup was 160°.

**Figure 2:** Maximum punch force as a function of bending angle at $F_{\text{max}}$ of uncoated sheets, conventionally hot stamped sheets, and sheets in as-delivered condition
the bending angle of the carburized ones decreases to less than 35°. In contrast, the punch force increases. Contrary to the results in Figure 2, there is an influence of the holding time and the temperature. The punch force, as well as the bending angle, tend to increase with rising carburization temperature and longer dwell times. This can be traced back to the diffusion of the carbon atoms. In the beginning, only the area below the surface is involved in the carburization. Therefore, the carbon-related strengthening affects only a fraction of the whole cross-section. As a result, the punch force is on the level of the uncoated or conventionally hot stamped samples. With increasing holding time, more carbon atoms diffuse into the base material and within the sheet itself. This leads to a more homogeneous hardness distribution, which is directly linked to the carbon distribution. Since the whole cross-section experiences an increase in strength at longer holding times, the punch force goes up. This behavior also explains the improved bendability when extending the holding time. At short carburization times, there is a distinct hardness gradient within the material. While the hardness in the mid-section is still unchanged compared to the conventional hot stamping process, an increase of more than 250 HV0.2 is observable below the surface. This high hardness impairs local formability so that crack initiation occurs in an early stage of the bending process. At longer holding times, the hardness below the surface decreases since the carbon distribution homogenizes. To illustrate the influence of holding time, exemplarily samples are depicted in Figure 3, where the bending test was stopped after initial reduction in force. Furthermore, the fractured surface of the respective parameter combinations is included as well.

Regarding the influence of the temperature, it can be seen, that a higher temperature increases the punch force at the expense of the bending angle. Raising the carburization temperature boosts the carburization process. Within the same holding time, more carbon atoms diffuse into the steel sheet. As a result, higher overall and local hardness can be achieved at 950 °C. While a higher overall hardness leads to an increase in the punch force, elevated hardness below the surface also reduces local formability, which decreases the bending angle. The effect of temperature weakens with longer holding times, when there is enough time for diffusion, even at lower temperatures. Therefore, the difference between 900 °C and 950 °C decreases when increasing the carburization time from three to six hours.

In the non-carburized condition, bending angles of around 110° - 120° are achievable. The very good bendability can be seen when this is compared to other hot stamping alloys, for example, those with pronounced ductility, where the maximum bending angle amounts to >80° [14]. In terms of the carburized condition, the bendability is lower compared to the conventional 22MnB5 with >50° [1].

![Graph showing the relationship between punch force and bending angle for carburized sheets at different conditions.](image)

**Figure 3:** Maximum punch force as a function of bending angle at $F_{\text{max}}$ of carburized sheets

### 3.2. Hardness distribution of locally carburized sheets

The second part of this study focuses on sheets with tailored properties. Instead of all-over carburization, only small parts of the sheets are coated with graphite. As explained in 2.2., boron-nitride is used as a barrier to localize the carburization process. To validate the effectiveness of the locally limited carburization process and to correlate the bending behavior with the material condition, hardness in the cross-section of the specimens is measured. The results of samples with double-sided
and one-sided carburization of the deformation zone are shown in Figure 4. The measuring area corresponds to the sheet thickness of 1.6 mm and the width of the samples of 20 mm. To improve the presentation of the hardness distribution, the hardness mapping is distorted. Since the tailoring strategies nr. 2 and nr. 3 require the same carburization process, only one image is presented. For the carburization process, the width of the samples was divided into three sections with 6.67 mm each. The graphite coating was applied both-sided and single-sided in the mid-section. Three hours of holding time at 900 °C were chosen as carburization parameters. In the as-delivered condition, a hardness of 350 ± 6 HV0.2 was present in the material, while as-quenched hardness after conventional hot stamping was 421 ± 13 HV0.2.

The results show that the increase in hardness due to carburization is mainly limited to the graphite coated area. The transition zone between non-carburized and carburized is in the range of only a few millimeters and depends on the edge distance. In the case of double-sided carburization, the increase in hardness is symmetrical. The carburization process affects the whole sheet thickness so that there is a significant increase in hardness in the mid-section as well. Regarding the one-sided carburization, there is a uniform hardness gradient from one surface to the other. In the mid-section, only a small increase in hardness is observable. Furthermore, the hardness level below the surface on the carburized side is lower compared to the subsurface hardness of the specimens with double-sided carburization. This can be explained by an increased thermodynamical driving force for diffusion due to the higher concentration differences between both sides in the case of the one-sided samples.

**Double-sided local carburization**

![Double-sided local carburization](image)

**One-sided local carburization**

![One-sided local carburization](image)

| Vickers hardness | Measuring area | CP-W®800 | t₀ = 1.6 mm | n = 3 |
|------------------|----------------|----------|-------------|-------|
| 290              | 20 x 1.6 mm²   | T = 900 °C | t = 3 h    | HV₀ = 340 HV0.2 |
| 370              |                |          |             |       |
| 450              |                |          |             |       |
| 610              |                |          |             |       |

**Figure 4:** Hardness distribution of locally carburized sheets

### 3.3. Bending behavior of graded sheets

After analyzing the hardness distribution of locally carburized samples, the respective bending behavior is presented. The results are shown in Figure 5. Besides the specimens with tailored properties, also the results from the fully carburized condition are enclosed for comparison.

The measurement data shows clearly, that the tailoring strategy affects the punch force as well as the bending angle. The biggest difference is observable between the samples being carburized on the compressive-loaded side and the tensile-loaded side. Regarding carburization on the inner side, where compressive stress is predominant, only a small effect on the bending behavior is present. The punch force is on the same level as the conventionally hot stamped samples and the ones without carburization. The bending angle shows high scattering. This can be traced back to the hardness distribution. As derivable from Figure 4, there is a small increase in the hardness in the non-carburized half of the cross-section due to the diffusion of carbon atoms. At very high bending angles, the tensile force increases significantly in the former mid-section. Depending on the degree of carburization, the local formability might already be reduced which results in an early failure during testing. However, since only half of the tested samples failed early, a borderline case is probably present. With increasing holding time, the influence of this is expected to increase.
If the tensile-loaded side is carburized, there are fewer differences between the various tailoring strategies. Limiting the carburization to the deformation zone slightly improves the bending angle at the cost of a lower punch force. This can be explained by the diffusion of carbon atoms from the graphite-coated area into the boron-nitride-coated areas due to the difference in concentration. This results in a small decrease in hardness in the tensile-loaded sub-surface area compared to the fully carburized samples. Reducing the carburization process to the tensile-loaded side, a more significant increase in bending angle of more than 35% can be seen. At the same time, punch force decreases by less than 7%. As already explained in section 3.2, the hardness in the sub-surface area is smaller compared to double-sided or even full carburization, which improves local formability.

![Figure 5](image)

**Figure 5:** Maximum punch force as a function of bending angle at $F_{\text{max}}$ of locally carburized samples

The samples with perpendicular arranged carburized and non-carburized areas are a special case. Since only one half of the specimens was carburized, the punch force is slightly lower compared to the other samples. Apart from the punch force and the bending angle, especially the fracture behavior is of interest. The experimental procedure is designed to bend the sheets until the traveled distance of the punch reaches its maximum. While none of the non-carburized samples fractured during testing, all carburized ones – even those being carburized on the compressive-loaded side – did fail completely. As shown in Figure 5, samples with perpendicular arranged carburized and non-carburized zones only fractured unilaterally. During testing, the maximum punch force is achieved at a comparable low bending angle, as plotted in Figure 5. Due to the low formability, cracks initiate on the carburized side. With further punch traveling the whole carburized side fractures, but the crack is stopped in the transition zone between both areas. The force curve reaches a second maximum at around $120^\circ$, which corresponds to the bending angle at $F_{\text{max}}$ of the samples without carburization shown in Figure 2.

### 4. Summary and Outlook

In this study, the influence of additional carburization on the bending behavior was investigated. The first part focused on the characterization of sheets with homogeneous material properties. It was shown, that the hot stamping process and the two-step heat treatment of uncoated samples have a positive effect on the punch force and the bending angle as well. Further experiments on fully carburized specimens indicated, that the additional carburization process improves the punch force at the cost of the bending angle. In this context the positive effect of longer carburization times on both, the bending angle and punch force was proven.
In the second part of this investigation, different layouts for tailoring of the mechanical properties by local carburization were analyzed in terms of the hardness distribution and bending behavior. It was shown, that the process of local carburization enables a targeted increase in hardness with high geometrical accuracy. The results from the three-point-bending tests revealed, that especially the carburization of the tensile-loaded side is crucial for an increase in punch force but also significantly limits the bending angle. Moreover, possible manipulation of crack propagation was shown by employing samples with perpendicular arranged carburized and non-carburized areas.

However, within this study, the carburization parameters were limited to one holding time and one temperature in terms of samples with tailored properties. Further research should consider other parameter combinations. Moreover, additional experiments should focus on the determination of the onset of failure rather than just on maximum punch force and bending angle at $F_{\text{max}}$.

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