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Prevention of coating-induced agglomerations within the weld seam during laser beam deep penetration welding of aluminum-silicon coated press-hardened steel

Marcel Möbus[1], Peer Woizeschke[2], Thorsten Mattulat[1]

[1] BIAS - Bremer Institut für angewandte Strahltechnik GmbH, Klagenfurter Str. 5, 28359 Bremen, Germany
[2] TU Dortmund University, Department of Mechanical Engineering, Professorship LMP+ (affiliated with ISF), Baroper Straße 303, 44227 Dortmund, Germany

Abstract

Press-hardened steels like 22MnB5 (1.5528) have great potential in terms of their use in the field of lightweight construction. However, due to the aluminum-silicon coating, applied for press-hardening, strength-reducing agglomerations can occur within the seam after laser deep penetration welding of already hardened material. To investigate the hypothesis that the agglomeration formation can be reduced by beam modulation strategies, laser deep penetration welding experiments with changing beam modulation strategies such as "transversal", "circular" and "vertical eight" shaped patterns were carried out using constant welding speed and laser power. After comparing the resulting cross-sections to coated and decoated samples welded without beam modulation, the hypothesis was found to be true in case of all modulation strategies examined as no agglomerations could be detected within the samples. In addition, in case of the beam modulation strategies "circle" and "vertical eight", the fracture type could be changed from a separation fracture along the melting line to a shear fracture crosswise to the seam in sheet metal plane comparable to the decoated samples.

Keywords: Laser beam welding, beam modulation, agglomeration prevention, aluminum-silicon coating

1 Introduction

Steel-intensive lightweight construction makes it possible to reduce the weight of e.g. automobiles by using thin-walled steel components with maximum strength, including press-hardenable manganese boron steels. One of the most widely used manganese boron steel grades is 22MnB5 (1.5528), which has very good formability when untempered (ferritic) and an extremely high tensile strength of about 1650 MPa when tempered (martensitic) [1]. To prevent tinder formation during press hardening, MnB steels are coated [2]. The most widespread coating systems of press-hardening materials currently on the market are aluminum-silicon based (AS) coatings, which allow direct press hardening [1]. When welding coated and already hardened MnB steels, the coating primarily dissolves into weldments as solid solution with an aluminum content of about 2.6 atom-% and partially developes as an inter-metallic phase with Fe and an aluminum content of about 6.7 atom-% [3]. The resulting presence of intermetallic phases in the weld metal leads on the one hand to a reduction in joint strength [4], and on the other hand alloying leads to an increase in the critical cooling rate required for martensite formation. A considerable reduction of the achievable joint strength occurs especially in laser beam deep penetration welding, since the intermetallic brittle phases accumulate at the melting line as a result of the melt pool flow [3]. However, this also makes it possible to influence the melt pool flow and thus the agglomeration formation by means of suitable process manipulation like multiple remelting, as pursued in the case of multi-dimensional local beam oscillation or modulation strategies. In addition, spatial beam modulation can increase the seam or bond width. This is why beam modulation strategies have been investigated based on the hypothesis that temporal and/or spatial beam modulation strategies can prevent the formation of

*E-mail address of corresponding author: moebus@bias.de

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agglomerations and homogeneously distribute the intermetallic phases in the melt pool, increasing the overall joint strength.

2 Experimental

The experimental setup is shown in Fig. 1. A processing optic RLSK 2.1 by HIGHYAG Lasertechnologie (nowadays part of the II-VI Group). was used with a disk laser source TruDisk 12002 by TRUMPF. The spot diameter and the Rayleigh length were measured to 570 µm and 9.6 mm. "AS-150"-coated and partially de-coated (using a TruMicro 5050 ultrashort pulse laser by TRUMPF) 1.5 mm thick 22MnB5 (1.5528) sheets were clamped as displayed in Fig. 2 while laser deep penetration welding in lap joint configuration. In this study, three beam modulation strategies (Tab. 1) are compared with the laser deep penetration welding process without beam modulation with respect to the agglomeration formation and the lap shear strength. All experiments were carried out with the constant laser beam power of 2.5 kW and the welding speed of 0.96 m/min. The experiments with beam modulation were done with a focal position of 0 mm, an oscillation frequency of 60 Hz and an oscillation amplitude of 400 µm. The linear welded samples were welded with a focal position at -16 mm in order to reach a comparable seam width of 930 µm on the sample surface. One welded sample per parameter was cut into ten tensile test samples and 15 metallographic samples for cross-section analyses by using a wire-cut electrical discharge machine. The resulting lap shear tests were carried out using a materials testing machine of the type AllroundLine Z250 by ZwickRoell to determine the maximum endured tensile force and the fracture type (see Fig. 3). Metallographic cross-sections were etched and microscope images were taken to measure the seam width and analyze the agglomeration formation. Regardless of the type of fracture, the lap shear strength σ was calculated from the seam width at the sheet metal transition a, the test sample width l and the maximum tensile force F using the equation $\sigma = \frac{F}{a \cdot l}$.

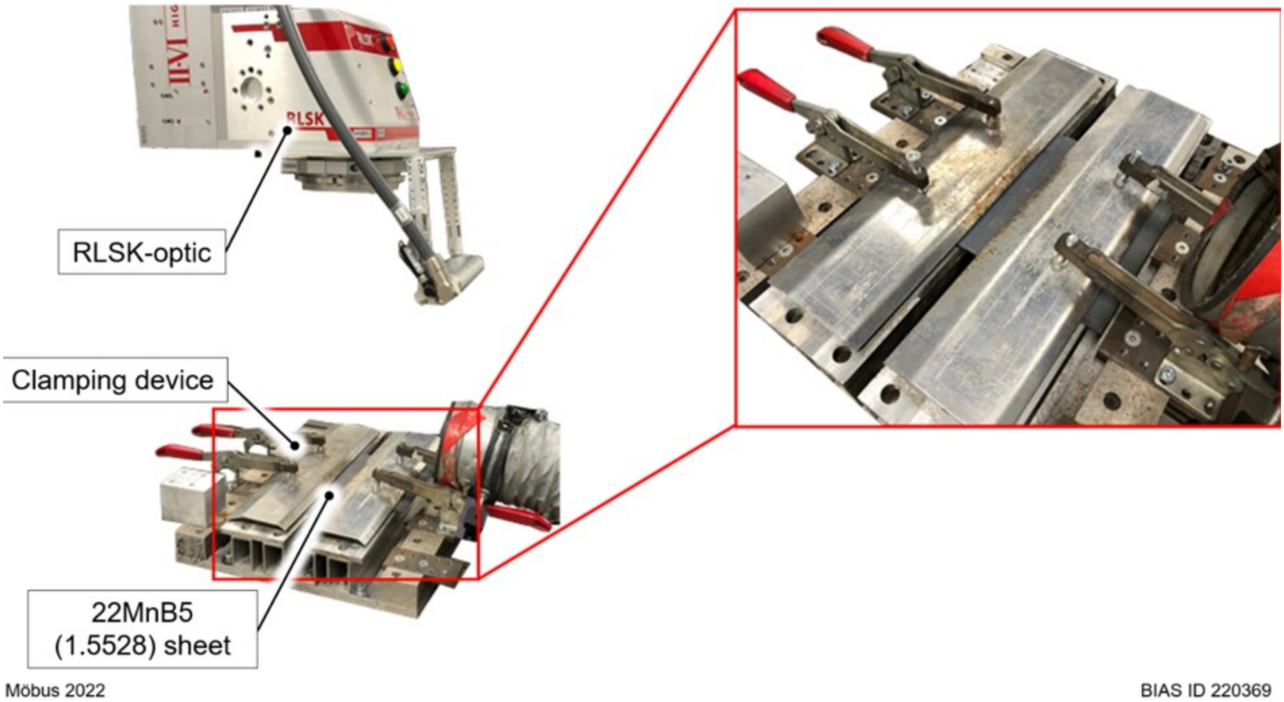


Fig. 1: Experimental setup

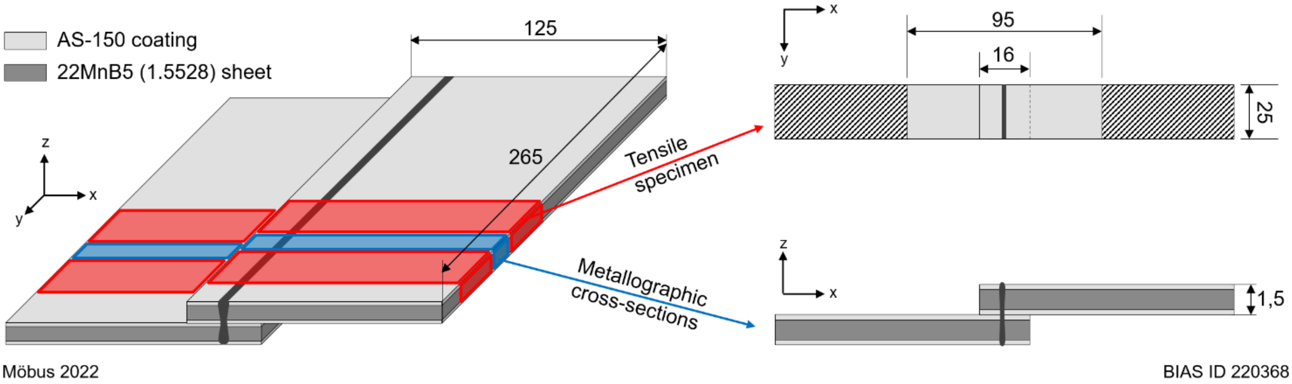
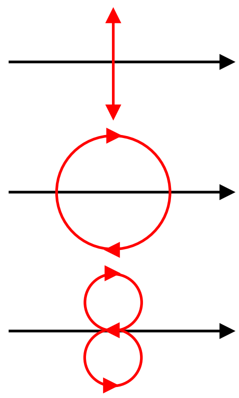


Fig. 2: Dimensions of the weld, lap shear test and analysis specimens

Tab. 1: Laser beam welding parameters and beam modulation strategies (global welding direction displayed in black, oscillation pattern displayed in red)

Laser beam welding parameters		**Beam modulation strategies**
Laser power	2.5 kW	without (linear)
Focal diameter	570 µm	transversal
Rayleigh length	9.6 mm	circular
Focal position linear weld	-16 mm	vertical eight
Focal position with oscillation	0 mm	
Welding speed	0.96 m/min	
Oscillation frequency	60 Hz	
Oscillation amplitude	400 µm	
Joint type	Lap joint	



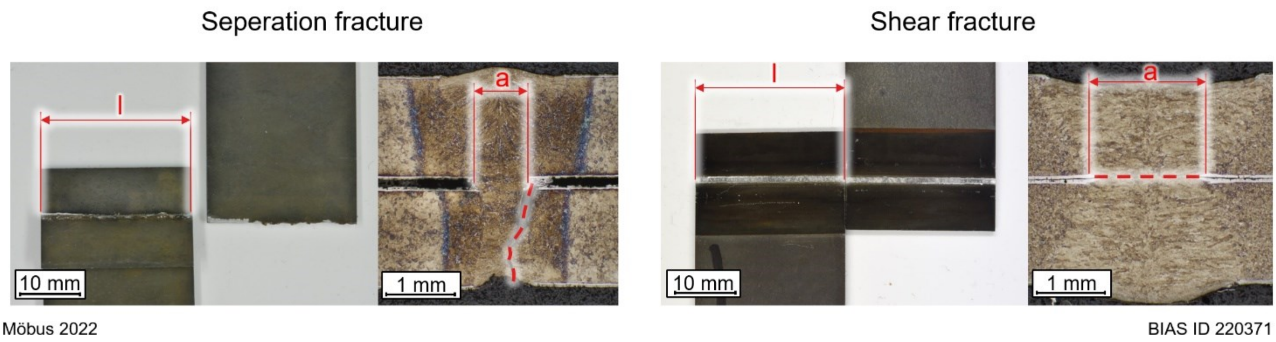


Fig. 3: Shear testing fracture types, sample width (*l*) and seam width at the sheet metal transition (*a*)

3 Results

The results of the analysis of the metallographic cross-sections are shown in Fig. 4. The welding without beam modulation resulted in the formation of agglomerations along the melting line, as it was also shown in [3]. In case of all beam modulation strategies, all 15 metallographic cross-sections per strategy are free of agglomerations bigger than 50 µm in diameter.

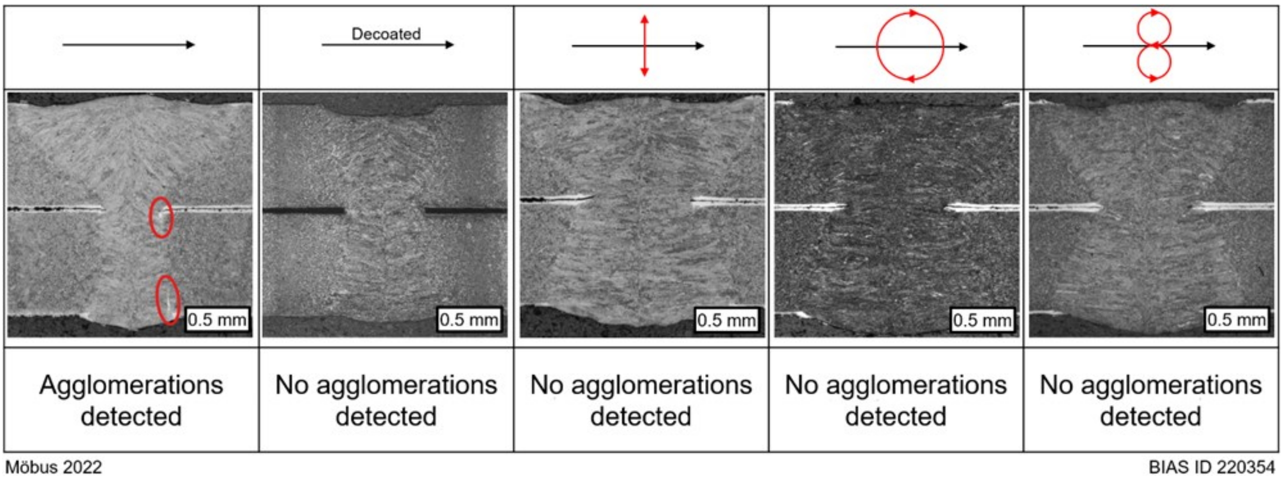
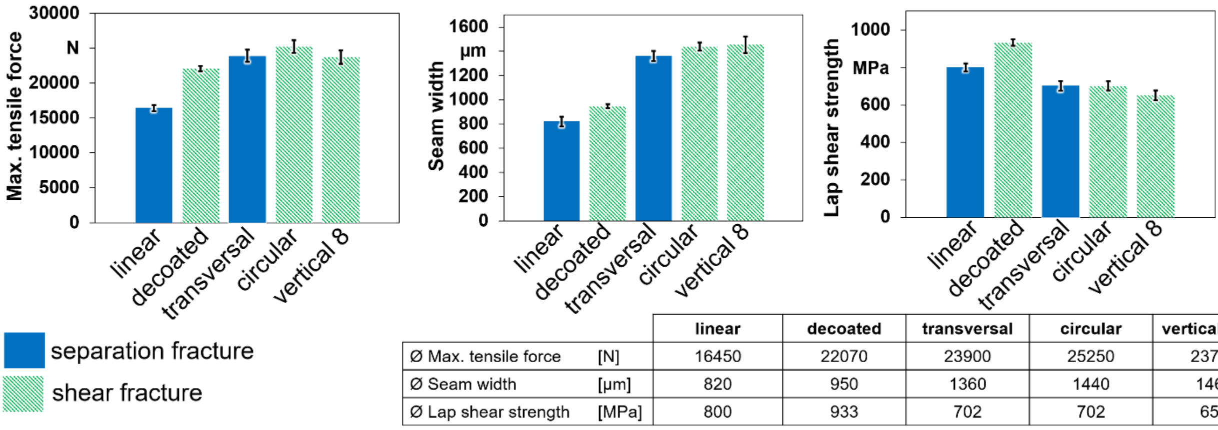


Fig. 4: Exemplary metallographic cross-sections

Fig. 5 shows the results of the tensile lap shear tests. The average maximum endured tensile force increases significantly for all modulation strategies and for decoated linear welded samples compared to the coated specimens welded linear without beam modulation. Furthermore, by applying the beam modulation strategies “circle” and “vertical eight”, the fracture type varied between the separation fracture along the melting line and the shear fracture crosswise to the seam in sheet metal plane, comparable to the decoated samples. The seam width also increases for all modulation strategies compared to the coated and decoated specimens welded linear without beam modulation, while the lap shear strength is significantly lower for the samples welded with beam modulation strategy.

The Energy-dispersive X-ray spectroscopy (also known as EDS, EDX, or EDXA) measurement in Fig. 6 shows that the aluminum content of the homogeneously distributed intermetallic phases (Test 6, 3.9 atom-% Al) is comparable to the content in the agglomerations along the melting line (Test 5, 4.1 atom-% Al) and that the entire structure of the weld seam generally has a high aluminum content (Test 2, 3.2 atom-% Al).



		linear	decoated	transversal	circular	vertical eight
Ø Max. tensile force	[N]	16450	22070	23900	25250	23700
Ø Seam width	[µm]	820	950	1360	1440	1460
Ø Lap shear strength	[MPa]	800	933	702	702	652

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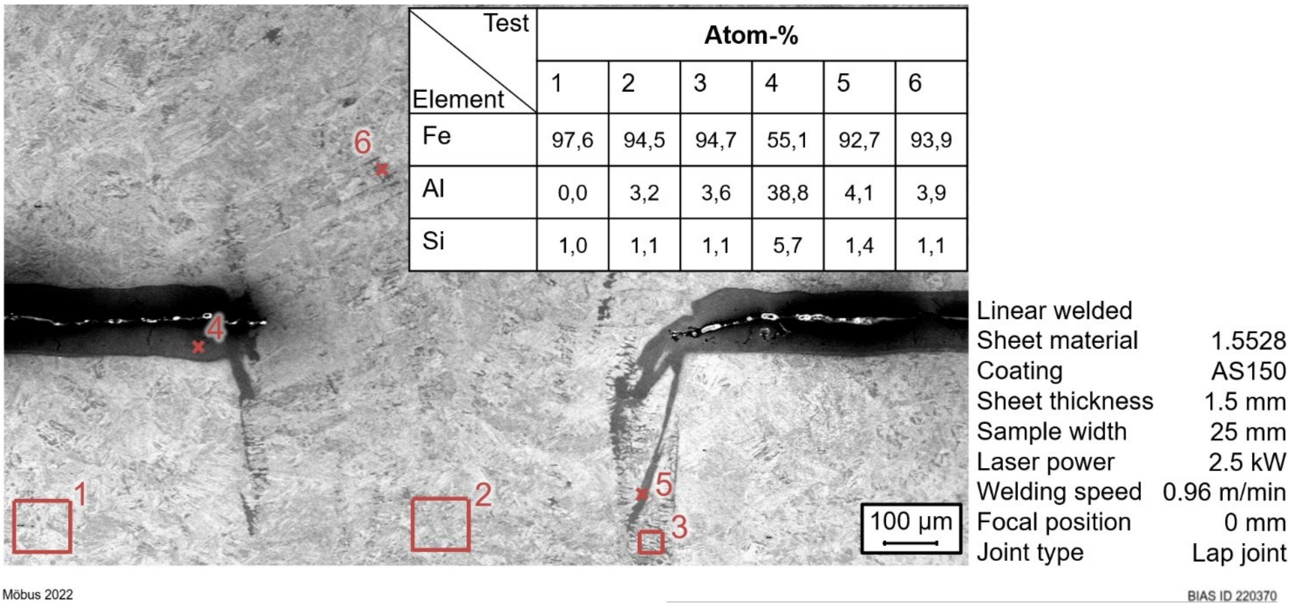
Fig. 5: Results of the lap shear tests



Element \ Test	Atom-% 1	2	3	4	5	6
Fe	97,6	94,5	94,7	55,1	92,7	93,9
Al	0,0	3,2	3,6	38,8	4,1	3,9
Si	1,0	1,1	1,1	5,7	1,4	1,1

Fig. 6: EDX- (Energy-dispersive X-ray spectroscopy) measurement results of the welded 22MnB5 sample with AS-150 coating and without beam modulation.

4 Discussion

Since no agglomerations are visible in the cross sections of all specimens welded with beam modulation, the hypothesis that beam modulation strategies can prevent their formation can be evaluated as true with high probability. However, in the case of beam modulation, the increase in maximum tensile force is not only due to the prevention of agglomeration formation, but primary to the increased seam widths. The results of the increased seam widths also explain the lower lap shear strength across all beam modulated specimens compared to the linear welded samples. The EDX-analysis showed with 3.2 atom-% (test 2) a higher content of aluminum within the weld than it was found in [4], where the aluminum content was measured to 2.55 atom-%. The strength of the samples welded with beam modulation is reduced compared to the decoated samples without beam modulation, which suggests that not only the agglomerations but also the homogeneously distributed aluminum phases and the structural transformation as a result of the welding process in general reduce the strength of the welded samples.

5 Conclusions

Based on the experiments of this study, it can be concluded that the investigated beam modulation strategies prevent the formation of the typical agglomerations along the melting line and can be used to increase the seam width and therefore also the maximum tensile force that can be applied. The application of the beam modulation strategies distributes the coating entry homogeneously in the weld seam and, thus, the fracture type changes partly from separation fracture to shear fracture. However, the uniform aluminum content due to the coating-based aluminum input within the entire seam in combination with an increase in seam width at the sheet transition also result in a reduction of the lap shear strength.

Acknowledgements

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