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The role of zinc layer during wetting of aluminium on zinc-coated steel in laser brazing and welding

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Abstract

The zinc layer of zinc-coated steel is known to be a crucial factor for the spreading of liquid aluminium on the coated surface. For industrial brazing and welding processes these zinc-coatings enable a fluxless joining between aluminium and steel in many cases. Yet, the reason for the beneficial effect of the zinc to the wetting process is not completely understood. Fundamental investigations on the wetting behaviour of single aluminium droplets on different zinc-coated steel surfaces have revealed a distinct difference between coated surfaces at room temperature and at elevated temperature regarding the influence of different coating thicknesses.
In this paper the case of continuous laser brazing and welding processes of aluminium and commercial galvanized zinc-coated steel sheets are presented. It is shown that in the case of bead-on-plate laser beam brazing, the coating thickness has a measureable effect on the resulting wetting angle and length but does not have a significant impact in case of overlap laser beam welding. This might be linked to different heat transfer conditions. The results also strongly indicate that proper initial breakup of oxide layers is still required to accomplish good wetting on zinc-coated surfaces.

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1. Introduction

Due to an increasing demand for light weight constructions within the last decade, the ability to join dissimilar materials has become of huge importance. A most relevant challenge in fusion welding is the joining of aluminium

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to steel which have a poor solubility in solid state. Hence brittle intermetallic phases are formed depending on the temperature time cycle. Detailed descriptions of the general problems regarding the joining of aluminium to steel are given, e.g. by *Moeller and Thomy (2013)*. Nevertheless, laser and laser-hybrid brazing and welding have become a process often investigated to join these materials by wetting the steel surface with liquid aluminium, as summarized by *Thomy et al. (2007)*. *Kreimeyer (2007)* established that a comparatively long wetting length is an important factor to achieve good mechanical properties of the joint of dissimilar materials. With a proper heat input it can also be managed to accomplish only a very small intermetallic phase layer, as was fundamentally investigated by *Bouché et al. (1998)*. *Radscheit (1997)* pronounced that by succeeding in achieving a phase layer thickness of less than 10 µm good joint properties between these similar materials can be guaranteed.

Wetting the steel surface with liquid aluminium requires both surfaces to be free of oxide, which is commonly achieved by using flux, or, in the case of arc-based joining processes, cathodic cleaning. Flux or the arc enable wetting by cleaning the surface from residue, breaking the oxide layer of the aluminium melt and (in the case of flux) modifying the surface tension. Zinc-coatings on commercial steel sheets, though, have been observed to favor the wetting of aluminium without using any flux. Indeed, it is reported by *Sierra et al. (2008)* that the wetting result on zinc-coated steel surfaces is even worse if flux is used in addition. Contrary to deep-penetration laser welding, where *Schmidt et al. (2008)* showed that the low melting and evaporation temperature of zinc coatings can cause process instabilities, the zinc layers are generally considered to be helpful in the case of laser brazing. The beneficial impact of zinc layers on the wettability of steel surfaces is not only limited to aluminium. It is also known for other materials like magnesium, as reported from *Tan et al. (2013)*, or nickel, as reported from *Govekar et al. (2009)*, or even copper, as reported by *Koltsov et al. (2010)*. A common phenomenon reported for all of these wetting processes, e.g. by *Zhang and Liu (2011)*, is an accumulation of zinc in the outer boundary of the weld toe after solidification. *Agudo et al. (2007)* have found the microstructure of such accumulation to reach zinc containment of 60 wt.-% or higher. *Vollertsen and Thomy (2011)* suggested that the wetting length has a strong correlation with the temperature field on the coated steel surface and the location of the melting isothermal. Yet, there is no generally accepted explanation either for the origin of the observed zinc accumulation or for the overall benefiting effect to the wettability of steel surfaces in the presence of a zinc-coating.

To fundamentally investigate the wetting process of a single aluminium droplet on commercial galvanized steel substrate, model experiments have been conducted by *Gatzen et al. (2014)* that provide nearly completely controlled conditions in terms of thermal and dynamic boundary conditions of both the droplet and the wetted steel surface. The model experiments enable to almost independently vary droplet temperature, droplet size and substrate temperature. In an experimental series to analyze the wetting on surfaces with different coating thicknesses and types both at room temperature and at 400°C was investigated. With the coated steel surface being at room temperature during droplet deposition, no significant dependency on the wetting angle or wetting length was measured. However, in case of a pre-heated substrate, a slight increase in the wetting angle for higher coating thicknesses could be observed. It was also reported that the time for a complete solidification of the droplet is decreased for higher coating thicknesses. Hence, it was concluded that the thickness of the zinc coating has an effect on the heat transfer from the droplet to the substrate.

To be able to transfer these general findings to continuous joining processes, where conditions are much less controlled or even controllable, the aim of the study presented in this paper is to characterize the effect of different commercial zinc-coatings on low-carbon steel sheets on the wetting process of aluminium in a laser brazing and laser welding processes. To this end, both bead-on-plate laser beam brazing and laser beam overlap welding are conducted. The brazed and welded seams are analyzed in terms of wetting angle and wetting length depending on the zinc-coating. By employing a partially coated steel sheet in some of the bead-on-plate brazing experiments a general qualitative analysis of the different wetting behaviors on zinc-coated steel and on un-coated steel is conducted.

2. Experimental methods

2.1. Materials and procedures

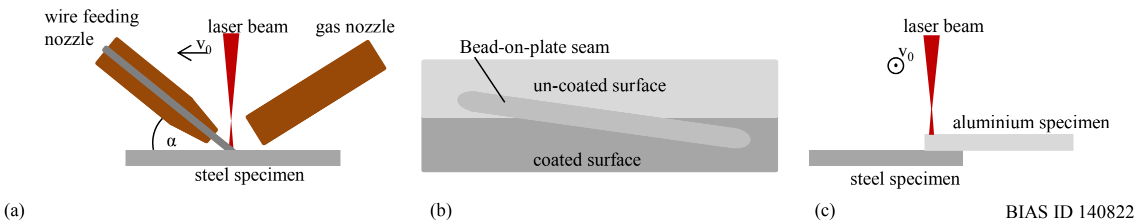

Fig. 1. (a) Setup for bead-on-plate laser brazing; (b) partially coated specimen; (c) setup for laser beam overlap welding.

Both bead-on-plate laser beam brazing and overlap laser welding experiments were carried out with a Trumpf TruDisk8002 solid state laser (wavelength 1030 nm) capable of providing a maximum output power of 8 kW. Fig. 1 (a) and (c) give a sketch of the two joining geometries conducted in these series.

Four different types of commercial galvanized zinc-coatings of low-carbon steel sheets, including electro-galvanized and hot-dip galvanized coatings, with a length of 140 mm, a width of 30 mm and with almost the same thickness were investigated for both joining geometries. The specifications, specimen thickness and the average measured zinc-coating thickness d_{Zn} are given in Table 1.

Table 1. List of zinc-coated low-carbon steel sheets used for the brazing and welding experiments.

base material	coating specification	type	specimen thickness [mm]	measured coating thickness [µm]	ave. coating thickness d_{Zn} [µm]
DC04	+ZE50/50	electro-galvanized	0.7	5.0 – 7.0	6.0
DC04	+ZE75/75	electro-galvanized	0.8	4.0 - 9.0	6.5
DX56	+Z100	hot-dip galvanized	0.8	6.0 – 8.0	7.0
DX56	+Z140	hot-dip galvanized	0.81	10.0 – 11.0	10.5

For the bead-on-plate brazing experiments an eutectic AlSi12 (wt.%-12Si) filler wire of diameter 1.0 mm was fed in front of the laser beam with an inclination of $\alpha = 39°$ to the sheet surface. The chemical composition of the wire, besides aluminium, is listed in Table 2. The defocused laser beam has a spot diameter of d_s = 1.79 mm on the surface. With this diameter, irradiation was almost completely on the aluminium melt pool except for the first few milliseconds of the brazing process. In order to investigate the wetting behaviour of aluminium melt propagating from a zinc-coated to an un-coated steel surface, on some of the specimen the coating was partially removed by milling, so that a braze seam reaching from a completely zinc-coated to an un-coated surface could be achieved, as sketched in Fig. 1 (b).

Table 2. Alloying elements of the aluminium filler wire AlSi12.

Si	Fe	Cu	Mn	Mg	Zn	Ti
11 - 13	0,6	0,3	0,15	0,1	0,2	0,15

The welding experiments in overlap configuration were conducted with an EN AW-6082 T6 aluminium alloy specimen of dimension 150 mm x 30 mm x 1 mm that was positioned on top of the coated steel sheet, as sketched in Fig. 1 (c). The chemical additions of the aluminium alloy are listed in Table 3. The overlap length was 5 mm. The laser spot, with a diameter of d_s = 2.14 mm, was completely set onto the aluminium surface, so that heating of the steel surface could only be accomplished by heat conduction trough the aluminium interface.

Table 3. Alloying elements of the aluminium EN AW-6082 T6.

Si	Fe	Cu	Mn	Mg	Cr	Zn
0,7 - 1,3	0,5	0,1	0,4 -1,0	0,6 - 1,2	0,25	0,2

In both processes, the process zone was covered with Argon. The complete brazing and welding parameters used for the two different joining geometries are listed in **Table 4**.

Table 4. brazing and welding parameters.

	Laser beam brazing	Laser beam welding
Laser power P_L	2 kW	3 kW
Welding/brazing speed v_0	2 m/min	1 m/min
Wire feeding rate v_w	3 m/min	-
Spot diameter d_s	1.79 mm	2.14 mm
Argon gas flow rate	20 l/min	20 l/min

2.2. Specimen characterization

After joining, cross sections of each seam were taken to analyze the wetting length b_d and wetting angle θ. The wetting length b_d was defined differently for each joining setup. For the bead-on-plate brazing cross sections the wetting length was determined to be the overall width of the aluminium interface, whereas for the overlap joints the wetting length was defined as the distance from the initial aluminium sheet edge to the outer boundary of the weld toe after solidification as is indicated in Fig. 2. θ was determined as the angle between the steel interface and the tangent applied the outer bound of the aluminium drawn from microscope images at a magnification of 100:1.

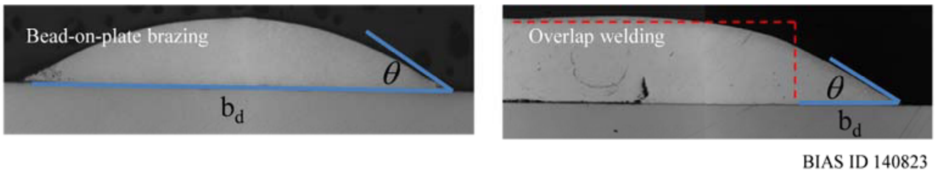

Fig. 2. Analysis of the wetting length and wetting angle.

3. Results

3.1. Bead-on-plate laser brazing

To demonstrate the general difference in the wetting behavior on a zinc-coated surface compared to an un-coated steel surface, the brazing process was performed on a partially zinc-coated steel sheet. The brazing process started on the coated part and was guided gradually to the uncoated part of the steel surface, as shown in Fig. 1 (b). The resulting braze seam is shown in Fig. 3 (a). The seam and hence the observed wetting characteristics can be divided into three sections, which are a complete zinc-coated zone, an uncoated zone and a transition zone in the middle of the braze seam.

Complete wetting with obviously small wetting angles occurs on the completely zinc-coated surface right after the start of the brazing process. The transition zone begins at the position where the outer weld toe of the seam reaches the edge of the coating, indicated with a yellow dashed line in Fig. 3 (a). An important aspect of the wetting behaviour right after reaching the transition zone is the fact that the wetting stops almost instantly when the spreading aluminium melt reaches the un-coated steel surface. After this point, the wetting behavior became unsymmetrical relative to brazing direction, meaning that good wetting is still observed on the coated side of the surface, while on the un-coated side wetting is significantly limited. At the same time, the overall height of the braze seam is increasing with further propagation towards and over the coating edge. In Fig. 3 (b) a cross section of the seam at the end of the transition zone right before the seam is completely deposited on the un-coated steel surface is given. From the cross section a wetting angle of 14° can be measured on the coated side of the surface. On the un-coated steel side an angle of 37° is measured while partial melting of the steel is observed. This is indicating a significant change in the overall temperature distribution compared to the coated side of the steel surface and a generally higher temperature on the steel surface in the absence of the coating. On the completely uncoated surface, bonding of aluminium to the steel surface still occurs, but with much shorter interfacial length and with strongly increased bonding angles compared to the seam observed on the completely zinc-coated side.

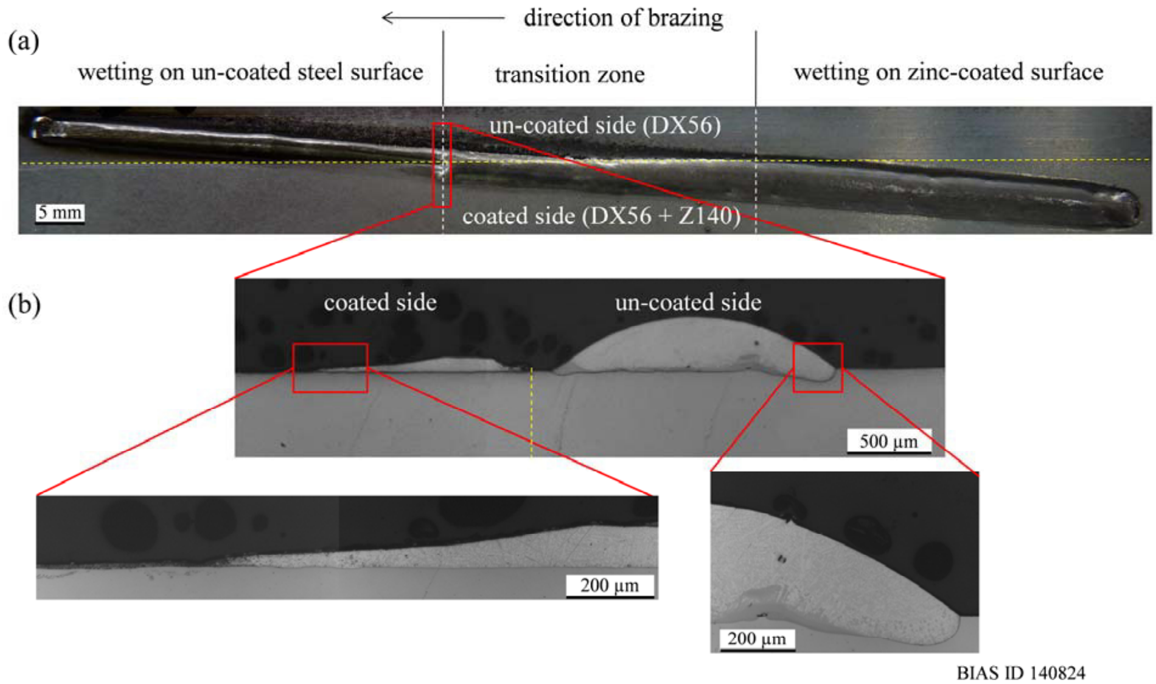

Fig. 3. (a) Resulting braze seam after bead-on-plate laser brazing on an partially zinc-coated steel surface; (b) cross section at the end of the transition zone.

To further characterize the effect of different zinc-coatings on the seam properties, bead-on-plate brazing experiments were carried out on commercial zinc-coated steel sheets. Typical braze seam appearances are given in Fig. 4. The seam appears smoother on the hot-dip galvanized steel sheets compared to the electro-galvanized steel sheets. Also less fume residue occurs on these coatings. The most steady seam appearance was found for the Z140 zinc-coating which has the highest average coating thickness of d_{Zn} = 10.5 µm. Nevertheless, no obvious differences in the general wetting capability could be observed from the braze seams. For each of the different coating types a completely wetted surface was achieved.

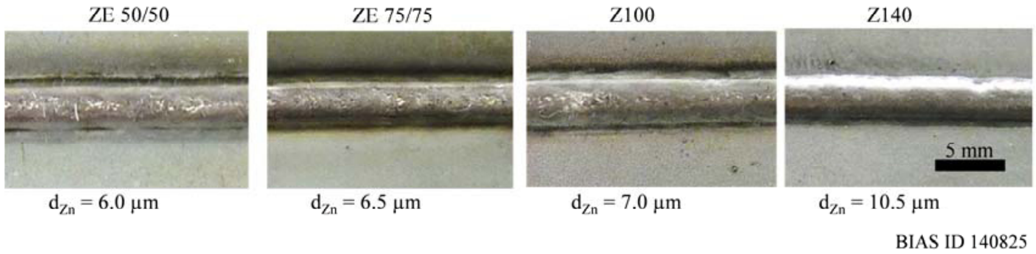

Fig. 4. Seam appearance after brazing for different coatings.

Representative cross sections for all investigated coating types are shown in Fig. 5. No melting of the steel or incomplete bonding was observed. Seemingly the seam on the Z140 coating is slightly higher and narrower.

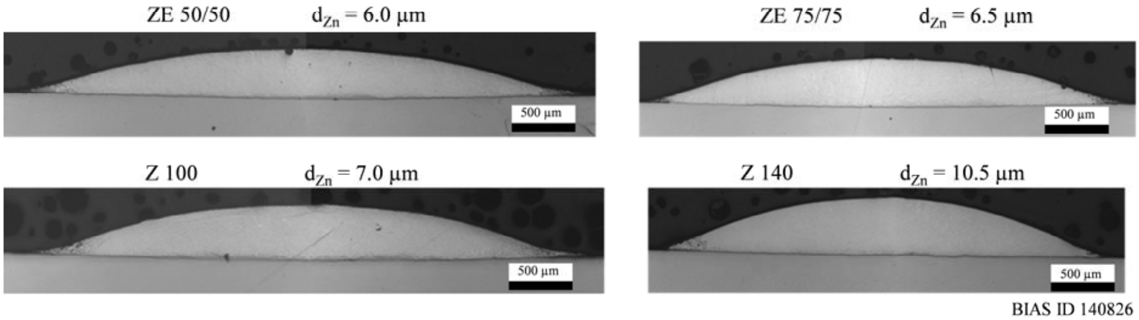

Fig. 5. Seam cross sections after bead-on-plate laser brazing on different coatings.

According to the description in section 2.2 the wetting length and wetting angle have been measured from the cross sections. The result for different coating types, represented by their average coating thickness d_{Zn}, is given in Fig. 6.

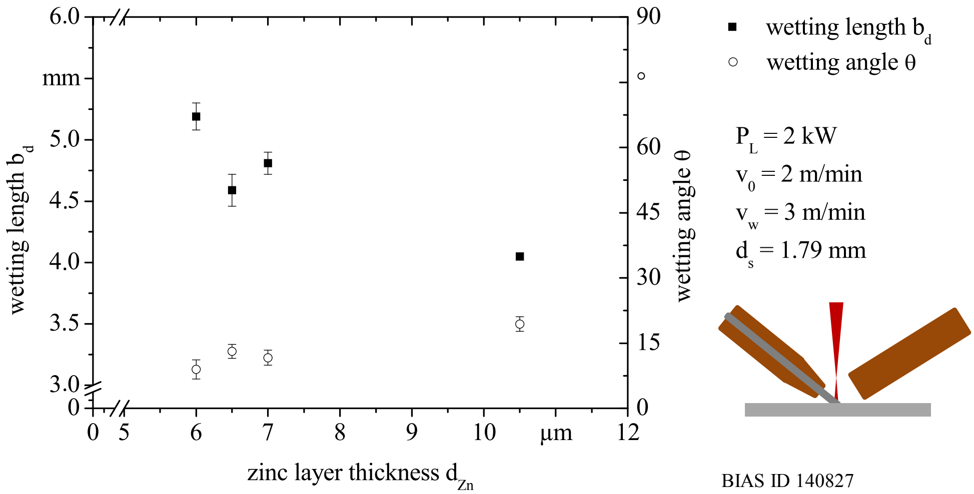

Fig. 6. Analysis of the wetting length and wetting angle.

By trend the wetting length is smaller for higher coating thicknesses. It decreases from $b_d = 5.2$ mm for an average coating thickness of $d_{Zn} = 6$ µm to a value of $b_d = 4.0$ mm for a thickness of $d_{Zn} = 10.5$ µm. An opposing trend was observed for the wetting angle where an average value of $\theta = 10.6$ ° is measured for $d_{Zn} = 6.0$ µm and a value of $\theta = 20.7$ ° for an average coating thickness of $d_{Zn} = 10.5$ µm. This indicates that, although no general differences to the wetting capability during the brazing process was observed, a change in the coating thickness of only a few micrometer has a measurable effect on the width and height of the braze seam in the case of a bead-on-plate joining configuration.

3.2. Laser welding in overlap configuration

To investigate the effect of the coating type on the wetting result for joining in overlap geometry, welding experiments are conducted as described in Section 2.1. The appearances of the resulting seams for the four different coatings are shown in Fig. 7. In each case a smooth weld seam was achieved. The aluminium has wetted the coated surfaces. No obvious differences in the wetting behavior on different coating types could be observed.

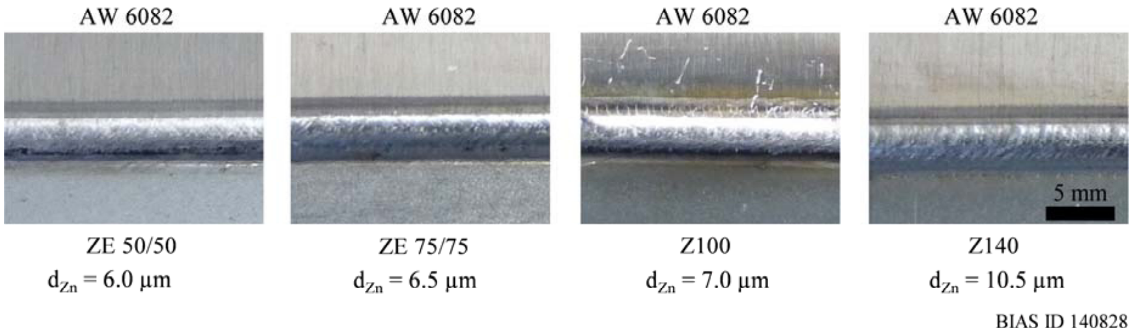

Fig. 7. Overlap weld seam appearance for different zinc-coatings.

A collection of typical seam cross sections is given in Fig. 8. It is obvious that the aluminium sheet was molten over a length of a few millimeters. Yet is has not completely wetted the steel surface over the entire molten interface. Wetting of the coated steel surface predominantly occurred near the front of the aluminium sheet close to the original laser beam position. At some distance from the beam axis in the overlap region incomplete wetting occurred more often. However, the overall length of the un-wetted area strongly varies over the seam length.

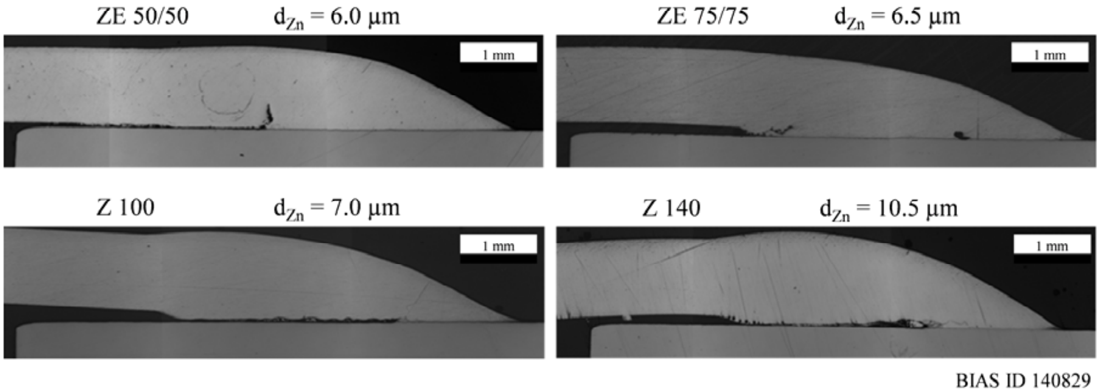

Fig. 8. Seam cross sections after overlap laser welding for different zinc-coatings.

The wetting length and wetting angle for each of the coatings is shown in Fig. 9. The wetting length, according to Section 2.1, is measured only from the edge of the overlapping aluminium sheet to the outer weld toe where complete wetting occurred for all investigated cases. An average wetting length of $b_d = 1.2$ mm was found for the smallest and highest coating thickness of $d_{Zn} = 6$ µm and $d_{Zn} = 10.5$ µm. The highest value of $b_d = 1.6$ mm was measured for a coating thickness of $d_{Zn} = 6.5$ µm and a slightly lower wetting length of $b_d = 1.5$ mm was found for a coating thickness of $d_{Zn} = 7$ µm. This result indicates no significant dependency or trend regarding the wetting length and the coating thickness. This is a major difference to the observations during the bead-on-plate brazing described in the previous section. The same was found to be true for the wetting angles which have values between $\theta = 25°$ and $\theta = 31°$ and are seemingly do also not depend on the coating thickness. Overall, the wetting angles are higher compared to those measured from bead-on-plate brazing.

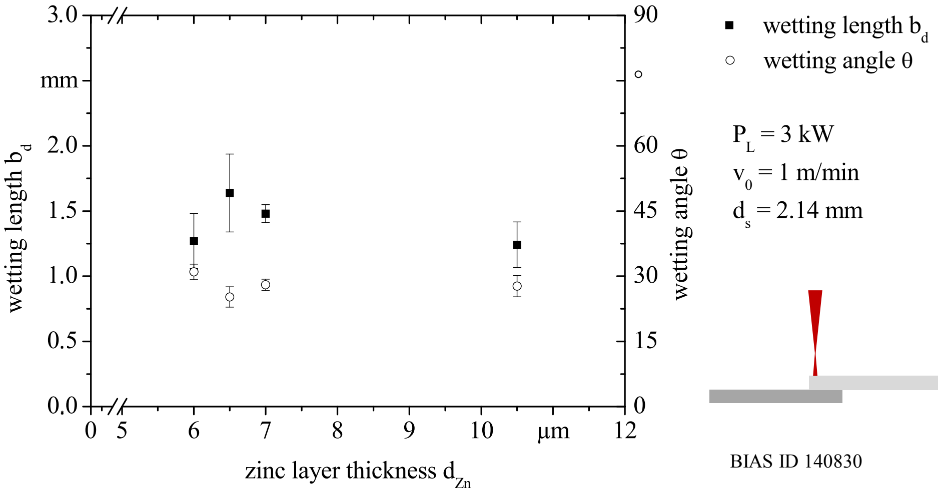

Fig. 9. Analysis of the wetting length and wetting angle.

4. Discussion

The ability of a thin zinc layer on top of a steel surface to promote the wetting of aluminium without using flux was demonstrated with bead-on-plate brazing experiments on a partially zinc-coated steel surface, see Section 3.1. The general wetting capability changes significantly when the aluminium melt is propagating from a zinc-coated to an un-coated steel surface. The spreading of the aluminium melt is instantly stopped when reaching the de-coated steel side of the surface right at the beginning of the transition zone.

An interesting observation is that the wetting length and wetting angle have a certain dependency on the coating thickness that appears only in the bead-on-plate brazing. A similar tendency was observed by *Gatzen et al. (2014)* for single aluminium droplets wetting different zinc-coated steel surfaces at elevated steel temperature (400 °C surface temperature). In both cases removal of heat from the liquid aluminium is potentially mainly accomplished by heat conduction through the coated steel surface. Hence, these results suggest a certain contribution of the zinc coating to the overall energy exchange. A reasonable explanation that the comparably thin zinc layers can have such an effect on the heat transfer during bead-on-plate brazing could be a significant transfer of latent heat to melt and evaporate the zinc-coating. Especially the amount of latent heat of evaporation could scale up to a degree where it could have a measurable impact on the overall energy dissipation and hence the wetting length and angle especially since the evaporated zinc is irreversible removed from the aluminium-steel interface. Thicker coatings could therefore result in higher amounts of evaporating zinc, which in turn result in quicker removal of heat from the aluminium melt. Hence, solidification temperature is reached earlier and will stop the spreading process sooner.

Observations with a high-speed camera during the process confirm the possibility of a significant amount of evaporating zinc during brazing.

However, the effect of the coating thickness on the resulting wetting length and angle appears to be small in the case of the overlap welding, where no such dependency is observed. This could be explained with a general change in the heat transfer conditions. The aluminium sheet provides an additional heat sink that can be expected to yield a dominant contribution to the overall heat dissipation. Although a higher laser power is used in the overlap welding, it can be assumed that less heat is provided to the melting or evaporation of the zinc-layer, and hence the effect of the zinc layer on the overall heat exchange becomes less important.

An important precondition for a successful wetting between steel and aluminium is the initial removal of the oxide layer from the aluminium surface. In the absence of flux, the oxide layer can be broken by thermal expansion of the melt or due to mechanical stresses, as was detailed reported by *Zaehr (2011)*. In case of the bead-on-plate brazing experiments, the steep feeding angle of the wire supports proper breaking of the initial oxide layer since it enforces a stronger deformation of the molten aluminium when it hits the steel surface. Due to the low melting temperature of the zinc it is assumed that after the initial breaking of the oxide layer, the aluminium is intermixed with the liquid zinc, inhibiting a further oxidation of the aluminium at the steel interface.

Following this argumentation, the lack of wetting observed during overlap welding could result from an oxide layer that is not completely broken over the entire liquid aluminium interface during the process. The oxide layer therefore might be broken only near the original laser beam axis where the highest temperatures and hence the highest thermal expansion occurs. This indicates that, beside the beneficial effect if zinc-coatings, proper arrangements for a complete breakup of oxide layers have still to be provided to achieve complete wetting on the coated surface.

5. Conclusion

In this paper, the wetting process during bead-on-plate laser beam brazing and laser beam overlap welding of aluminium and zinc-coated steel with different coating thicknesses and types has been investigated. All investigated zinc-coatings enable the spreading of aluminium melt for both bead-on-plate brazing and overlap welding. A measureable effect of the coating thickness could only be found for the resulting wetting length and wetting angle in case of bead-on-plate brazing. However, the impact of coating thickness to the general wettability can be considered to be very small. From the work it might be concluded that there is at least a two-step mechanism of the wetting when welding aluminium to zinc coated steel: The first important step is the breakage of the layer of oxide on the aluminium melt by thermal and mechanical effect during the process. The second step is the spreading of aluminium on the steel surface which is promoted by the zinc layer, independent of the coating thickness. This zinc layer generates in situ a clean and oxide free metallic surface. This is important to inhibit the formation of new oxide layers on the aluminium melt during spreading.

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