Investigation of the impact of process parameters on the layer formation of AlSi coated boron-manganese steel

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Abstract. Hot stamping has established itself as a technology for manufacturing safety-relevant car body components. Its usage has found increased importance due to rising political and social pressure e.g. for improved fuel conservation. Due to reduced sheet thickness, hot stamping parts offer lightweight solutions while at the same time providing improved crash performance due to their high strength. Boron-manganese steel is commonly used in hot stamping processes. Due to hot scale formation during heat treatment and the subsequent forming process, additional coatings, typically AlSi-coatings, are applied. Since hot stamped parts are formed at temperatures of 600 °C to 800 °C no suitable lubricants have yet been found. This leads to increased friction and severe wear in the process, which negatively affect tool lifetime and overall part quality. Additionally, process temperatures influence the layer formation and surface roughness due to diffusion processes. A deeper process understanding is needed to acquire detailed knowledge of the resulting impact on tribological behavior. Within this study, the effect of coating thickness on the resulting layer is analyzed by comparing the resulting material composition and surface roughness. To this end, the layer formation and surface roughness are analyzed for two different layer thicknesses (AS150 and AS80) in relation to furnace temperature, holding time and heat up rate. Both are characterized by means of heating experiments conducted on an annealing furnace. The change in layer composition and surface roughness are determined via metallographic investigation and tactile measurement. The results of this study help to improve the process understanding of the tribological conditions within the hot stamping process and to develop future measures for reducing tool wear.

1. Introduction
Current developments in the automotive industry show the reduction of energy consumption as one of the most important challenges. At the same time the specifications for safety-relevant components are increasing which in turn leads to more necessary components and weight \cite{1}. These contrary requirements for modern components can be fulfilled with the usage of ultra-high strength steels like the boron manganese steel 22MnB5 \cite{2}. The hot stamping process combines forming at temperatures of 650 °C to 850 °C and quenching in one process step and is used for the production of high strength components made out of boron manganese steel \cite{3}. This allows for an improved formability alongside a reduction in necessary forming forces and springback behavior \cite{1}. Additionally, the quenching process allows for an improvement of the mechanical properties resulting from the martensitic transformation at cooling rates above 27 K/s \cite{4}. The tensile strength increases from around 500 - 700 MPa \cite{5} to approximately 1500 MPa \cite{4}. The improved mechanical properties of the material
allow for a reduction in sheet thickness [2]. Due to furnace temperatures of 900 °C to 950 °C and varying holding times dependent on sheet thickness, the workpiece material undergoes austenitization [6]. Because of the high process temperature, uncoated boron manganese steel will decarburize and experience scale formation on the surface [7]. The oxide layer leads to a reduction in heat transfer between contact partners and damages the tool surface due to hard particles [8]. To prevent this effect from occurring hot stamping parts are coated with aluminium-silicon (AlSi) based coatings [9]. Previous investigations by Sherepenko et al. [10] have found that heat treatment parameters like furnace temperature and holding time in the furnace to have a significant influence on the formation of the coating layer for AlSi-coated 22MnB5 steels. Previous studies came to the same conclusion for the aluminum-silicon based coating AS150 [11]. Due to high process temperatures above 800 °C hot stamping is considered a lubricant free process, which in turn lead to high friction and wear occurrences. While the layer coating formation has been investigated regarding weldability because of the coating layer [12], the impact on tribological properties due to layer coating and heat treatment have not yet been analyzed. Detailed knowledge between the cause and effect relation of material properties and the resulting tribological behavior is needed for the calculated design of properties of the final part. In addition to the heat treatment parameters, the thickness of the initial coating was shown to exhibit a significant influence on the layer formation during the austenitisation process [12]. The goal within the scope of this paper is to analyze the influence of heat treatment parameters on the coating layer formation for a reduced coating thickness with AS80 and compare the results to the previously investigated AS150 coating [11]. The study will further help create a baseline ongoing studies on the impact of heat treatment parameters on tribological mechanisms and wear in the industrial hot stamping process.

2. Methodology and experimental setup

2.1. Material and experimental setup

The workpiece material used in the study is the industrial standard boron manganese steel 22MnB5. While the previous investigation utilized an AS150 (150 g/m²) coating, the current experiments used a different coating strength with AS80 (80 g/m²). The sample size consisted of 50 mm x 70 mm. The aluminum-silicon based coating exhibits resistance to both corrosion and elevated temperature oxidation [12]. Due to its excellent properties under hot stamping conditions it has found use in sheet steels in automotive manufacturing and is regarded as the current industrial standard. The usage of the coating is limited to the hot stamping since it exhibits poor forming qualities at room temperature with the coating breaking and therefore losing its barrier effect [10]. The aluminum-silicon coating experiences continuous diffusion of iron particles from the base material during the heat treatment process, creating an AlSiFe layer with a higher melting point, which prevents the melting or evaporation of the AlSi coating [13]. The heat treatment experiments were conducted on an annealing and hardening furnace ME 87/13 by RHODE. The furnace can achieve temperatures of up to 1300 °C with KANTHAL heating elements mounted on support rods on three sides of the furnace walls, providing an even temperature distribution. Double layer insulation prevents heat escaping from the furnace surface while guaranteeing a homogenous furnace atmosphere for the heat treatment of the samples. The samples were not quenched after the heat treatment process and allowed to cool to room temperature. This was done to prevent further impact from the quenching step on the layer formation. Martensite transformation was therefore not achieved.

2.2. Parameters and methodology

For the heat treatment, parameters specific and relevant to the industrial hot stamping process were selected. The parameter levels are furthermore determined by the industrial process windows for the austenitization of the material and were also used in previous studies on the coating layer [11]. The parameters furnace temperature and holding time in the furnace had shown to exhibit a significant influence on the layer formation of AS150 coatings and were selected to be analyzed for the AS80 coating in this study. The parameter of heating rate was found to exhibit no significant influence on the
layer formation; therefore, it is excluded from further experiments. The order of experiments was randomized to assure the reproducibility of the findings. The parameter settings were furthermore varied at the same three industrial related level settings (low, mid, high) to ensure the comparability of the findings. The parameters and selected levels are listed below in Table 1.

Table 1. Parameters and level variations selected for heat treatment

| Parameter                        | Levels                  |
|----------------------------------|-------------------------|
| Furnace temperature in °C        | 880; 910; 930           |
| Furnace duration in s            | 60; 270; 600            |

Using tactile measurement, the roughness Rz of the samples was determined after heat treatment. The samples were subsequently cold mounted and polished to perform micrograph analysis under a Keyence VK-X200 microscope to identify the effects on layer formation resulting from the heat treatment. Additionally, the resulting micrograph images were separated into different phases according to phase color and the area of each phase given as a percentage in relation to the overall image size to compare the changes in phase area dependent on the heating parameters. The open source software ImageJ was used to apply the classification image sections into the different phases. A detailed explanation of the process can be found in [11].

3. Results and discussion

3.1. Furnace temperature and holding time

The samples were placed in the annealing furnace at 880, 910 and 930 °C to investigate the influence of the austenitisation temperature. Furthermore, the samples were held at different holding times of 60, 270 and 600 seconds after they had reached the desired temperature after approximately 180 seconds. Each parameter combination was repeated 3 times to ensure repeatability, while a quenching process was not performed on the samples after heat treatment. The roughness measurements of the AS80 samples, as displayed in Figure 1 in orange, were performed on a perthometer and show no significant change in surface roughness due to furnace temperature. The AS80 coating exhibits similar behavior compared to the AS150 coating at lower roughness values, shown in blue.

![Figure 1. Influence of heat treatment parameters heating duration and furnace temperature on surface roughness Rz for AS80 and AS150 coatings](image-url)
While the AS150 coating shows a significant non-linear effect of the heating duration with an increase from 910 to 930 °C, the AS80 coating shows no significant change at all parameter settings. The previous study [11] ascribed the jump in surface roughness dependent on the time in the furnace to ongoing diffusion processes in the layer which was ongoing at 60 and 270 seconds. This can be explained by the more active diffusion of iron elements to the coating from the basematerial due to the higher diffusion coefficient of iron into aluminum compared to aluminum into iron [14]. After the coating layer has reached a saturation point and completely transformed into intermetallic AlSiFe, aluminum and silicon elements continue diffusing into the basematerial [15]. Based on this, it can be concluded that the diffusion process on the surface near areas is finished for the thinner AS80 coating. The micrograph images show a porous surface for AS80 at all holding times similar to the surface AS150 exhibits at 600 s. Which supports the theory and also leads to the conclusion that the diffusion of AlSi particles into the base material draws from the surface near area of the coating. Due to the inhomogeneous appearance of the uppermost layer, no viable height measurements could be performed. The AS150 coating layer split into two different phases in previous investigation with two additional phases visible going into the basematerial. Using EDX measurements the same phases could be encountered for the AS80 coating. As seen in Figure 2, the coating again splits into four main phases. While the Phase 1 layer consisted of separate spots initially which gradually formed into a thin line for AS150, the fully formed line is already clearly visible at all parameter settings for AS80.

**Figure 2.** EDX measurement for AS150 (top) and AS80 (bottom)
The intermetallic Phase 1, consisting of AlSiFe, and Phase 2, consisting of AlFe and AlFe2, exhibit similar values for the content of all three elements Al, Si and Fe with no change in general composition visible with ongoing heat treatment. Deviations can be observed in the borderphase with an increase in aluminum, as well as the basematerial, which sees a rise in both aluminum and silicon values, suggesting that the diffusion of aluminum and silicon into the basematerial continues even after the diffusion of iron into the coating layer is finished for AS80. The analysis and comparison of the relative area for the phases in the micrograph images captured via Keyence measurements can be found in Figure 3. For AS150 a significant increase could be identified for Phase 1 with an increase in the holding time from 60 to 600 seconds. The furnace temperature exhibits no significant effect but an interdependency with the heating duration, with a diminishing effect on Phase 1 area at the highest parameter setting.

\[
\begin{align*}
\text{Phase 1 formation at 880 °C} & \quad 15 \quad \text{-} \quad \text{-} \\
\text{Phase 1 formation at 930 °C} & \quad 15 \quad \text{-} \quad \text{-}
\end{align*}
\]

**Figure 3.** Influence of the holding time on the relative area of Phase 1

Like AS150, the thinner coating layer AS80 sees a significant increase in size due to increasing holding times at a furnace temperature of 880 °C, although the relative area is smaller in size compared to AS150. A trend in increase due to the holding time can also be observed at a furnace temperature of 930 °C similar to AS150, along with a noticeable increase in the phase area compared to AS150. Unlike the AS150 coating, a rise in furnace temperature also exhibits a significant increasing effect for Phase 1. Phase 2 sees a decrease in the total area size with an increase in all parameter settings as seen in Figure 4.

\[
\begin{align*}
\text{Phase 2 formation at 880 °C} & \quad 15 \quad \text{-} \quad \text{-} \\
\text{Phase 2 formation at 930 °C} & \quad 15 \quad \text{-} \quad \text{-}
\end{align*}
\]

**Figure 4.** Influence of the holding time on the relative area of Phase 2
An interdependency between both heat treatment parameters can be observed for AS150, with the significant decrease in area size due to increased holding times at 880 °C diminished at 930 °C, correlating with the reduction in total layer height at higher holding times. While only a decreasing trend due to increasing holding times is visible at 880 °C, the decrease becomes significant at 930 °C. Furthermore, the size of the Phase 2 area is reduced compared to AS150. The analysis of the formation of both phases lead to the conclusion, that the diffusion process is influenced by both the austenitization time and the furnace temperature. This can be partially confirmed with the findings from the previous study [11]. The effects of the heating parameters on the layer formation of AS80 appears to be more pronounced, which is likely due to the reduced layer thickness. It can therefore be concluded that the thinner coating can reach a saturation point faster due to there being less aluminum and silicon elements available for diffusion reactions.

Further analysis and comparison of the micrograph images of samples held for 60 seconds, as seen in Figure 5, show a porous surface near area which partially explains reduction in Phase 2 in addition to ongoing diffusion processes from the coating to the Base material.

**Figure 5.** Micrograph images of samples held at 880 and 930 °C for 60 seconds

The micrograph images of samples held for 600 seconds, as seen in Figure 6, confirm the findings of the image analysis with a visible and significant increase of Phase 1 from 60 to 600 seconds. At the highest furnace temperature of 930 °C the relative area of Phase 1 grows further in size and at both 60 and 600 seconds holding time. The size of AS80 Phase 1 grows beyond that of the Phase 1 of AS150 as found in previous studies [12].

**Figure 6.** Micrograph images of samples held at 880 and 930 °C for 600 seconds
While the Phase 1 initially consists of single specks which form a discontinuous layer for the AS150 coating, the continuous layer is already formed for AS80. This along with the reduced coating strength and more pronounced porosity of Phase 2 lead to the conclusion that the surface near Phase 2 area is diminished due to diffusion of the elements into the basematerial as described in previous studies [11]. This confirms the theory that the thinner coating can reach a saturation point faster. The reduced coating thickness can negatively impact friction and wear behavior in the hot stamping process due to the increased possibility of the tool material breaking through the coating layer and disrupting the protective barrier effect which prevents decarburization and scale formation. Furthermore findings of Jüttner et al. [12] ascribe a negative impact from the increase of the Phase1 AlSiFe layer on further process steps like welding. It can also be concluded that the thinner AS80 coating is more susceptible to the in- and decreasing influence of heat treatment. It is likely that only lower parameter settings than the ones investigated in this study are needed to achieve similar desired results as with the AS150 coating. This in turn hints at a potential for reducing both the necessary process temperature and cycle time when using AS80 to reach the desired layer composition for hot stamping processes.

4. Summary and outlook
The formation of the layer coating of AlSi coated 22MnB5 steel under hot stamping conditions has been investigated in this study. The thinner AS80 coating has been compared to the previously investigated industrial standard AS150. Neither furnace temperatures nor holding times were found to exhibit a significant influence on the surface roughness Rz. Similar to the surface roughness both parameters were shown to have a significant influence on the phase formation, with the holding time being more significant. While the same phases formed for both AS150 and AS80 coatings, traces of coating elements can be found in the basematerial of AS80. This, along with the micrograph images, leads to the conclusion that although the AS80 coating exhibits a similar behavior compared to the AS150 coating, the influence of the heat treatment parameters is far more pronounced. This can be led back to the reduced layer thickness, which allows the coating to reach a saturation point for the diffusion of iron from the basematerial faster. This opens up the potential of reduced cycle times to reach desired coating properties for the hot stamping process. For further investigations intermediate settings between the investigated ones have to be analyzed, due to the shortened process window to reach the coating saturation. Additionally, future research has to focus on the effect of the AS80 coating on friction and wear in strip drawing test to investigate possible adverse effects due to the reduced coating thickness and interdependencies with other significant process parameters like contact pressure and workpiece temperature. The findings of this study lay the groundwork for further analysis on the impact of the layer formation and heat treatment parameters on friction and wear in hot stamping and will help deepen the understanding of cause and effect relations in the process.

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