

Investigation of hot stamping transition zones at tailored carburization at elevated temperatures

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Abstract. Hot stamping is an established process for producing safety-critical components in the automotive industry while maintaining lightweighting concepts. The high strength achievable due to hardening and the geometrical complexity based on hot-forming are two major advantages of the process. A combination of locally ductile and high-strength zones can further improve crashworthiness. One approach to attain this is the tailored carburization process, which involves a local enhancement of the carbon content to strengthen the respective areas. Preliminary investigations have shown a possible reduction in process time by applying a diffusion annealing process route at elevated temperatures of up to 1050 °C. The resulting accelerated carbon diffusion effects similar material properties with tensile strengths of up to 1500 MPa, but only requires one-third of the dwell time. One effect that has not been investigated yet is the impact of the elevated carburizing temperatures on the expansion of the transition zones. Therefore, within this work the carburization parameters are varied and the resulting transition zone is characterized. Besides the laboratory samples, transitions at hot stamped components are also investigated.

Keywords: Hot stamping; Heat treatment; Carburization; Tailored properties.

1 Introduction

Lightweight construction is an important approach in the mobility sector, given the need to reduce carbon emissions. At the same time, the requirements regarding the passenger safety are increasing and must be fulfilled. Therefore, over the last decades hot stamping has been established in the production of safety critical components as a process incorporating both aspects. On the one hand the high strengths of up to 2000 MPa [1] resulting from the hardening enable an intrusion protection. On the other hand, low sheet thicknesses can be used to reduce the weight and thus emissions.

The process consists of an austenitization of the blank and its simultaneously quenching and forming in water cooled tools. Thereby, the material transforms from an austenitic into a martensitic structure resulting in the high strengths. Compared to the forming of other high strength materials the process enables a high geometrical part complexity and a low springback behaviour due to the processing at high temperatures [2]. These components have a good capability in intrusion protection but due to the low residual deformation capability a restricted energy absorption in a crash.

In order to increase the overall crash performance, there are different approaches to locally modify the materials respectively parts properties. For instance, the adjustment of the temperature history either during austenitization or quenching. Hereby, the transformation in fully martensitic material is locally

inhibited by either an incomplete austenitization or a too low and thus insufficient cooling rate. The respective component areas have an inferior strength but an increased ductility. Because these processes are depending on the influence of the local temperature profile the resulting transition zones are determined by heat conduction. These not intentionally adjusted zones can expand up to 80 mm [3]. Furthermore, to realize the properties, complex furnace concepts with masks which in some cases need to be actively cooled and tools with actively heated and cooled tool segments are needed.

Another approach is to locally exchange the material with a steel of higher ductility or with a different sheet thickness. The blank pieces are joined via butt welding prior to austenitization [4]. Thereby an overlapping process window for the hot forming as well the compatibility concerning the weldability are crucial. Furthermore, the properties in the heat affected zones and weld zone need to fit the ones of the base material to avoid inferior performance [5]. The resulting expansion of the transition zones are significantly smaller compared to the temperature depending processes.

Beside the processes aiming for a more ductile section of the part, tailored carburization functions on the principle of a local strength enhancement by increasing the carbon content. The base material is a steel usually not utilized in hot stamping e.g. CP-W 800 [6] or DC01 [7]. The principle is based on a carburizing step of the blank upstream of austenitization and hot stamping. As the blank as a whole is subjected

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to the same thermal conditions, there is no need for complex furnace or tool concepts. This makes the process flexible, integrable into existing hot stamping lines and suitable for small batch production or prototyping.

The extra incorporated carbon strengthens the martensite or enables its formation in the first place. For the CP-W 800 an increase of the tensile strength of around 40 % compared to the hot stamped but not carburized material can be achieved. But the used carburization parameter combination with 950 °C and 6 h prolongs the processing time significantly. Therefore, prior publications [8, 9] dealt with the application of higher carburization temperatures to accelerate the diffusion and thus reduce the process time. To limit the absorbed carbon content, which otherwise leads to a severe decline in ductility, and to homogenize the carbon through the thickness, an adapted process route was established. This approach consists of a shorter carburization phase with a subsequent diffusion annealing step. With a temperature of 1000 °C for one hour carburization and one hour diffusion annealing similar mechanical properties are achievable but at a third of the dwell time [9].

Another advantage of tailored carburization is the geometrical flexibility regarding the zone's position and size. Especially the latter is enabled by the comparatively small transition zone of about 5 mm to 10 mm [6]. These values were determined at the conventional process route at lower temperatures. To maintain this advantage the aim of this study is to investigate the influence of elevated carburization temperatures and the additional diffusion annealing step on expansion, mechanical properties as well as transformation behaviour of the transition zone.

2 Material and Methods

2.1 Materials and heat treatment

The base material is the complex phase steel CP-W 800 [10] with a sheet thickness of $t_0 = 1.6\text{mm}$. The samples have dimensions of 58 mm x 20 mm. A graphite foil which was attached with a graphite adhesive to the samples functions as the carbon source. To prevent volatilisation of the carbon, the coated samples are wrapped in a hardening foil package during heat treatment. In order to avoid a carburization of the to be non-carburized zones, these surfaces are coated with a boron nitride barrier layer. The tailored carburization process consists of carburization, diffusion annealing and hot stamping. The latter is simulated by water quenching the samples after austenitization. Diffusion annealing was performed at the respective carburization temperature T_{carb} for one hour. The austenitization was carried out at 900 °C for 5 min. To investigate the influence of the carburization temperature and time, different parameter combinations were used for the production of samples. Those are 1000-1h-1h, 1050-0.5h-1h, 1050-1h-1h and 1050-2h-1h in the following notation carburization/diffusion annealing temperature_carburization time_diffusion

annealing time in °C_h_h. That means the variation 1000_1h_1h was carburized at 1000 °C for one hour and subsequently diffusion annealed at 1000 °C for one hour.

2.2 Hot stamping of cruciform cups

In order to investigate the transition zones not only in laboratory samples but real parts, tailored carburized cruciform cups are produced via hot stamping. The blank preparation is the same including austenitization. Afterwards the blanks are transferred to the water-cooled cruciform tool which is equipped with a counter punch to ensure a sufficient cooling rate on the bottom of the cup. In this study the investigated configuration is a lengthwise half carburized cup which is shown in Fig. 1. To analyse the transition zone a 15 mm x 60 mm segment is extracted from the centre of the bottom. Furthermore, the blank temperature when the tool is closing was varied in two steps, namely 800 °C and 600 °C, to examine the influence of the transfer time.

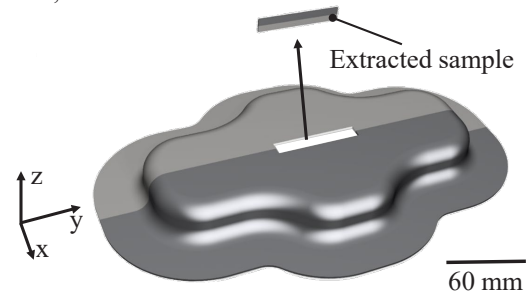


Fig. 1. Illustration of a lengthwise half carburized, hot stamped cruciform cup with an extracted sample.

2.3 Hardness measurement

In order to investigate the material properties in the transition zones Vickers hardness measurements were performed. To this end, the samples are cut, sanded and polished and tested on a Qness 60A/A+ EVO from ATM Qness GmbH according to DIN EN ISO 6507. The measuring point pattern extends over the entire sample with a minimum edge distance of 200 μm . Over the thickness ten measuring points are evenly distributed with a distance of 400 μm along the sample in the edges. In the centre the distance is reduced to 250 μm to increase the resolution in the area where the transition zone is expected.

3 Results and discussion

In the following the transition zones of laboratory scale samples as well as specimens extracted from cruciform cups with locally adjusted properties are investigated and compared. The grading is analysed via microhardness measurements and light microscopy images.

In Fig. 2 a) the average hardness profiles of partly carburized samples with the same duration but at different temperatures, namely one hour carburization and one hour diffusion annealing at 1000 °C and 1050 °C. For analysing the influence of the carburization duration Fig. 2 b) shows the hardness

profile at half an hour and two hours carburization. As expected, the unmodified areas have a similar hardness level of about 400 HV0.2. Which is in good agreement with the result from fully not-carburized samples [8]. As there is no carbon source in the hardening foil package for fully not-carburized samples, there is no need for the application of a barrier layer. Hence, this also indicates a sufficient retention of the protective ability against carburization of the boron nitride coating at elevated temperatures.

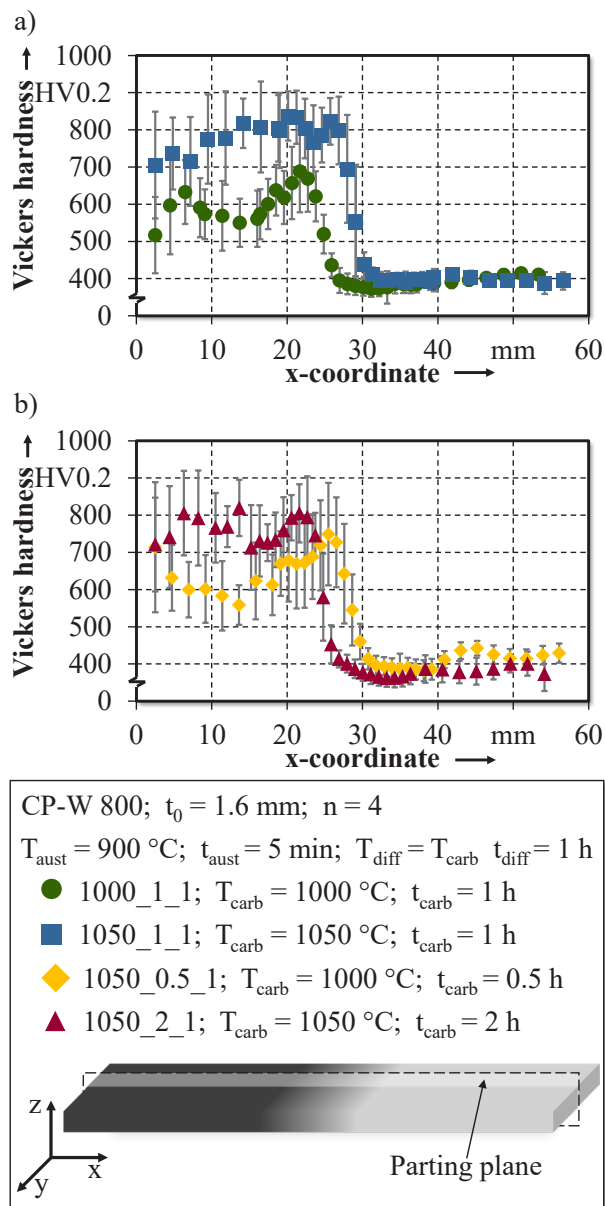


Fig. 2. Hardness profile of samples heat treated for a) 1 hour and 1 hour at 1000 °C and 1050 °C and b) 0.5 hour and 2 hours at 1050 °C with and subsequent one hour of diffusion annealing.

The different heat treatment temperatures do not have an influence on the unmodified sample regions but on the carburized zones. The higher temperature but same heat treatment durations result in an increase in hardness of about 150 HV0.2 which can be attributed to the more incorporated carbon. Therefore, the transition appears comparable regarding the course and expansion but the achieved hardness level is higher in case of

1050 °C. By halving the carburization time and maintaining the diffusion annealing duration, the hardness level decreases to a similar range as the combination 1000 °C for one hour and one hour. Otherwise, doubling the carburization time leads to no distinct increase. On the one hand, the reason for this could be the already high hardness level and the associated lower effect of the carbon increase.

On the other hand, the quite large standard deviations in all carburized regions must also be mentioned here. Firstly, the average values and thus also the standard deviations are calculated from the same x-position of ten measurements along the sheet thickness. Therefore, the possible hardness gradient and fluctuations of are taken into account. Secondly, the values consider all four samples at once. Especially in the transition zones due to the manual sample preparation and measuring point pattern arrangement the position can vary and thus the carbon content.

The fluctuations over the sheet thickness are also visible in the hardness mapping of representative samples in Fig. 3. In accordance with the hardness profiles the non-carburized sections are homogeneous within the zone as well as along the thickness. The transitions to the carburized regions are also evident and expand a few millimetres. These are comparable with those at lower carburization temperatures [6]. Therefore, the elevated temperatures and the additional diffusion annealing step do not lead to an excessive increase of the transition. This makes them significantly smaller than for temperature depending tailoring processes [3] and are on a similar scale to welding-based methods. This enables a very free arrangement and size adjustment of the to be tailored zones.

The carburized zones have an inhomogeneous hardness distribution. At the parameters 1000_1h_1h and 1050_0.5h_1h, there are about 15 mm wide areas with a medium hardness along the whole sheet thickness. These are recognizable by the green and yellow colouring. But towards the transition to the non-carburized zone the hardness increases until it merges in the non-carburized level. A possible explanation is the formation of residual stresses caused by non-simultaneously and nonuniform phase transformation, thermal contraction and volumes of the evolving phases of the close transition zone. Nakhimov and Novikova [11] had similar findings investigating the residual stresses of case hardened steels. The hardness of the carburized zones at the parameters 1050_1h_1h and 1050_2h_1h is on a higher level. Nevertheless, in case of the latter the maximum hardness is located after the transition zone. Compared to the non-carburized zones the carbon enriched sections show a more pronounced inhomogeneity. This is presumably due to the utilisation of a solid carbon source and the manual processing. This can lead to a more fluctuation in carbon intake and thus hardness distribution.

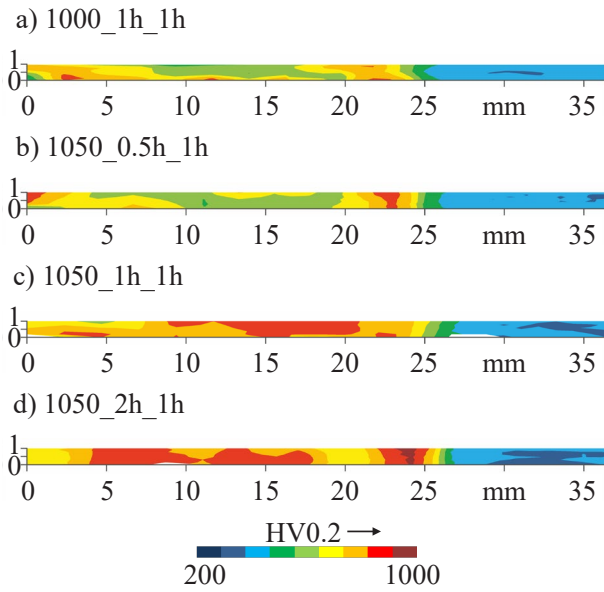


Fig. 3. Representative hardness mappings of the locally carburized laboratory samples. The figure shows only a part of the non-carburized areas due to their homogeneity and in order to be able to show the transitions and the carbonized areas on a larger scale.

In addition to the hardness measurements, Fig. 4. shows the light microscopy images of the variants heat treated for one hour with and subsequently without carbon at 1000 °C and 1050 °C. Basically, at both combinations the non-carburized zone consists of a homogeneous mixture of predominately coarse needle-like structures and ferrite. The first is presumably to a large extent martensite due to the hardness around 400 HV0.2. A further component could be bainite, which is hardly different from martensite in the present structure and with the used measurement method.

The transition zones differ in the appearance as at the lower temperature the amount of needle-like structures increases but the size of these remains constant. On the contrary, at the higher heat treatment temperature, the total area shares are comparable but both the ferrite grains as well as the martensite needles reduce in size. This trend is turning around towards the carburized areas. That means compared to the transition zones, the total area shares of the phases remain constant but the sizes are reduced at the lower temperature and the amount of ferrite reduces and the martensite needle size stays small. The correlation of the reduction with increasing carbon content has been demonstrated by Morito et al. [12]. It can be explained with a higher nucleation site density as dislocations from the lattice distortion due to the interstitial solute carbon and carbides can promote nucleation [13]. This is in good accordance with the hardness measurements. The 1050 °C heat treated variant is harder in the carburized zone due to the higher amount of martensite and its smaller size. Depending on the measurement position in the transition zone the finer grain structure is equalized in terms of resulting hardness by the ferritic share.

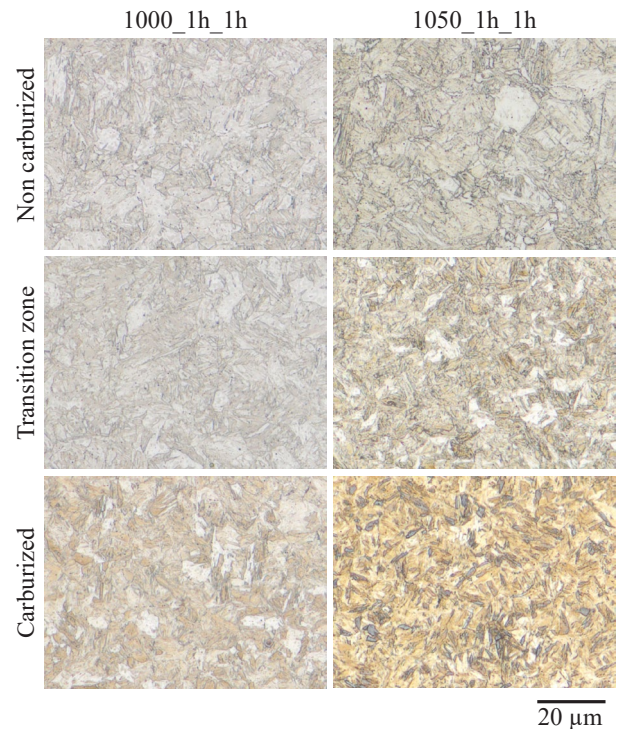


Fig. 4. Light microscopy images with a 500x magnification in the non-carburized, transition and carburized zones for the carburization, diffusion annealing combinations 1000_1h_1h and 1050_1h_1h.

In comparison with the laboratory samples, which are water quenched, the hardness development in the different zones of specimens extracted from hot stamped cruciform cups is also investigated. The hardness profiles at different tool closing temperatures of the blank are illustrated in Fig. 5. A quenching and forming start at 800 °C results in a homogeneous hardness within the non-carburized zones of all three samples. The values are between 320 HV0.2 and 380 HV0.2 and thus slightly smaller than the level of the laboratory samples. This can be explained by the significantly higher cooling rates by water quenching compared to a quenching in forming tools leading to more and finer martensite. A delay in tool quenching respectively one that starts at 600°C results in a decrease of the hardness to about 250 HV0.2. One reason for that can be the formation of softer phases like ferrite due to the slow cooling period at the beginning leading to an insufficient quenching rate to enable mainly a diffusionless phase transformation to martensite.

Nevertheless, the 600 °C samples show a steeper incline in hardness towards the carburized zone of up to approximately 800 HV0.2 in about 4 mm in two cases. In the third sample, the hardness increases to approximately 600 HV0.2 over the same distance. Also, the transitions start at different positions which supports the above-mentioned statement regarding the fluctuations in the transition zones average hardness. This effect is more pronounced as the guided but manual inserting of the blank is an additional factor in this case. Similar to the latter course at 600 °C is the trend for all three samples at a tool closing at 800 °C. A reason for this could be the previously investigated different warm forming behaviour [14]. This results in dissimilar deformation and thus in a shifting of the transition zone

which is not completely within the sample in case of the 800 °C. Based on the same principle as at the non-carburized zones, the higher hardness would be expected in the material quenched from a higher temperature or a similar hardness. The incorporated carbon effects a stabilisation of austenite and a shifting of diffusion-based phase transformations to slower cooling rates which enlarges the process window to obtain a martensitic transformation [15].

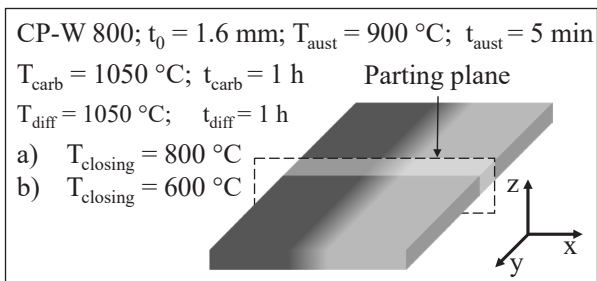
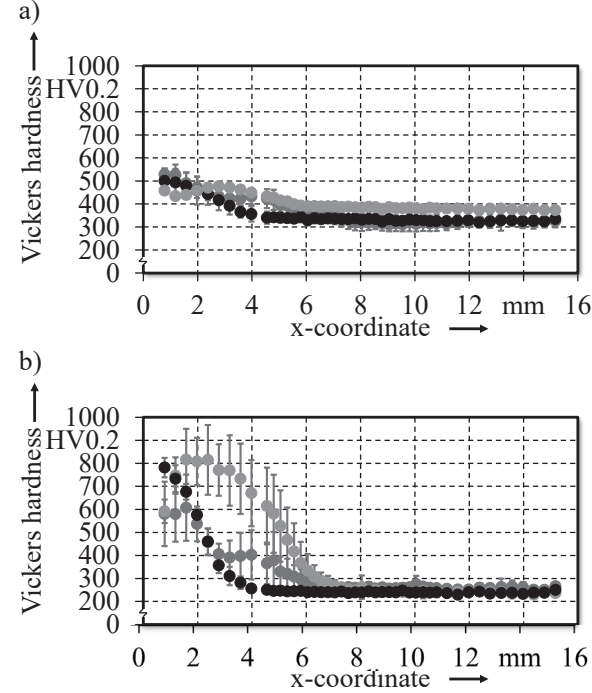


Fig. 5. Hardness profile of single samples extracted from hot stamped cruciform cups where the tool is closed at a blank temperature of a) 800 °C and b) 600 °C.

The hardness mappings of two representative samples quenched and formed beginning at the two different temperatures are shown in Fig. 6. The non-carburized zones are homogeneous with a higher level at the 800 °C sample. In this specimen the transition zone has a similar appearance as the laboratory sample in terms of expansion and with a vertical conversion. At the same time the sample at 600 °C shows a more diagonally transition with higher hardness values. The hardness increases towards a point on the surface which results in a horizontal and vertical gradient. One possible explanation for this local maximum near the surface is a premature contact with the water-cooled tool at this spot. Normally the positioning on spring-mounted spacer pins should prevent such occurrences but due to the multistep heat

treatment the flatness of the blank cannot entirely be ensured.

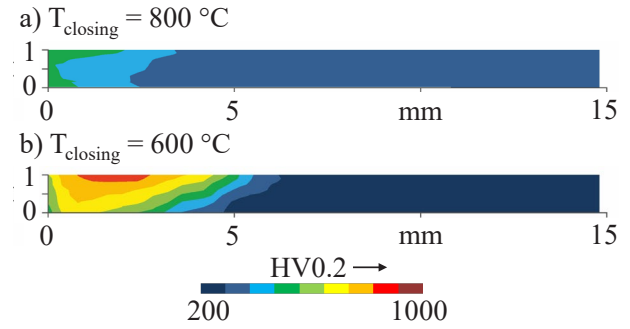


Fig. 6. Representative hardness mappings of samples extracted from cruciform cups at different tool closing temperatures.

Furthermore, the light microscopy images of the different zones in Fig. 7. confirm the hardness measurements. On the one hand, the quenching from a higher temperature in the non-carburized section results in mostly needle-like phases, so martensitic or bainitic structures, while those are sporadically embedded in a ferritic matrix at the lower temperature. On the other hand, the deferred cooling does not hinder the formation of martensite in the carburized zones resulting a similar appearance as in the water-cooled sample of the combination 1050_1h_1h. The grain structure at 800 °C is coarser and rather resembles with the transition zone of the laboratory sample which reinforce the displacement argument.

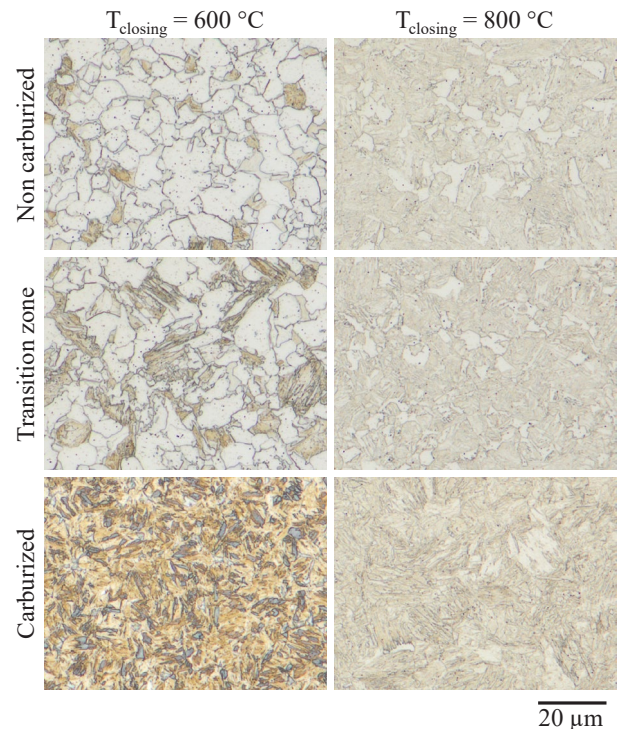


Fig. 7. Light microscopy images with a 500x magnification in the non-carburized, transition and carburized zones for the samples extracted from cruciform cups quenched and formed at 600 °C and 800 °C.

That means the transfer time or in this case the temperature of the blank at which the tool is closing is crucial to adjust the evolving phases and thus the properties. Thereby, the carburized zone transforms at 600 °C quenching temperature to martensite. In the

same case, the non-carburized zone is mainly ferritic with a decrease in hardness of about 100 HV0.2 compared to the material quenched at 800 °C. On the one hand, this shows that the extra incorporated carbon seems to generate a more insensitive material. On the other hand, this circumstance could be used to realise a higher grading by purposely lowering the forming temperature.

4 Conclusions

To sum up, the elevated carburization temperatures as well as the additional diffusion annealing process step do not lead to excessive growth of the transition zone. Hence, the high geometric freedom of the zone arrangement and size can still be utilised as an advantage of local carburising. The following further findings were obtained:

- Boron nitride as a protective layer is also at higher temperatures sufficient.
- The heat treatment parameters do influence the resulting mechanical properties.
- The results from laboratory samples were confirmed with the specimens extracted from hot stamped cruciform cups.
- The transfer time does influence the effective phase transformation especially in the non-carburized zone which could also be used for further grading.

In future works, the mechanical properties and the transformation behaviour of the cruciform cups should be investigated. Especially the properties at different part positions are of interest, namely the transition between flat bottom and flange, because of the different forming and cooling conditions. Here, the opportunity regarding the adapted transfer time respectively forming temperature to achieve a higher grading should be further analysed.

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