Examination of controlled thermal radiation exchange for the production of tailored properties on press-hardened components

Alborz Reihani[1, a *], Sebastian Heibel[1,b] , Thomas Schweiker[1,c] and Marion Merklein[2,d]

[1] Mercedes-Benz AG, Bela-Baenyi Str., 71059 Sindelfingen, Germany

[2] Lehrstuhl für Fertigungstechnologie, Friedrich-Alexander Universität Erlangen-Nürnberg, Egerlandstr. 13, 91058 Erlangen, Germany

[a]alborz.reihani_masouleh@mercedes-benz.com, [b]sebastian.heibel@mercedes-benz.com, [c]thomas.schweiker@mercedes-benz.com, [d]marion.merklein@lft.uni-erlangen.de

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Abstract. Through the development of furnace technologies and tool concepts, partial press hardening has become an established process in the automotive industry for setting tailored properties on press-hardened components. Tailored properties on press-hardened components offer the potential to improve crash performance as well as to facilitate downstream joining processes and mechanical treatments. One approach to adjust these properties through local pre-cooling is based on a special oven chamber with an integrated masking technology, called TemperBox®. The integrated mask protects the blank locally from incident heat radiation and simultaneously absorbs the blank's own radiation. An important parameter during this process is the pre-cooling time in the TemperBox®. The pre-cooling time can influence the phase transformation and the component properties. Therefore, blanks made of the conventional press hardening steel 22MnB5 AS150 are partially precooled in the TemperBox® for different periods of time and the component properties are investigated on the basis of formed hat profiles. In addition, a simulation approach for calculating the heat radiation exchange with the finite element software LS-Dyna® is shown. Based on the simulative and experimental investigations, it is demonstrated that there is a dependency between pre-cooling time and the components properties.

Introduction

In modern automotive engineering, press-hardened steels are increasingly used in highly stressed structural components. Through a combination of forming in the austenitized state and rapid cooling, conventional press hardening steels such as 22MnB5 achieve tensile strengths up to 1600 MPa [1], which are used in all Mercedes-Benz models. In addition to the intention of achieving higher strengths and thus fully exploiting the potential for lightweight construction, the demand for steels with higher ductility is increasing. These enable targeted energy absorption as a result of plastic crash deformation. In particular, the connection areas of the B-pillar to the sill or to the roof frame as well as axially loaded side member structures have to be made more ductile. In order to integrate ductile areas on the press-hardened component, four different semi-finished product concepts and component concepts are available according to the current state of the art: Tailored welded blanks, tailored rolled blanks, patchwork blanks and tailored tempering parts [2]. For the production of tailored tempering parts, a variety of partial heat treatment processes can be distinguished due to technological developments in furnace and tooling technology. The three basic process routes in partial heat treatment are partial austenitization before forming, locally varying cooling during and after forming, and partial tempering after press hardening [2]. Through controlled heat treatment in the respective process routes, component areas with lower strength and simultaneously higher ductility can be produced. The high ductility on the component enables improved energy absorption and deformation capacity as a result of crash-like deformation and at the same time facilitates the downstream joining operations.

In this work, the influence of partial austenitization before the forming phase is investigated. A chamber furnace from AP&T AB is used for the experiments. This furnace has two chambers for heating and homogeneous austenitization of the blank and the TemperBox® for partial austenitization. The time- and temperature-dependent influence of thermal radiation plays a key role in achieving tailored properties on press-hardened components. In order to calculate this influence in advance, an approach for simulating the heat radiation exchange in LS-Dyna® is demonstrated and validated by experimental investigations.

Process for controlled phase transformation before hot stamping

In industry, controlling the temperature of semi-finished products during the heating phase is an established method for adjusting tailored properties [3]. The use of new furnace technologies enables a controlled phase transformation on the blank after the heating phase. A furnace technology for partial austenitization can be found in the TemperBox®, in which a cooled mask made of aluminium protects the blank from thermal radiation and at the same time absorbs the thermal energy of the blank. The process steps of partial press hardening with the TemperBox® are shown in Fig. 1a. First, the blank is trimmed and, depending on the blank geometry, material and sheet thickness, heated for several minutes and thus homogeneously austenitized. Afterwards, the austenitized blank is automatically positioned in the TemperBox® and partially cooled.

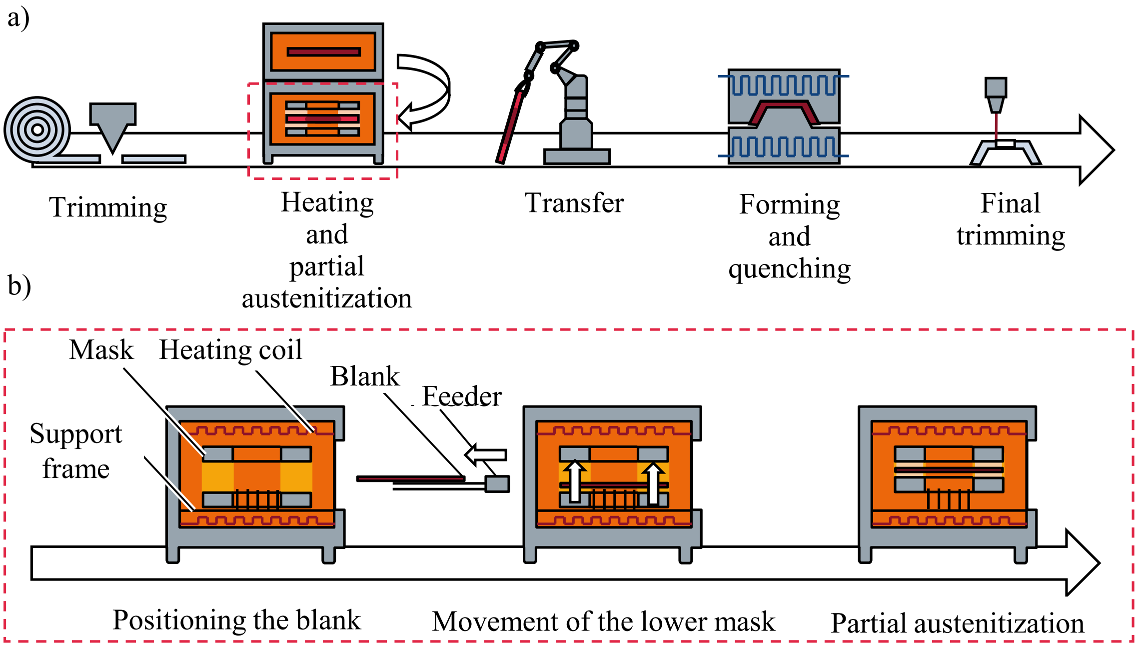

Fig. 1: Process steps in partial press hardening with TemperBox®

The process steps within the TemperBox® are shown in Fig. 1b. In the first step, the homogeneously austenitized blank is positioned on the support frame within about 4 to 6 seconds. Then the lower movable mask moves in the direction of the upper fixed mask and picks up the blank via centring cones. Depending on the geometry, material and sheet thickness, the blank is then partially precooled for about 45 to 140 s by the cooled aluminium mask. While the side of the mask facing the heating coils has a smooth surface to prevent the mask from heating up, the heat radiation is absorbed on the side of the mask facing the blank due to the higher roughness. After partial austenitization, the blank is positioned in the tool, for instance with a robot or a furnace feeder, and then formed and partially quenched. During the forming and quenching process, blank cooling begins as a result of thermal energy extraction due to tool contact. This thermal energy extraction or thermal conduction leads to the diffusionless transformation of the austenitized area of the blank into a martensitic microstructure. The effect of heat conductivity on the phase transformation of the blank depends on pre-cooling time and the phase transformation from austenite to ferrite, pearlite and bainite that has taken place beforehand. After the quenching process is completed, the components are cooled in air and trimmed to size. In the following, the basics of calculating the heat radiation exchange are described and application-related aspects of partial austenitization with the TemperBox® are presented.

Calculation of radiation exchange

In hot stamping, different heat transfer mechanisms occur depending on the process step. During the transfer phase, the semi-finished product temperature decreases due to heat radiation and convection with the environment, and in the forming and quenching phase, additional heat conduction occurs due to tool contact. Technological developments in plant and tooling technology extend the complexity of the thermal problem. For instance, in the TemperBox®, the exchange of heat radiation between surfaces in a closed space takes on a separate role. In comparison to the heat transfer mechanisms convection and heat conduction, in which the heat energy is transported from warm to cold areas, heat radiation also involves an exchange of heat energy from cold to warm areas [4]. This heat radiation exchange depends in particular on the orientation and position of the radiating surfaces, their temperatures and radiation properties [5]. A geometric quantity that is used to simplify the calculation of the heat radiation exchange is the view factor. The view factor describes the proportion of heat radiation that is transferred from one surface to another, depending on the position and orientation [4]. The starting point for the derivation of the view factor is the photometric fundamental law. For two surfaces in empty space shown in Fig. 2, the photometric fundamental law gives the radiant flow $d^2\varphi_{12}$ from the surface increment dA_1 to the surface increment dA_2 as a function of the intensity L_1, the distance S and the angles θ_1 and θ_2 [4]:

$$d^2\varphi_{12} = L_1 \frac{\cos\theta_1 \cos\theta_2}{S^2}\, dA_1 dA_2. \tag{1}$$

The integration of the photometric fundamental law (Eq. 1) over two finite surfaces and the assumption that the radiation intensity L_1 remains constant over the surface, the radiation flow can be described with the following equation:

$$\varphi_{12} = L_1 \int_{A_1} \int_{A_2} \frac{\cos\theta_1 \cos\theta_2}{S^2}\, dA_1 dA_2. \tag{2}$$

With the relation $\varphi_1 = \pi L_1 A_1$ as the radiant flux emitted from the surface A_1, the view factor is obtained as:

$$F_{12} := \frac{\varphi_{12}}{\varphi_1} = \frac{1}{A_1} \int_{A_1} \int_{A_2} \frac{\cos\theta_1 \cos\theta_2}{\pi S^2}\, dA_1 dA_2. \tag{3}$$

From the equation Eq. 3 it can be seen that the view factor is a geometric quantity that determines the proportion of radiation that is emitted from surface A_1 to surface A_2.

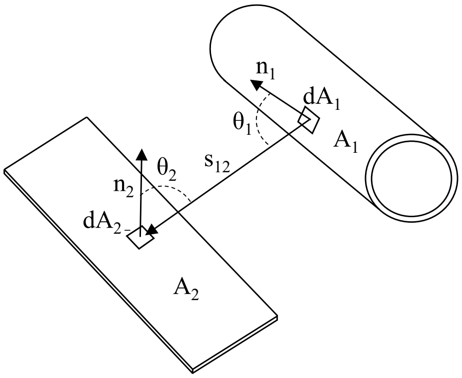

Fig. 2: Two finite-sized surfaces and their orientation and position in empty space [5]

Influence of the pre-cooling time in TemperBox®
Within the scope of this work, a test component in form of a hat profile is partially press-hardened at a trial facility of Mercedes-Benz AG and examined with regard to the semi-finished product temperature, hardness, tensile strength and elongation at break. For the investigations, the aluminised, cold-rolled and micro-alloyed 22MnB5 AS150 with a sheet thickness of $s_0 = 1.5$ mm is used. Table 1 summarises the chemical composition of 22MnB5 AS150.

Table 1: Chemical composition of 22MnB5 AS150

Alloying elements	C [%]	Mn [%]	B [%]	Cr [%]	Si [%]	Al [%]	Ti [%]	N [%]	Mo [%]
22MnB5/1,5 mm	0.23	1.18	0.003	0.18	0.25	0.04	0.04	0.004	0.004

The blanks are first heated in the chamber furnace with a furnace temperature of $T_O = 950$ °C and a furnace holding time of $t_O = 350$ s. Then the austenitized blanks are transported from the furnace chamber to the TemperBox® by a furnace feeder in 4.5 s and positioned there on the support frame between the masks. During the following partial cooling, the blank is distanced by pins intergated in the mask to ensure the distance of approx. 2 mm between the blank and the masks as well as to avoid direct contact between the masks and blank. For the parameter variation, the pre-cooling times 15 s, 30 s, 45 s, 60 s, 75 s and 90 s are chosen with regard to the direct influence on the phase transformation and cooling rate as well as due to the significance for the resulting component properties.

The partially austenitized blank is placed on the lower tool half after a transfer time of $t_T = 11$ s and is formed after 15 s by tool contact on both sides. In the hardening phase, the blank is partially quenched with a pressing force of $F_P = 1250$ kN and a hold time of $t_Z = 25$ s. The forming and hardening process is then repeated. The hydraulic press Imposite 2500 from Dieffenbacher GmbH is used for the forming and hardening process. The tools for the hat profile are made of tool steel 1.1730, which favours diffusionless phase transformation from austenite to martensite as a result of heat conduction effects due to its high thermal conductivity coefficient of $\lambda = 50$ W/(m·K).

The finite element software LS-Dyna® R12 is used to simulate the partial austenitization in the TemperBox® and the press hardening process. By calculating the view factors in LS-Dyna®, the heat radiation exchange between different surface segments can be mapped. Blankenhorn et al. [6] revised and used this calculation method to map the radiation exchange of a B-pillar segment in a paint curing oven. For the calculation of the thermal radiation exchange in the TemperBox® the keyword *BOUNDARY_RADIATION_ENCLOSURE is used. For this purpose, the TemperBox® is modelled as a closed furnace chamber consisting of housing, heating coils, masks and blank (Fig. 3).

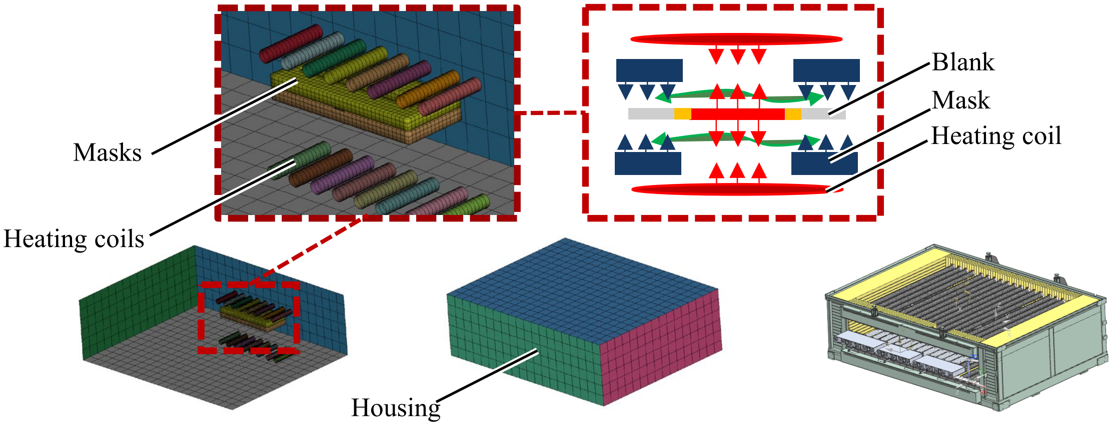

Fig. 3: Simulation model for the calculation of partial austenitization

The models for imaging the housing and the heating coils are constructed with shell elements whose unidirectional element normals point in the direction of the acting bodies. Since the heating coils affect the masks and the blank from below as well as from above, the blank and the masks are constructed with solid elements to avoid the restriction of the unidirectional radiation exchange. The thermal boundary conditions for the calculation of the radiation exchange are shown in Table 2. These were summarized from time-temperature measurements and literature values.

Table 2: Boundary conditions for the calculation of radiation exchange

Boundary conditions	Heating coil	Mask	Housing	Blank
Emission coefficient	-	0.2 [7]	-	0.75 [7]
Temperature	1633.15 K	Measurement of the time-temperature curve	323.15 K	Simulation

After the simulation of the partial austenitization, the history variables at the elements and the temperatures at the nodes of the blank are converted from volume elements to shell elements using the software Envyo®. This allows the forming and holding phases to be calculated more efficiently. In the forming and hardening phase, the process parameters such as hold time and pressing force are taken from the experimental investigations, whereby a constant Coulomb' friction coefficient of $\mu = 0.45$ is assumed. Another central aspect in the hardening phase is the heat transfer coefficient, which is integrated into the simulation as a function of the applied surface pressure based on the investigations by Svec [8]. The material model used for the 22MnB5 AS150 blank is *MAT_244, which calculates the phase transformation based on the work of Åkerström [9] and the Vickers hardness using the mathematical approach of Maynier [10].

To measure the temperature of the semi-finished product, type K thermocouples are welded on the surface of the blank in the heated and cooled area. From the measurement results shown in Fig. 4 it is evident that an increase in the pre-cooling time has an influence on the course of the semi-finished product temperature in the heated and in the cooled area. A comparison between the curves of the semi-finished product temperature at $t_C = 15$ s, $t_C = 30$ s and $t_C = 45$ s shows that the temperature in the heated and cooled area changes continuously. An increase in the pre-cooling time from 15 s to 45 s results in the semi-finished product temperature rising from 850 °C to 906 °C in the heated area after partial austenitization and decreasing from 742 °C to 633 °C in the cooled area.

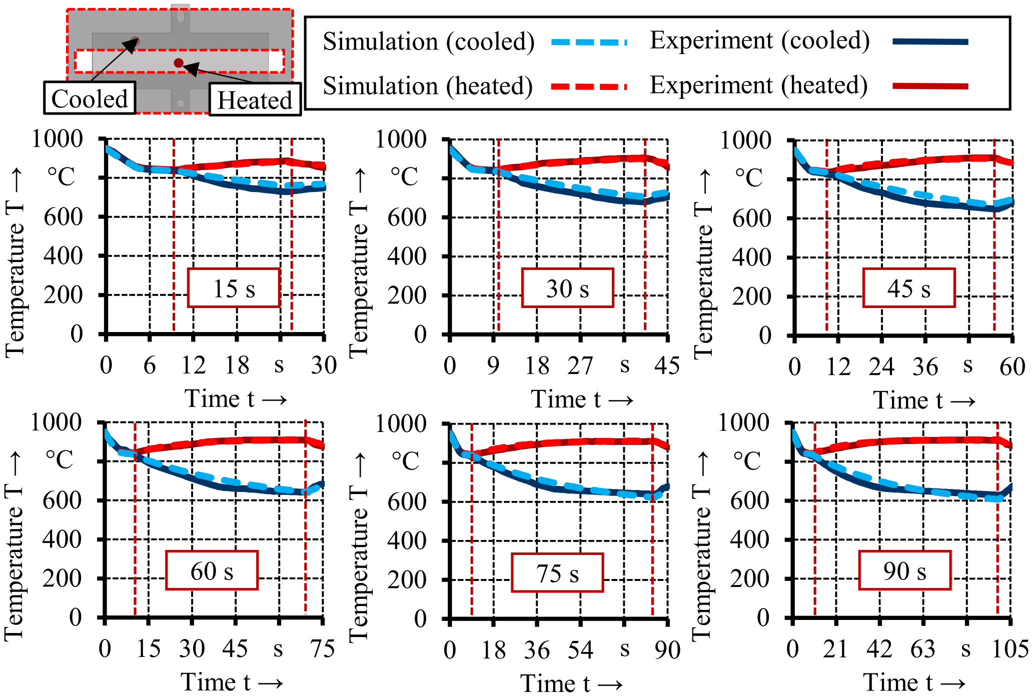

Fig. 4: Experimentally determined and simulatively calculated time-temperature curves at different pre-cooling times

Vickers hardness is an important mechanical parameter for the analysis of press-hardened components, that allows to evaluate the component properties of the semi-finished product and the resulting phase transformation. For this reason, hardness tests according to Vickers are carried out in cross-section with the semi-automatic hardness tester DuraScan 70 G5 from Struers GmbH. The results of the averaged hardness measurements for the different pre-cooling times are shown in Fig. 5. To determine the differences between experiment and simulation, the numerically calculated hardness curves and the experimentally determined hardness curves are compared. The diagrams show that the hardness curves can be calculated with good agreement. Analogous to the experimental results, no drop in hardness can be detected in the covered area from a pre-cooling time of $t_C = 45$ s onwards.

A significant characteristic of partially press-hardened components is the transition zone between hard and soft areas, which has an impact on their performance. The results of the hardness curves show that the pre-cooling time has an influence on the transition zone. With increasing pre-cooling time, homogeneous soft and hard areas are formed, which are characterised by narrower transition zones. Numerically, this effect can be determined by calculating the view factors and thermal interaction between the heating coils, the masks and the blank in a closed furnace chamber.

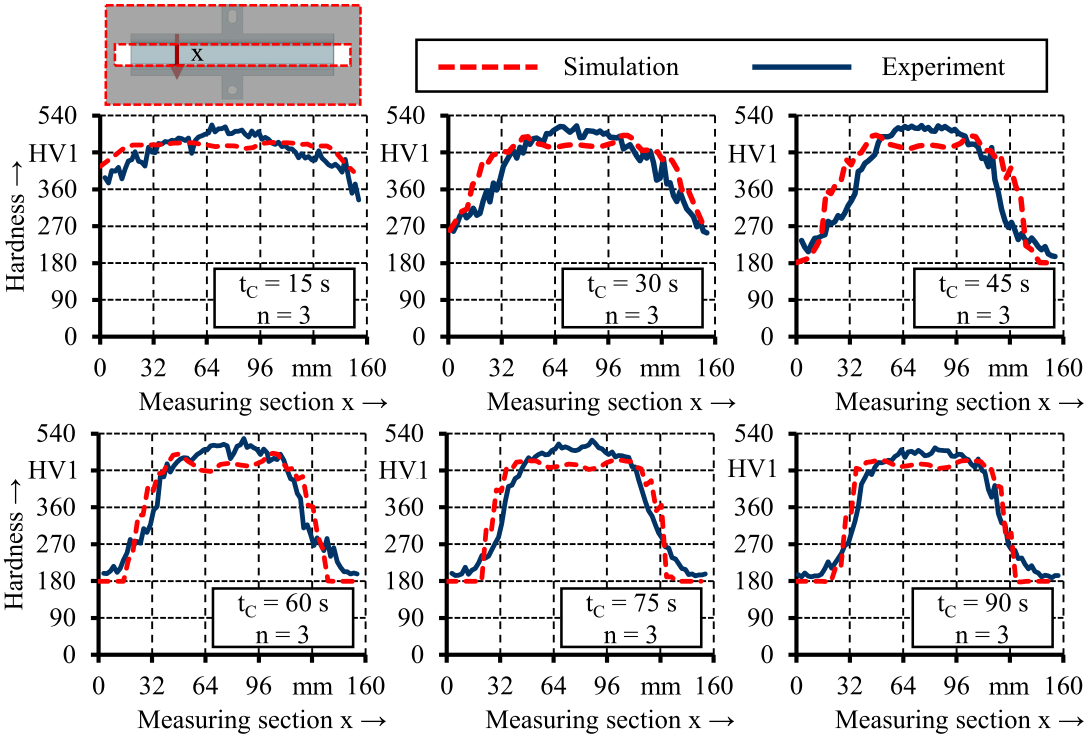

Fig. 5: Simulatively calculated and experimentally determined hardness curves

In addition to the hardness tests, tensile tests are carried out on a Z100 universal testing machine from Zwick Roll AG. The resulting mechanical properties of tensile strength and elongation at break are shown in the Fig. 6 for different pre-cooling times in the cooled and heated area.

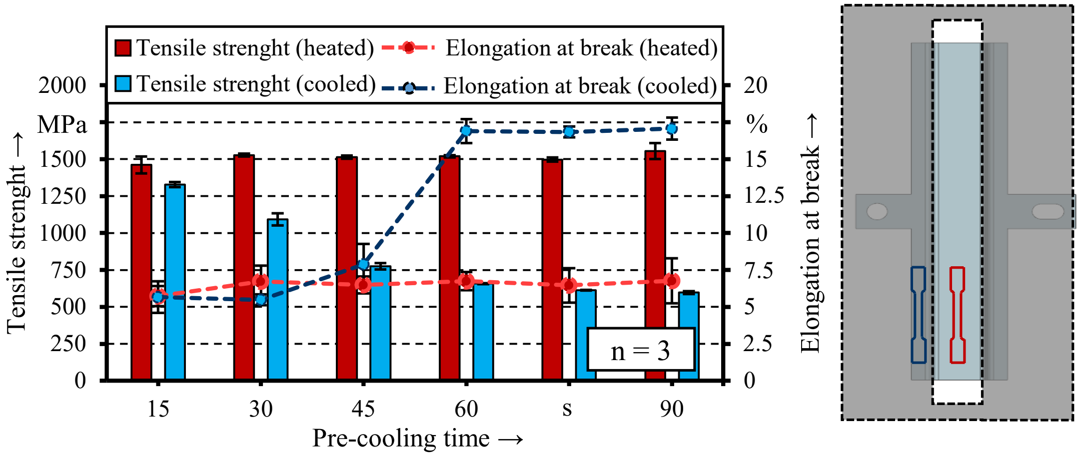

Fig. 6: Tensile strength and elongation at break in the cooled and heated area

Analysis of the diagram shows that the tensile strength in the cooled area decreases with increasing pre-cooling time up to 60 s. At the same time, the elongation at break increases significantly starting from the pre-cooling time of 60 s. The results with cooling times of 30 s and 45 s lead to a premature localisation of the strain due to the inhomogeneity of the strength. This effect is confirmed by the higher standard deviation in the respective mean tensile strengths and elongations at break. In the heated area, an effect of the pre-cooling time on the tensile strength and the elongation at break is not discernible.

Summary

In summary, the present work has shown that the partial pre-cooling time in the TemperBox® has an influence on the phase transformation and the resulting mechanical properties. Furthermore, an approach to simulate the partial austenitization with the TemperBox® was presented and validated. Overall, the combination of the view factor calculation and the use of the material model *MAT_244 is suitable for the prediction of the semi-finished product temperature and the Vickers hardness after press hardening with partial austenitization.

Future work will focus on extending the simulation model by measuring temperature-dependent emission coefficients at the blank surface and representing the temperature- and pressure-dependent tribological conditions between the forming tools and the heated blank. In addition, process-specific influencing variables such as the mask spacing, the recess geometry, the sheet thickness and the partial pre-cooling time are investigated both on semi-finished products with lower or higher strength classes and on new component concepts such as patchwork blanks.

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