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Occurrence of coating-related accumulations within the seam in laser beam deep penetration welding of aluminum-silicon coated press-hardened steels

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Abstract

In the laser beam deep penetration welding of press-hardened and Al-Si-coated Mn-B steels coated to protect the base metal from scaling during press hardening, a reduced joint strength is observed in relation to the base metal. One influencing factor is the insertion of coating constituents into the weld seam during the welding process. The objective of this study was to investigate the influence of partially decoated sheets on the amount of accumulation occurring in the seam of the overlap weld of two sheets. For this purpose, the samples were partially decoated in different ways before the joining process. The welds were analyzed using cross-sections. The results indicate that especially the coating on the contact surfaces of the sheets in the lap joint affects the visible accumulation of coating constituents. The partial decoating of one or both contact surfaces was able to significantly reduce the amount and size of the accumulations.

Keywords: welding; deep penetration laser welding; ultra-high-strength steel; 22MnB5

1. Introduction

It is well known that lightweight design is a significant factor in the automotive sector to reduce the consumption of resources and furthermore decrease CO_2 emissions. One of the most important methods here is the use of advanced high-strength steels (AHSS) and ultra-high-strength steels (UHSS), which offer weight reduction without negatively affecting the crash properties. Among these steels, press-hardened steels, such as the manganese-boron steel 22MnB5 (1.5528), have a very high tensile strength of above 1500 MPa after

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hot forming. According to Abdulhay et al. (2011), other advantages besides high tensile strength include excellent quenchability, high impact stability and, due to the high temperatures during processing, good formability and low springback. The material achieves these mechanical properties by direct press-hardening, a process in which the components are heated until the austenitizing temperature of about 900 °C to 950 °C and then simultaneously formed and quenched at the critical cooling rate of 27 K/s required for the transformation to a fully martensitic microstructure; see e. g. Geiger et al. (2005). According to Karbasian and Tekkaya (2010), the sheets are usually coated with an aluminum-silicon coating (Al-Si coating) prior to hot forming, which is favored on the market to prevent the decarburization and oxidation of the component surface during press-hardening. The Al-Si coating is applied by hot-dip refining, whereby an intermetallic diffusion layer is formed between the substrate and the overlay even before press-hardening; see e. g. Kim et al. (2011). According to Wang and Chen (2006) the coating continues to alloy during press-hardening with the substrate due to diffusion processes during austenitization and partially oxidizes, resulting in a multilayer coating system consisting of layers with different element compositions.

Lap joints are generally used for welding press-hardened components due to the springback that can occur during press hardening, as they can compensate for dimensional deviations and joint gaps; see e. g. Radonjic and Liewald (2016). In terms of welding processing, according to Gu et al. (2012), arc, resistance spot and laser beam welding hardly differ in terms of the resulting material hardness. However, in arc and resistance spot welding, the energy input is increased significantly compared to laser beam welding, resulting in a comparatively larger heat-affected zone and thus a large locally softened area.

According to the investigations of Kügler et al. (2016), residues of the coating are carried into the weld pool, especially during the laser beam welding of lap joints, where they partially agglomerate as phase at the fusion line, preferably at the transition between the top and bottom sheet. In tensile tests, the coating-related accumulations can have a crack-initiating effect and lead to fractures at the fusion line; see e. g. Saha et al. (2016a). The occurrence of these coating-related accumulations is, therefore, still a major barrier to the industrial implementation of the laser welding of press-hardened steels. Further investigations regarding the effect of the Al-Si coating on the formation of coating-related accumulations by Kim et al. (2011) showed that a major part of the coating dissolves in the melt zone, while only a small share precipitates as an intermetallic phase due to insufficient melt flow in the weld structure. Saha et al. (2016b) analyzed the phases in the weld microstructure of laser beam welded press-hardened steels using transmission electron microscopy (TEM) and nanoindentation. They found that the weld microstructure is dominated by soft delta-ferrite and hard martensite, with the delta-ferrite phase resulting from the dissolution of the Al-Si coating.

Regarding strategies to avoid the formation of coating-related accumulations, Sun et al. (2019) showed that the use of a dual-beam module is a suitable approach in laser welding press-hardened steel. The reduction of the formation of these coating-related accumulations at the fusion line of the welded seam is attributed to an improved melt flow and an enlarged weld zone, resulting in a more homogenous weld structure.

2. Aim and Scope

The formation of coating-related accumulations can occur in welding Al-Si coated, press-hardened steels, with negative effects on the mechanical properties of the welded seams. However, it is not yet known which of the four different coating layers in the case of the commonly welded lap joint is/are significantly responsible for the accumulation formation and what options are available to avoid them. The aim of the study is, therefore, to separately analyze the influence of the individual coating layers with regard to the formation of coating-related accumulations. As mentioned above, the coating-related accumulations occur primarily in the area of the contact surfaces of the metal sheets and are often in contact with the middle coating layers. This leads to the hypothesis that a partial decoating of the sheets at the contact surfaces is sufficient to prevent the formation of coating-related accumulations in the welding seam. Based on this, methods can be derived to effectively prevent coating-related accumulations and thus enable the more economical production of homogeneous welds with increased joint strength.

3. Experimental

3.1. Materials

The base material for the welding experiments, whose composition is shown in Table 1, was the Al-Si coated press-hardened Mn-B steel 22MnB5 (1.5528). The coating amount was 80 g/m^2, corresponding to approximately 50 µm of coating thickness. The dimensions of the sheets were 190 mm in length, 50 mm in width and 1.5 mm in thickness. The materials used are common in industrial applications, especially in safety-relevant components in the automotive sector.

Table 1. Chemical composition of 22MnB5

	C	Si	Mn	P	S	Al	N	Cr	Ti	B
min. in wt.-%	0.21	0.15	1.10					0.10	0.015	0.0015
max. in wt.-%	0.25	0.40	1.35	0.023	0.010	0.080	0.010	0.25	0.045	0.0040

3.2. Welding setup

A TRUMPF TruDisk 12002 multi-mode disk laser with a wavelength of 1030 nm was used as the laser beam source. The beam was transferred via an optical fiber with a core diameter of 0.2 mm to a HIGHYAG RLSK laser processing head, which is typically used for welding in automotive production. In the welding optic, an imaging ratio of 3:1 was used, resulting in a focus diameter of 0.6 mm. During this study, the focal plane of the laser beam was set onto the workpiece surface and the process movement was achieved by scanning the laser beam. Using this experimental setup, which is illustrated in Fig. 1, lap joints with seam lengths of 180 mm were produced. To reduce the metallographic workload and the amount of test material used, three adjacent welds were performed per weld sample. To prevent any heat accumulation caused by welding multiple seams per sample, the specimens were allowed to cool down to room temperature (max. 23 °C, measured using Testo 925 temperature measuring instrument and an associated surface sensor) before the next welding process was performed. The laser power was configured to 2.5 kW and the welding speed was determined to be the maximum velocity in which the sheets were fully welded through, in this case, 2 m/min.

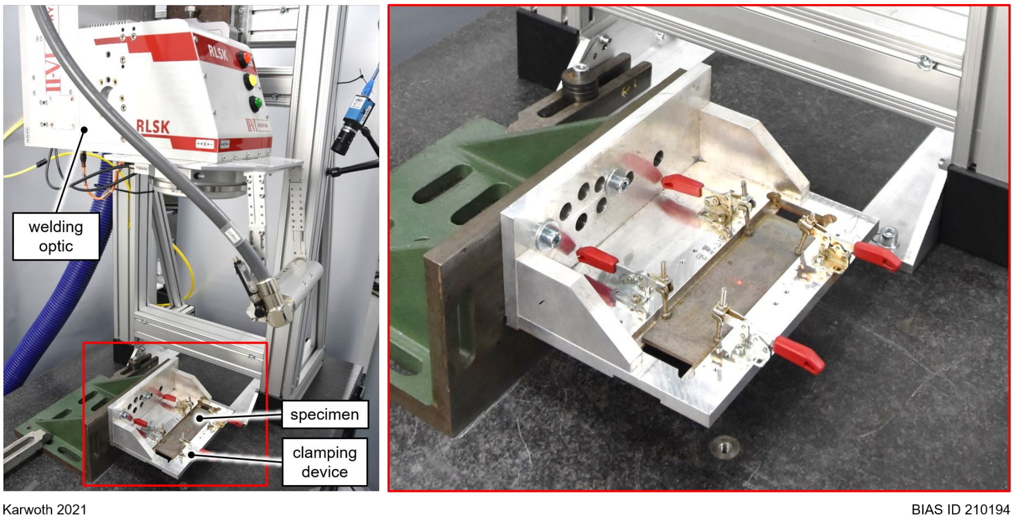


Fig. 1. Experimental setup for the welding experiments

3.3. Welding with partially decoated samples

To separately investigate the influence of the individual coating layers on the formation of coating-related accumulations, welding tests were carried out on different decoating combinations; these are shown in Table 2. The decoating of the respective surface was carried out using a TRUMPF TruMicro 5050 Picosecond-Laser (ps-Laser). In addition to the porous top layer consisting of intermetallic phases, the diffusion layer extending to the base material was also removed by setting the removed material thickness to 50 µm. Three areas were decoated for every sheet, distributed evenly over the length of the sheet and each with a length of 15 mm and a width of 40 mm (cf. Fig. 2). It should be noted that for the decoating combinations in which one or both layers of the joint interface faces were partially removed, a gap resulted (illustrated exemplary in Fig. 2 for combination no. 8). To consider the possible effects of this welding gap, the decoating combination no. 8 was repeated using completely decoated sheet faces, resulting in a technical zero gap. Each decoating combination was welded three times.

Decoating combination no. 0, in which no decoating was carried out, served as a reference for the quantitative evaluation. Using the decoating combinations nos. 2 to 7, the influences of the upper and lower as well as both middle coating layers could be investigated separately from each other. Decoating combination no. 8 was used to analyze the effects of a reduced material amount in the interface zone.

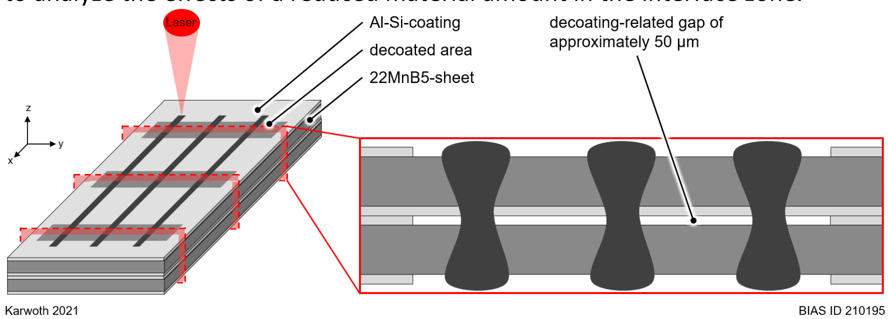
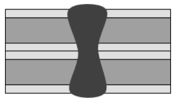
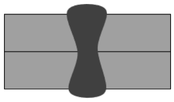
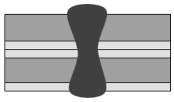
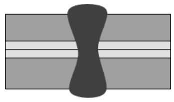
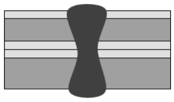
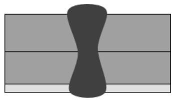
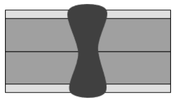
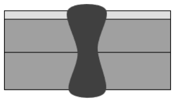
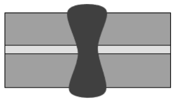


Fig. 2. Schematic illustration of decoating combination no. 8 and the resulting joint gap

Table 2. Decoating combinations

	0	1	2
			
	3	4	5
Decoating combinations			
	6	7	8
			

3.4. Qualitative evaluation of the cross-sections

To analyze the position and shape of the coating-related accumulations inside the weld, six metallographic cross-sections were generated per decoating combination and then subjected to visual analysis. The respective cross-sections were examined based on a table according to nine different evaluation criteria, as illustrated in Fig. 3. The tabular data collected from the cross-sections thus served as a basis for the qualitative evaluation and allowed statements to be made about the deposition characteristics of the coating-related accumulations. Furthermore, conclusions could be drawn regarding the influence of the different coating layers on the formation of the accumulations.

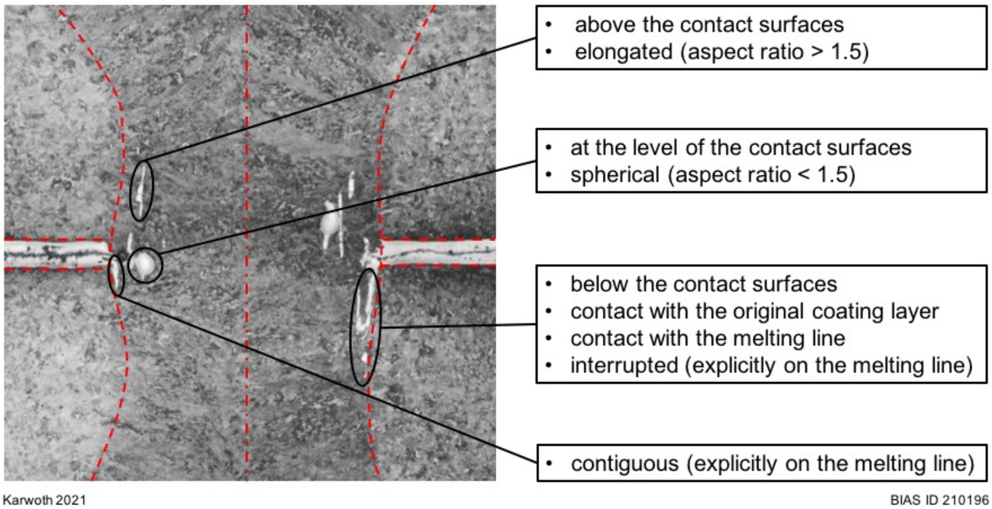


Fig. 3. Evaluation criteria for the qualitative analysis

3.5. Quantitative detection of coating-related accumulations

In addition to the qualitative metallographic analysis, the weld samples were also subject to a graphical examination for the quantitative detection of coating-related accumulations. For this purpose, the first step was to record the fusion line of the weld in the metallographic cross-sections to evaluate the weld structure separately from the rest of the sheet. Subsequently, the color curves of the cross-sections were adjusted to increase the contrast between the coating-related accumulations and the weld microstructure. The images were binarized for the automatic extraction of the coating-related accumulations. Afterwards, the amount of coating-related accumulations was determined as a percentage of area, relative to the area of the entire weld microstructure.

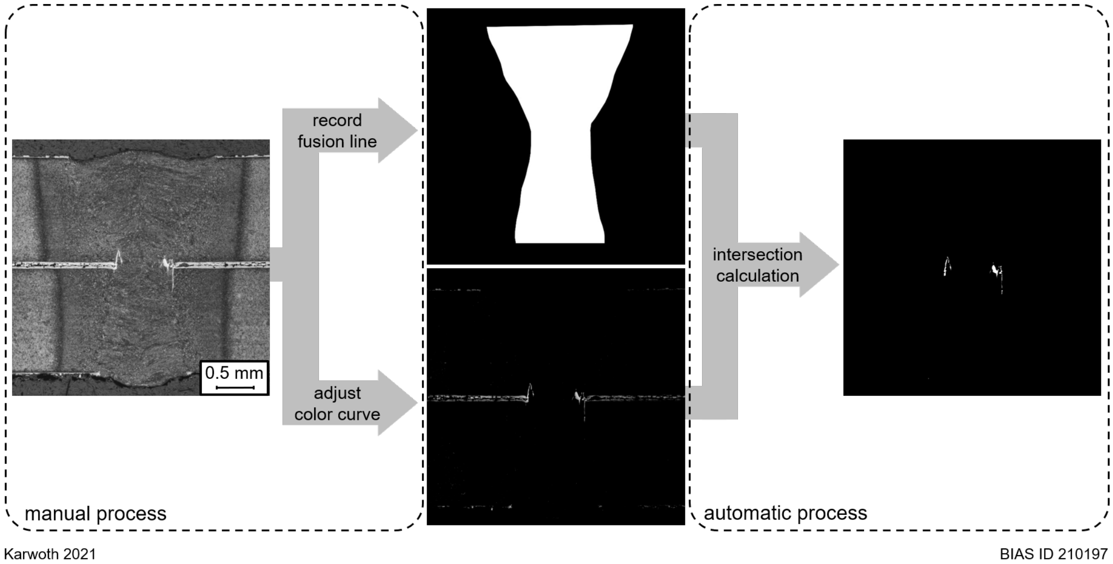


Fig. 4. Principle of the semi-automatic detection used to determine the intersection of weld microstructure and coating-related accumulations

4. Results

The cross-sections of the weld specimens that were partially decoated on the top face, on the bottom face, and on both these faces and the reference specimen are illustrated as an example in Fig. 5. Within these investigations, no influence of the outer coating layers on the formation of coating-related accumulations could be detected. The qualitative evaluation of these partially decoated weld specimens showed that, as with the reference specimens, primarily elongated accumulations form at the fusion line below the contact surfaces of the sheets. These coating-related accumulations are predominantly in contact with the original layer.

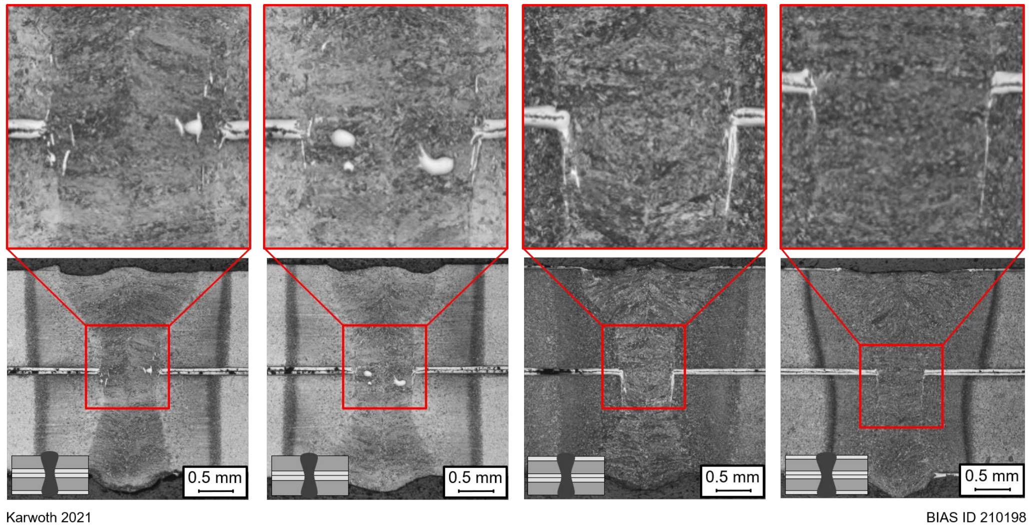


Fig. 5. Exemplary cross-sections of decoating combinations nos. 2,3,4 and 0

Fig. 6 shows example cross-sections of the decoating combinations in which the contact surfaces of the sheets were decoated. It can be seen that no coating-related accumulations form in any of the respective combinations. Compared to the completely decoated weld specimens, the weld microstructure does not show any differences with regard to the possible formation of accumulations.

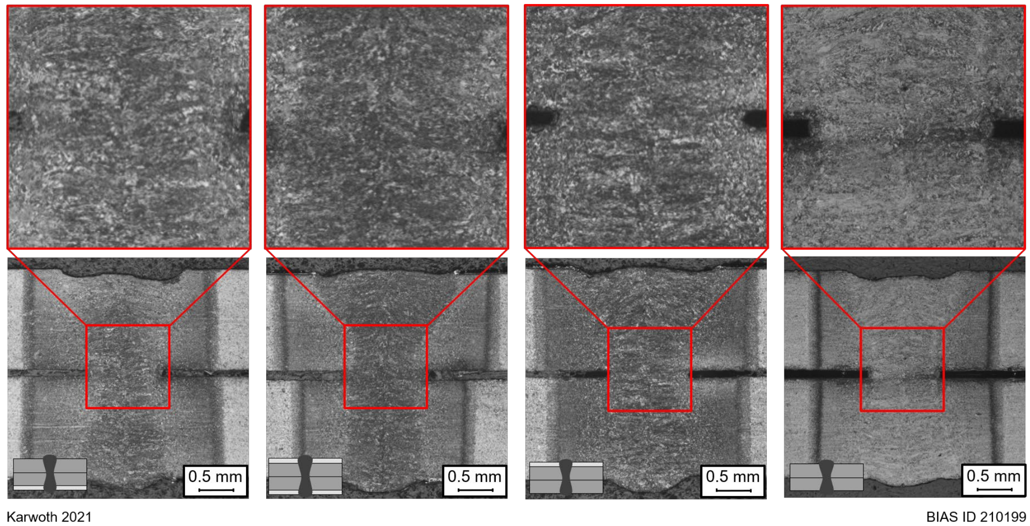


Fig. 6. Exemplary cross-sections of the decoating combinations no. 5,6,7 and 1

When comparing the weld specimens according to decoating combination no. 8 (cf. Fig. 7), it can be seen that the partial coating removal of a contact surface and the resulting joint gap of approx. 50 µm seems to completely prevent the formation of coating-related accumulations in the weld structure. Instead, coating-related accumulations occur in the joint gap with contact to the weld structure, although these do not extend into the structure.

Further investigations on weld specimens with the same decoating combination but without a joint gap, show that coating-related accumulations occur in the weld structure when no welding gap is present. These are primarily located below the contact surfaces at the fusion line. However, compared with the reference sample (decoating combination no. 0), in which neither of the two contact surfaces was decoated, the extent of coating-related accumulation was reduced from approximately 0.20 % to 0.12 %.

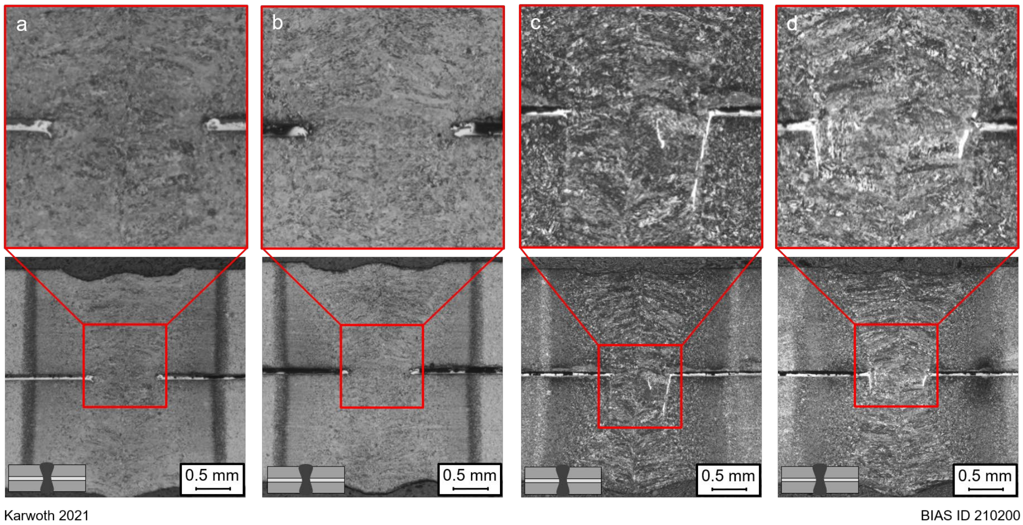


Fig. 7. Example cross-sections of decoating combination no. 8 with a joint gap of 50 µm (a, b) and without a gap (c, d)

5. Discussion

With regard to the working hypothesis, no influence of the outer coating layers could be observed in the conducted experiments. In contrast, the two coating layers on the contact surfaces of the sheets have a significant influence on the coating-related accumulation formation, meaning the formation of these can be completely prevented by decoating the contact surfaces of lap joints. Since the coating-related accumulations occur in particular at the fusion line below the contact surfaces, downward melt flow during welding could be an evident cause here. This is supported by the findings of Eriksson et al. (2011), who stated that laser keyhole welding is accompanied by a downward melt flow in the area of the keyhole front, whereby the direction is independent of the specific welding velocity and laser power. Such flow components could cause the introduction of coating components from the joint interface surface into the bottom sheet. Furthermore, this directed melt movement could partly prevent the dispersive and homogenous distribution of the coating constituents in the melt pool, which is, according to Kim et al. (2001), the origin of the formation of coating-related accumulations.

It was shown that the extent and size of the coating-related accumulations can be significantly reduced by partially decoating one of the interface layers if no welding gap is present. In addition, decoating one of the two contact surfaces seems to completely prevent the accumulation of coating residues in the weld structure if a joint gap is also present. This results in coating residues agglomerating in the joint gap and not being introduced into the weld structure. Based on this finding, an industry-relevant economic strategy for welding without the formation of coating-related accumulations can be derived: The preparation of the welded parts (in lap joints) can be extended by an additional decoating step. This decoating only needs to be done for one joining partner and only in the direct vicinity of the planned welding seam at the joint-interface side. After clamping, the components are separated by a defined welding gap (matching the decoating thickness), which prevents coating-related accumulations. This method would significantly reduce the time needed for decoating compared to a complete decoating of the sheets, and would thus represent an economically interesting method, also for application in series production.

6. Conclusions

The following conclusions can be drawn from the investigations:

- Welding of Al-Si coated, press-hardened steel in lap-joint configuration can result in coating-related accumulations within the seam stemming from the coating constituents of the two coating layers on the contact surfaces of the sheets after clamping.
- A feasible approach to preventing coating-related accumulations is to partially remove the coating from one contact surface of the lap joint, but only in the area of the welding seam. This results in a welding gap that has the same thickness as the removed layer, based on which no coating-related accumulations inside of the seam could be detected.

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