Parameter study on press hardened components with tailored properties

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Abstract. In automotive industry, crash relevant parts are mainly manufactured by press hardening. An innovative process variant aims at producing components with tailored properties. For this purpose, the microstructural transformation is locally influenced to produce areas with lower strength. Hence, the forming tool is locally equipped with heating elements. Due to the non-uniform temperature distribution, the final part geometry results from a complex interaction of localized spring back, shrinkage and microstructure evolution. To achieve high geometric accuracy, a strong focus lies on the implementation of appropriate process parameters. A parameter study is performed in order to identify those process parameters, which mainly influence component distortion of a top hat profile. An automated test setup with a locally heated press hardening tool is used. As a result, the achieved hardness values and the geometric deviations are presented in dependence of the main influencing parameters.

1. Introduction
For the quality of press hardened parts, the mechanical parameters and the shape accuracy are of high importance. In particular, achieving the necessary dimensional accuracy by reducing the distortion is a major challenge [1, 2]. Distortion during press hardening is especially relevant for long components (e. g. B-pillars, roof frames) or open profiles and must be taken into consideration in various production areas (e. g. tool design, tryout, quality control). Typical solutions for compensating distortion in conventional deep drawing processes such as implementing constructive elements (e. g. clamping devices, tool slides) or subsequent production steps (e. g. straightening) are not applicable in press hardening due to the necessary temperature control in the tool and the ultra-high strength of the final components. Therefore, the concept of Distortion Engineering, which has been the preferred approach for several years [2], is used within this study. In this context, the component distortion is described as an overall system property and an improvement is aimed at by evaluating the origin of distortion and influencing it via the process parameters [2]. It is important to identify all interactions (previous and subsequent processes, material, distortion mechanisms, geometry etc.) and to understand their effects. Especially for thermomechanical forming processes such as press hardening and even more for tailored tempering, this interaction is extremely complex [3, 4, 5]. The combination of heated and cooled tool segments results in temperature differences of up to 300 °C occurring in a relatively small area of the press hardened part [6]. This leads to increased component distortion. According to automotive suppliers, the deviation between the nominal and actual geometry of a B-pillar, for example, can vary from -3.3 mm to +2.3 mm. Basically, four correlating aspects cause distortion. These are the temperature regime, the stress-strain behavior, the phase transformation and the microstructure composition [7, 8,
9], which are in turn influenced by the material, the geometry and the process parameters [7, 8, 10]. In [11], the dimensional accuracy of press hardened parts is examined experimentally and numerically as a function of different process chains (direct or indirect press hardening, hot forming and quenching with air or in water etc.) and process parameters (e.g. holding time). The result shows that in order to minimize distortion, the critical cooling rate for martensite formation in the closed tool must be ensured. Thus, some main keys for achieving minimum distortion are the temperatures of the heated blank and the tool. For tailored tempering, [12] attributes the distortion to the large temperature differences of up to 500 °C in the tool, the microstructural transformations and possible inhomogeneous temperature distributions (so-called hot spots). The influence of tool temperature and holding time on the resulting shape accuracy was determined experimentally. The results show that by increasing the holding time from 1 s to 35 s, for example, the maximum deviation can be reduced from 1.76 mm to 0.78 mm. The effects of process parameters like holding time or process temperature on component distortion during press hardening are quite evident. The resulting potential for improvement must be utilized by defining a process window optimized for distortion. In the following, this will be investigated for conventional press hardening steels as well as for crash-optimized press hardening materials.

2. Materials and Methods

2.1. Materials

Within this study, the common press hardening steel 22MnB5 (1.5528) is compared to a press hardening steel with higher ductility, which is designed to absorb more energy in case of crash. Both materials are coated with an AlSi layer. In the following, these steels are referred to as material A and material B. The chemical compositions differ and were analyzed with a spectrometer analysis. The results are shown in Table 1.

**Table 1. Chemical composition of material A and B (main differences).**

| Material (22MnB5) | C in % | Si in % | Mn in % | B in ppm | Cr in % |
|------------------|-------|--------|--------|---------|--------|
| A                 | 0.20  | 0.23   | 1.15   | 21      | 0.2    |
| B                 | 0.09  | 0.37   | 1.68   | 27.9    | 0.06   |

Material B has a lower content of C and Cr. In contrast, the contents of Si, Mn, Nb and B are higher in comparison to material A. The differences in the chemical composition lead to a higher tensile strength for material A and a higher elongation at break for material B. Furthermore, these differences influence the hardening behavior, thus necessitating to analyze the influence of the process parameters on the components' properties and to define a suitable process window for manufacturing high quality parts.

2.2. Experimental setup

Experimental tests are carried out with an automated test setup, which corresponds to the typical press hardening process chain and consists of 4 steps (S1 to S4):

- **(S1)** heating in chamber furnace,
- **(S2)** handling out of the furnace by a linear transfer,
- **(S3)** handling into the press with a robot and
- **(S4)** forming and heat treatment (tailored tempering).

For the heating process (S1) a chamber furnace with a maximum temperature of 1050 °C and a power of 60 kW is used. The handling into and out of the furnace (S2) is realized by a linear transfer system, which is pneumatically driven and enables the robot to grab the heated blank for the next handling step into the press (S3). In order to enable transferring cold and hot material, vacuum and clamping grippers are mounted. With the test setup, total handling times of 9.5 s have been achieved for steps (S2) and (S3). The actual press hardening process is done in step (S4), which combines the forming and heat
treatment operation. For this operation a hydraulic straight sided press with a maximum force of 2500 kN is used. Figure 1 depicts the test setup for automated press hardening.

![Test setup for automated press hardening](image)

**Figure 1.** Test setup for automated press hardening.

The tool has the geometry of a top hat profile and consists of an lower (Figure 2, left) and a upper tool half (Figure 2, middle). The left sides of the tool halves are water cooled, so that a temperature of about 20 °C is ensured. The right sides are heated with heating cartridges. A total of 17 cartridges, each with a power of 375 W, are installed enabling tool temperatures of up to 450 °C. The heated segments prevent a microstructure transformation from austenite to martensite, so that the resulting tensile strength and hardness in this section of the workpiece are significantly lower compared to the cooled area of the blank.

The sheet metals used for the tests have a length and width of 300 mm x 210 mm, respectively, and a sheet thickness of 1.5 mm. Figure 2 (right) shows a press hardened part with tailored properties. The cool side of the tool ensures a high strength and the heated zone a higher ductility. However, it is particularly this two-part tool design and the thermal transition areas in the component that lead to increased distortion.

![Cooling / Heating](image) ![Cooling / Heating](image) ![Hard / Soft](image)

**Figure 2.** Lower tool (left) and upper tool (middle) of the used top hat geometry; press hardened part with tailored properties (right).
2.3. Measuring equipment and parameters

The automated test setup is equipped with measuring systems monitoring the furnace, sheet and tool temperatures, the process times and relevant press parameters like force and path. Table 2 shows the observed parameters within the press hardening process. Two of the main influencing and controllable parameters are the furnace temperature $T_{\text{furnace}}$, which directly affects the sheet temperatures, and the holding time $t_{\text{hold}}$ in the closed tool. Both have a significant effect on the geometrical and mechanical component properties. Other influencing parameters like tool temperature, press force and path are not varied in this test setup. A central Programmable Logic Controller (PLC) connects furnace, hydraulic press, industrial robot and the measuring systems.

| Abbreviation | Monitored parameter | Measuring Equipment |
|--------------|---------------------|---------------------|
| $T_{\text{furnace}}$ | Furnace temperature (S1) | PLC |
| $t_{\text{furnace}}$ | Heating time (S1) | PLC |
| $t_{\text{transfer}}$ | Transfer time of heated sheet into the press (S2)+(S3) | PLC |
| $T_{\text{insert}}$ | Sheet temperature at insertion in the tool (S3) | Two pyrometers (heated/cooled side) |
| $T_{\text{start}}$ | Sheet temperature directly before the forming operation (S4 start) | Two pyrometers (heated/cooled side) |
| $T_{\text{end}}$ | Sheet temperature directly after forming (S4 end) | Thermal camera |
| $T_{\text{uptool}}$ | Upper tool temperature of heated part | Thermal elements |
| $T_{\text{lowtool}}$ | Lower tool temperature of heated part | Thermal elements |
| $F_{\text{press}}$ | Press force | PLC |
| $S_{\text{press}}$ | Press path | PLC |
| $t_{\text{hold}}$ | Holding time of closed tool (S4) | PLC |

During the heating process a sampling rate of 8 Hz is used. For the transfer of the heated blank to the press and the forming operation a higher sampling rate of 20 Hz is used, hence a detailed analysis of the fast cooling process is possible. Two pyrometers of the type Optris CT Laser 3M are applied for the measurement of the insertion temperature $T_{\text{insert}}$. Both tool temperatures $T_{\text{uptool}}$ and $T_{\text{lowtool}}$ are measured with integrated thermal elements. Furthermore, the force and the path of the press are measured by the press integrated monitoring system. Finally, the temperature distribution after forming is monitored with a thermal camera Infratec VarioCAM HD head 800. All parameters are recorded synchronously for all test parts and stored within a database in a structured manner, thus allowing a systematic data analysis.

2.4. Experimental plan

The experimental plan (Table 3) enables investigating the effects of the main influencing process parameters on the mechanical and geometrical properties of the formed parts. The forming start temperature $T_{\text{start}}$ and the cooling rate are the main influencing factors, regarding the structure transformation from austenite to martensite. $T_{\text{start}}$ depends on the furnace temperature $T_{\text{furnace}}$ (with sufficiently long heating time) and the transfer time $t_{\text{transfer}}$. The transfer time was set to the minimum possible value (9.5 s) for this test setup. Considering longer transfer times is not relevant, because industrial processes usually work with even shorter transfer times. In order to vary the starting temperature two different furnace temperatures are used. The tool temperatures are adjusted to 20 °C in the cooled segment and 400 °C in the heated segments. Preliminary studies have shown, that temperatures of 400 °C significantly reduce the transformation to martensite. Furthermore, the holding times $t_{\text{hold}}$ are varied. A holding time of 5 s is typically used in industrial applications. The increase of the holding time up to 20 s results in lower temperatures for the removal of the formed part. This may
have an influence on the geometric properties. As already mentioned in chapter 2.1, two materials are used. Material A is a common used press hardening steel and material B is a crash optimized steel grade.

**Table 3. Experimental plan for press hardening with tailored properties.**

| Parameter | Values                      |
|-----------|-----------------------------|
| Material  | A, B                        |
| \(T_{\text{furnace}}\) | 900 °C / 950 °C            |
| \(t_{\text{furnace}}\) | 300 s                      |
| \(t_{\text{transfer}}\) | 9.5 s                      |
| \(T_{\text{uptool}}\) | 400 °C (heated tool segment), 20 °C (cooled tool segment) |
| \(T_{\text{lowtool}}\) | 400 °C (heated tool segment), 20 °C (cooled tool segment) |
| \(F_{\text{press}}\) | 1200 kN                     |
| \(t_{\text{hold}}\) | 5 s / 20 s                  |

The specimens are designated according to the following scheme: material – \(T_{\text{furnace}}\) – \(t_{\text{hold}}\) (i.e. A-900-5 means: material A, temperature of furnace is 900 °C, holding time in closed tool is 5 s). For every parameter combination five repetitions were performed. A total of 40 parts was produced in this study applying different parameter sets.

3. Results

The experiments were carried out according to the experimental plan. For each part the process parameters were analyzed. Subsequently, the fabricated parts were characterized according to their mechanical and geometrical properties.

3.1. Analysis of temperature profiles

The quality properties of the press hardened parts strongly depend on the temperature profile of the blank during the complete process chain (S1- S4). As soon as the furnace is opened, the temperature of the heated blank begins to decrease with a low cooling rate. During the transfer to the tool the cooling rate increases and the blank temperature further declines. Finally the highest cooling rate is achieved in the cooled tool segment during the forming operation. The cooling rate in this process is higher than the critical cooling rate of 27 K/s and ensures a fully martensitic microstructure. Contrary, the formation of martensite is prevented by a cooling rate lower than the critical one in the heated tool segment.

Figure 3 exemplarily depicts the time-dependent temperature profile during the last seconds of handling (S3) and press hardening (S4) for the parameter set A-900-5.

The insertion temperature \(T_{\text{insert}}\) is measured with two pyrometers. One is focused on the cooled side, the other one on the heated side of the tool. At insertion, both pyrometers show almost the same blank temperatures. For the later evaluation of \(T_{\text{insert}}\), the mean value of both pyrometers was used. The temperature \(T_{\text{Start}}\) is the forming start temperature of the blank, which is relevant for the critical cooling rate and therefore the complete phase transformation. The temperature of the upper and lower heated tool, which is measured by thermal elements, is for all parameter sets about 400 °C in this step. The example (A-900-5) in Figure 3 shows a blank temperature \(T_{\text{insert}}\) of about 700 °C at 361 s and \(T_{\text{Start}}\) of about 680 °C at 364 s.

Then the press movement and the forming operation begins. During the forming a measurement of the sheet temperature is not possible, due to missing accessibility. Only the tool temperatures of both heated tool segments (upper and lower tool) are constantly measured and raise about 10 K during this step.

As soon as the tool is opened, the local temperature distribution in the entire blank is measured by a thermal camera. To prevent error resulting from unfavorable measuring angles, the temperature values are extracted from areas on the cold and the warm side of the frame of the part. The example in Figure 3 shows, that a holding time of 5 s leads to a sheet temperature \(T_{\text{end, warm}}\) above the initial tool temperature. On the cooled side the temperature of the blank \(T_{\text{end, cold}}\) is significantly lower than
martensite finish temperature. Finally the formed part is removed from the tool. The right side of Figure 3 illustrates the press force and the press path.

Figure 3. Temperature profile (left side) and press force and press path (right side) during the last seconds of handling (S3) and press hardening (S4) for the parameter set A-900-5.

The measured figures (Table 4) show that when the oven temperature is higher, the insertion temperature only rises to a significantly lesser extent (only about 50% of the increase of the oven temperature). Considering the holding time, an elongation to the extend regarded here, has only small effect on the end temperature of the workpiece in the area of the warm segment of the die and even lower influence in the area of the cooled die segment.

Table 4. Illustration of insertion temperature and the temperatures of the sheet metal after forming in the cold and the warm area of the tool.

| Specimens     | T\text{\scriptsize{insert}} in °C | T\text{\scriptsize{end, cold}} in °C | T\text{\scriptsize{end, warm}} in °C |
|---------------|-----------------------------------|--------------------------------------|-------------------------------------|
| A/B-900-5     | 700                               | 82                                   | 411                                 |
| A/B-900-20    |                                   | 61                                   | 382                                 |
| A/B-950-5     | 726                               | 83                                   | 440                                 |
| A/B-950-20    |                                   | 67                                   | 385                                 |

3.2. Characterization of the component properties

The components produced are characterized according their mechanical and geometrical properties in terms of hardness profile and distortion, respectively and the resulting properties are related to the corresponding process parameters (e.g. holding time, furnace temperature, material). Furthermore, suitable component characteristics are identified which offer high informative value and allow a reasonable comparison and evaluation, respectively of different components without having to consider the large total number of measured values.

3.2.1. Mechanical properties

An important evaluation criterion for tailored press hardened components is the hardness distribution in the part. Hence, four measurement planes were defined at characteristic positions, two in the cold and two in the warm area. On each of these four planes five points were defined at which the hardness was measured. Precisely, two points on the flange (right and left flange), two points on the frame (right and left frame) and one point on the head were selected as illustrated in Figure 4. In order to combine the measurement results into one single hardness values, which is characteristic for the plane under consideration, the average value of the five measurements was calculated. The comparative hardness values are therefore:
- P1, cold: mean value of five measurement points on plane 1
- P2, cold: mean value of five measurement points on plane 2
- P3, warm: mean value of five measurement points on plane 3
- P4, warm: mean value of five measurement points on plane 4

![Figure 4. Measurement concept for hardness characterization.](image)

A non-destructive test method allowing for a quick and reliable characterization of the hardness is based on the micromagnetic properties of the press hardened components. The 3MA system (micromagnetic multiparameter, microstructure and stress analysis) combines the inspection methods multi-frequency eddy current, analysis of the upper harmonics, incremental permeability and Barkhausen noise [12]. A previous calibration is required in order to interpret the signal of the 3MA system for the specific tested materials. Figure 5 shows the test results for material A using the 3MA system. The hardness values were averaged for every plane and over all repetitions of one parameter set. Comparing the hardness values of the work piece area formed with the cold tool segments (P1, P2) and those of the area formed with the heated tool segments (P3, P4), the significant hardness step from approx. 480 HV to 300 HV proves that tailored properties could be realized. The highest hardness is achieved in plane 1, whereas the lowest hardness is achieved in plane 4. The small variations of about 20 HV between plane 1 and plane 2 and between plane 3 and plane 4, respectively indicate, that plane 2 and plane 3 are influenced by the heat transfer between the cold and the warm side. Within a distance of 40 mm between plane 2 and plane 3 the hardness decreases about 150 HV. Furthermore, the comparison of the hardness values determined for the work pieces, which were press-hardened with different process parameters shows that neither an increase of furnace temperature from 900 °C to 950 °C nor an increase of holding time from 5 s to 20 s lead to a significant change of the mechanical work piece properties.
Figure 5. Mean values of hardness in plane 1 to 4 (material A, different parameter sets, 3MA system).

The hardness of material B was measured with a mechanical hardness measurement test, because within this study no calibration data for the 3MA system is available. Five repetitions were performed in the flange each on the warm and on the cold side. Figure 6 shows the hardness values for material B. As expected, it shows a lower hardness level. If a furnace temperature of 900 °C is applied the maximum hardness is about 270 HV in the work piece area press-hardened with the cooled sections of the tools, while in the work piece area press-hardened with the heated section of the tools a hardness value of about 240 HV was achieved. A variation of holding time has no significant influence on the hardness. If a furnace temperature of 950 °C is applied the hardness significantly increases to approximately 350 HV in the work piece area press-hardened with the cooled part of the tool and about 250 HV in the work piece area press-hardened with the heated part of the tool. The shorter holding time of 5 s results in slightly lower hardness values than 20 s holding time.

Figure 6. Mean values of component hardness referring to the work piece areas press-hardened with the cooled and heated tool segments (material B, different parameter sets, mechanical hardness measurement system).

3.2.2. Geometrical properties
The geometry of the formed parts is characterized with an optical 3D scanning system type GOM ATOS 5. The parts are placed on a rotary table enabling for the automated recording of six scans per part. A pre-alignment of the components on the rotary table is ensured with three stoppers made of aluminum and a flat foam rubber. Figure 7 shows the scanning system (left) and the rotary table with a press hardened component (middle, right).
Figure 7. 3D scanning system GOM ATOS 5 and scanned part on the rotary table.

With the 3D scanning system the geometry of each part is detected over the whole surface. The software GOM inspect suite 2020 is used to compare the measured data with the geometry of the CAD model, in order to determine any deviations. The head surface is used as the primary reference for 3D scan and CAD alignment. Figure 8 exemplarily shows the deviations of the 3D scan from the target geometry for one part of the parameter set A-900-5. For the comparison of CAD and 3D scan, surface vectors, starting from CAD model, are used.

Figure 8. Example for a resulting 3D scan of the top hat geometry (parameter set: A-900-5).

In this example (Figure 8), the maximum distortion of approx. +0.8mm occurs in the lower part of the frame and in the outer area of the flange. These deviations are directed outwards and upwards, respectively. For a comparison of all scanned parts the measured data of each part is reduced to 16 geometric measurement points on each side of the xz-plane, as shown in Figure 9 (yellow dots, symmetric on both sides of xz-plane). In areas of highest deviations two comparative geometric values on the cold side (L1, cold / L2, cold) and two in the warm side (L3, warm / L4, warm) are defined. These comparative values include the mean values of measuring points of both sides of the xz-plane.
The precise deviations at the measuring points are exported by software. Then the comparative geometric values L1 to L4 are calculated. The mean values are finally calculated for all parameter sets and plotted in Figure 10 for material A and Figure 11 for material B. Figure 10 provides the following observations. Temperature and holding time have an effect on the component distortions. Maximum deviations of up to 0.95 mm occur in the warm area of the flange. An increase of holding time leads to increased deviations in this area. In the cold area the deviations are lower with a maximum of 0.67 mm. An increase of holding time results in a reduction of distortion for the temperature of 900 °C, whereas the distortion increase in case of 950 °C. Regarding the frame area, the deviations in the cold area are higher than in the heated area. The higher furnace temperature results in smaller deviations in the frame area. The parameter set A-950-5 leads to the lowest distortions for material A.

![Figure 9](image-url)  
**Figure 9.** Measurement points and comparative values for geometrical properties.

![Figure 10](image-url)  
**Figure 10.** Averaged deviations between 3D scanning data and CAD model (material A, different parameter sets).

Figure 11 shows the results for material B. Equal to material A, highest distortions occur in the warm zone of the flange with a maximum of 1.1 mm. An increased holding time worsens the deviations in this area for a temperature of 900 °C, but reduces the deviations for a temperature of 950 °C. Looking at the
cold side of the flange an increase of holding time leads does not have a significant influence at 900 °C, whereas it reduced the deviations at 950 °C.

Regarding the frame area, the deviations in the cold area are higher than in the heated area, equal to material A. The higher holding time results in smaller deviations in the frame area. The parameter set B-950-20 leads to the lowest distortions for material B.

![Figure 11. Averaged deviations between 3D scanning data and CAD model (material B, different parameter sets).](image)

4. Discussion
A parameter study is performed in order to identify process parameters, which mainly influence the final hardness profile and the component distortion of a top hat profile. Thus, two different press hardening materials A and B are used. In order to determine the influence of different process parameters, the furnace temperature and the holding time in the tool are varied. As a result, material A delivers parts with tailored properties and a high hardness in the cooled area of the part. The parameter variation does not lead to a significant influence on hardness. In contrast to this, the hardness profile of material B in the cooled area is clearly influenced by the furnace temperature. Thereby, the higher furnace temperature causes a higher difference of the hardness values between cooled and heated area. The reason for this is the transformation from austenite to bainite instead of martensite for low cooling rates. Material B requires higher cooling rates for a complete transformation to martensite than achieved in the test setup. The geometric analysis shows the highest deviations in the flange of the heated area. A clear trend of how the furnace temperature and the holding time affect the geometric deviations is not discernable. Hence, it cannot be ruled out that other parameters influence the deviation. One possible influence is the alignment of the tool parts to each other. Because upper and lower tool are not aligned by guiding elements, assembly and disassembly between the test series may have led to little deviations according to the alignment of upper and lower tool. In order to avoid this in future tests, one alignment has to be ensured throughout the whole experimental study. Furthermore, numerical investigations are planned in order to predict the mechanical properties dependent on different input parameters. Nevertheless, it has been shown that for both materials there are parameter combinations that lead to the desired tailored hardness properties and allow achieving high geometric accuracy.

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