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Novel approach to increase the energy-related process efficiency and performance of laser brazing

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Abstract

Although laser brazing is well established, the energy-related efficiency of this joining method is quite low. That is because of low absorptivity of solid-state laser radiation, especially when copper base braze metals are used. Conventionally the laser beam is set close to the vertical axis and the filler wire is delivered under a flat angle. Therefore, the most of the utilized laser power is reflected and thus left unexploited. To address this situation an alternative processing concept for laser brazing, where the laser beam is leading the filler wire, has been investigated intending to make use of reflected shares of the laser radiation. Process monitoring shows, that the reflection of the laser beam can be used purposefully to preheat the substrate which is supporting the wetting and furthermore increasing the efficiency of the process. Experiments address a standard application from the automotive industry joining zinc coated steels using CuSi3Mn1 filler wire. Feasibility of the alternative processing concept is demonstrated, showing that higher processing speeds can be attained, reducing the required energy per unit length while maintaining joint properties.

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Keywords: laser brazing; galvanized steel; process monitoring; efficiency

1. Introduction

In recent years efficiency is becoming more and more important for manufacturing in general. In this context laser processing offers great opportunities, but a profound understanding of the respective process is necessary to exploit its potential, as suggested by Bley et al. (2007), who investigated welding of zinc-coated steels. These steel

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grades are widely used in the automotive industry, which motivated further investigations to focus on defect-free welding (cf. Milberg and Trautmann 2009). Wilden et al 2009 pointed out that a substitution of welding by brazing is a step towards resource and energy efficient joining in the product life cycle. Besides pores and spatter are often an issue for laser welding according to Schmidt and Kägeler 2008. Also for this reason laser brazing with copper-base filler wire has become one key joining technology in the modern automotive industry. The technique is widely used for joining zinc-coated parts of the outer bodywork, which are typically exposed to the customer's eye. More specifically Kimpel 2013 examplifies that to be e. g. joining the roof to the side panel, parts of the trunk lid, etc.. In each case the customer exposed parts demand the highest possible surface quality, which is of course including leak-tightness. At best the joint does not appear like a joint after finishing.

Compared to alternative joining techniques, like e. g. arc brazing, laser brazing has dintinct advatages that pay off on the long term, legitimating the higher costs for the technology (see Riedelsberger et al. 2006). Most important benefits are high processing speeds and a low heat input, and the available, more and more upgraded process controls, as it is discussed by Graudenz et al.2012. Due to the minor thermal load of laser brazing the joints demand little rework, and well-engineered system technology significantly enhances the reliability of the technique. The increased reliability of laser brazing can be attributed to a well advanced knowledge of the temperature field (Grimm et al. 2007) and melt dynamics (Grimm et al. 2009).

However there are limits to the state of the art laser brazing. On the one hand the filler metal's high reflectivity of solid-state laser radiation, which can be up to 97 % according to Dausinger 1995, is impacting process efficiency. On the other hand the maximum processing speed applied in series production of up to 3 m/min is comparatively low for laser brazing. That is because in conventional process configuration the laser beam impinges nearly perpendicular and the filler wire is delivered under an angle of 45 degree, as described by Heitmanek et al. 2014. Therefore, the filler wire is shadowing the joining partners to some extent, which is resulting in an insufficient heating at high brazing speeds, which in turn is affecting the wetting and thus the seam quality. Grimm 2012 found that at higher processing speed the wetting takes place in a periodic manner, which is negatively impacting surface quality. To overcome speed and wetting limits two-beam laser brazing was introduced and has been investigated ever since. According to Hoffmann et al. 2004 the principle is to use one high-energy laser beam to melt the filler wire along with a forerunning low-energy laser beam to peheat the sheets in the processing zone and thereby support the wetting. Previously the authors pointed that out, showing the correlation between preheating temperature and wetting length (cf. Mittelstädt et al. 2014). In consequence of the process configuration the filler wire is typically aligned in the middle of the beam axes. Nontheless two-beam laser brazing solutions make a virtue of the necessity to have to deliver the filler wire at a nearly perpendicular angle, advertising that thereby hardly accessable contures can be joined and that a change in process-direction can be easier made (see e. g. Hornig 2006). However there are numerous two-beam processing heads available, but no product has yet established in series production. This is because of enhanced system costs and complexity. Overall two-beam laser brazing features benefits, as far as attainable processing speed and improved wetting is concerned, but has constraints as there are higher costs.

This contribution builds on the situation, that there are well documented benefits for laser brazing with preheating. The drawback of the technology, which is rather attributed to further system costs is addressed by the innovative processing concept that this work is introducing. A novel approach for laser brazing is presented that features a compareably steep filler wire alignment and the laser beam in leading configuration. By that means otherwise unexploited laser radiation that is reflected from the filler wire is directed onto the substrate.

2. Idea and Approach

The novel approach of this contribution is based on the alignment of filler wire axis and beam axis to one another, in which the laser beam is preceeding the the filler wire. The effect, which is intended by this process configuration, is illustrated in Fig. 1. On the left a detailed view of the filler wire tip in contact with the substrate and illuminated by the pilot laser is given. By redirection of the incident laser radiation onto the substrate in process direction, reflected and otherwise unexploited laser radiation shall be utilized. Due to the geometry of the filler wire, the incident laser beam is expanded, illuminating a wider area of the substrate. The sketch on the right in Fig. 1 points out the optical path of the radiation.

The applied processing set-up is given in Fig. 2. Related to the vertical axis the laser beam axis was set to 30 degree and the filler wire was delivered at 10 degrees. For the experiments a Trumpf TruDisk 8002D (200 µm fiber core diameter) solid-state laser was used. The used reproduction ratio of the brazing optics is 3:2 (f_{foc} = 300 mm; f_{col} = 200 mm), which is magnifying the mimimum beam diameter to 300 µm in the focal plane.

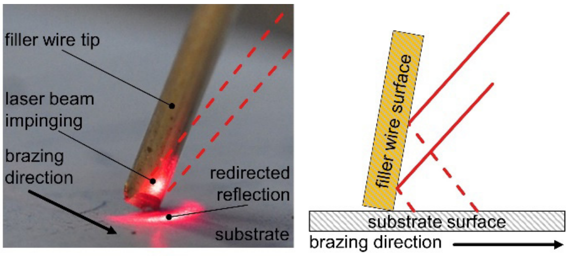

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Fig. 1. Close-up of the filler wire tip illuminated by the pilot laser (left); sketch of the optical path of the laser beam (right).

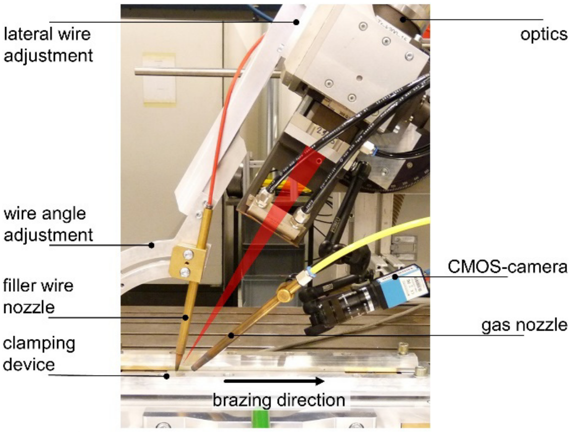

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Fig. 2. Processing set-up. Laser: TruDisk8002D; fibre-Ø: 200 µm; wavelength: 1030 nm; reproduction ratio: 3:2; laser angle: 30°; wire angle: 10°.

3. Experimental Methods

3.1. Materials

Galvanized steel sheets (0.75 mm thick) were used. Thereby two steel grades with differing zinc coatings, DC06 ZE75/75 (electrogalvanized) and DX54 D+Z100 (hot dip galvanized) were investigated, either coating thickness being about 7.5 µm. The filler wire in the experiments was CuSi3Mn1 (Ø = 1.2 mm).

3.2. Procedure

Brazing experiments contained bead-on-plate brazing, as well as brazing of fillet joints. General feasibility and process characterization of laser brazing in beam leading configuration was analysed by means of bead-on-plate brazing. The applicability of the approach was demonstrated in the latter by carrying out fillet joints. In doing so an application from the automotive industry is addressed, that is the roof to the side panel joint (also known as zero gap joint).

3.3. Process monitoring

High-speed video monitoring was used to investigate the process behavior. In order to filter out disturbing process radiation the utilized Vision Research Phantom V5.1 high-speed camera was synchronized with a Cavitar Cavilux pulsed diode illumination laser (810 nm) and equipped with a notch filter specified for transmitting only the illuminating wavelength.

In order to detect the reflected solid state laser radiation a monochrome CMOS-camera was equipped with a narrow-band-pass filter (central wavelength: 1030 ± 3 nm; half width: 6 ± 2 nm). To avoid overexposure of the high sensitive silicon detector, gray filters (OD 3 and OD 1.3) were used. Laser radiation monitoring was performed with a frame rate of 32 Hz.

3.4. Metallography

Bead-on-plate seams and fillet seams were both analyzed by optical microscopy. In order to determine the connection widths of the fillet joint cross-sections were taken from the seam. Furthermore X-ray computer tomography was performed to analyze the regularity and porosity of the fillet seam.

4. Results

4.1. Laser radiation monitoring

An unfiltered view of the laser radiation monitoring (LRM) camera is given in Fig. 3 a, showing the filler wire contacted with the substrate and illuminated by the pilot laser. By introducing a calibration to the sheet surface in process direction and transverse to it (not depicted), a conversion of pixels to millimeters is enabled. Fig. 3 b shows an image of the before described view with an adjusted frame exposure time to reduce overexposure of the illuminated area. Thereby the shape of the reflection, resulting from interaction between the solid filler wire tip and the pilot laser, is illustrated. To point out these interaction Fig. 3 c shows the pilot laser impinging of the substrate with no filler wire redirection, which is supported by the dashed line.

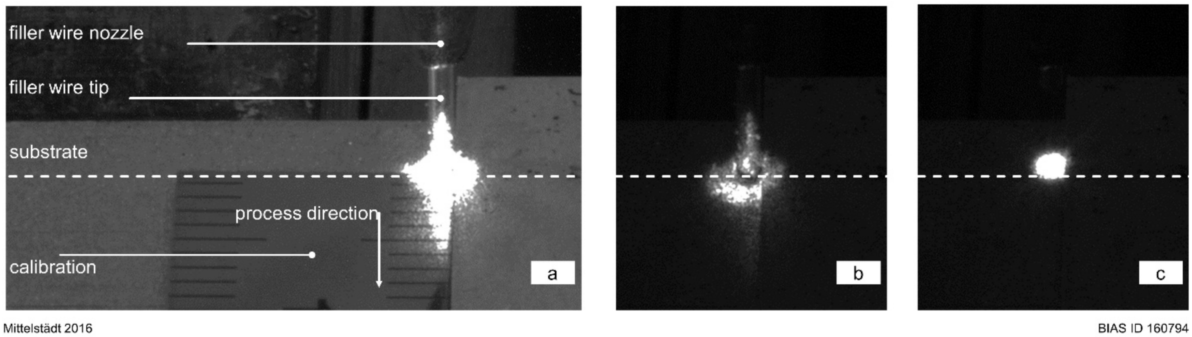

Fig. 3. a: unfiltered view of the laser radiation monitoring (LRM) camera; b: cropped image of the LRM camera with adjusted exposure; c: laser beam impinging on the sheet surface without filler wire interaction.

4.2. Bead-on-plate laser brazing

Bead-on-plate laser brazing was performed to demonstrate the general feasibility of this processing set-up and to understand the overall process behavior and parameter correlations. Stable processing could be observed whereupon consistent wetting was achieved. A typical seam appearance for stable bead-on-plate brazing is represented by Fig. 4.

For the fundamental investigations a processing speed of 1.5 m/min and therefore a high energy input per length was chosen. This resulted in a clearly visible impact on the zinc coating of the substrate. This again contributes to the understanding of the process characteristics. On the one hand the impact on the zinc-layer can be seen right next to the seam edges, showing small white region, which is typical for zinc-burn-off. On the other hand there is an area, which is approximately 9 mm wide (indicated by the dashed lines in Fig. 4 a), where the surface of the substrate was visibly influenced by the process. However to evaluate the regularity of the wetting, the seam width was analysed using optical microscopy. The edges of the seam are highlighted in Fig. 4 (b) and the course of the seam width is given in Fig. 4 (c). The measured median seam width in this depicted case was 3.42 mm, with a standard deviation of ± 0.05 mm.

High-speed video monitoring (HSM) showed, that stable processing is achieved when there is a controlled deposition of braze metal onto the substrate, forming a firm braze metal transition. Therefore, the ratio of filler wire feed rate to laser power with respect to the focus position is mandatory for stable processing. Furthermore the point of intersection of the laser beam axis and the wire axis is equally important. When the laser beam and the filler wire intersect too high above the substrate, the braze metal forms droplets and no seam is produced. On the other hand a too low intersection of the laser beam and the filler wire leads to a disturbed filler wire deposition, because the side of the filler wire, which is averted from the laser beam, is fused incompletely, which in turn results in an irregular seam formation. Moreover HSM indicates that the zinc-coating of the substrate is affected prior to the wetting. Besides it could be seen, that the wetting takes place rather iteratively than being completely continuous.

Process monitoring using the narrow-band filtered monochrome CMOS-camera-system was successfully used to detect the reflection of the laser radiation in the processing zone. An image sequence of both laser radiation monitoring (LRM), and synchronized high-speed video footage is given in Fig. 5. HSM shows the side view of the brazing process. The time-related display of the images supports the interpretation of the shape of the reflection in the LRM images. The sequence includes the beginning of the process to point out the correlation between filler wire geometry and the shape of the reflection in the gray-scale images obtained by LRM. After bead formation the wetting becomes very consistent.

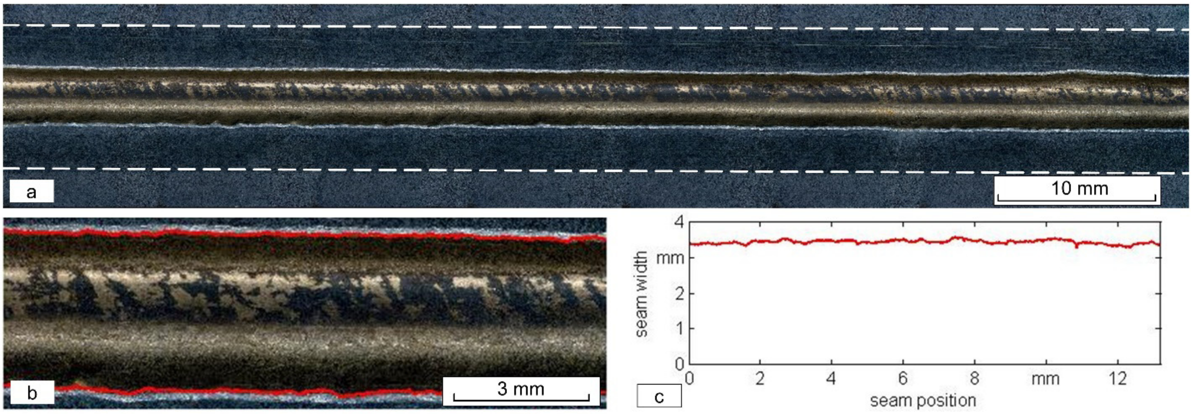

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Fig. 4. (a) Overview of the seam appearance for bead-on-plate laser brazing; (b) detailed picture of the seam edges; (c) course of the seam width. Parameters: DX54 D+Z100 (0.75 mm); CuSi3Mn1 (Ø = 1.2 mm); brazing speed = 1.5 m/min; filler wire feed rate = 3 m/min; laser power = 2 kW; focus position = +20 mm.

The first frame of the image sequence shows the beginning of the process when the laser beam is turned on, impinging on the bare substrate. The shape of the LRM (width 2.41 mm) is according to the expected and adjusted beam diameter on the substrate, that is 2.48 mm. The dashed line in each frame of both the LRM and the HSM marks the bottom of the initial laser incidence point. The second frame of the image sequence shows the solid filler wire tip intersecting with the laser beam, with the braze metal not yet in touch with the substrate. Therefore, the formerly irradiated area of the substrate is mostly shielded and no further laser reflection is detected. The third frame of the HSM sequence shows the actual beginning of the bead formation. At this point the filler wire is partially molten, not yet making full contact with the substrate. Reflected radiation can be identified from the wire tip, as well as from an area of the substrate, which is located in front of the initial laser incidence. Therefore, laser radiation must have been redirected from the filler wire tip. Because of the filler wire's round shape laser radiation is not only being reflected forward to the wetting, but also to the side, illuminating the substrate wider than before. The next frame in the HSM sequence shows the braze metal fully molten making full contact with the substrate. In doing so the melt is pulled slightly to the front. The geometry of the solid filler wire is tapered in direction of the melt. Prior to the weitting an influence on the coating can be seen. The LRM appears more intense overall, showing a small saturated area. The spread of the detected laser radiation indicates that the round shape of the solid filler wire is conserved to some extent. The fifth and final frame of the sequence shows the brazing process in its stable condition after 557 ms time elapsed. High intensity reflected laser radiation is detected and therefore saturated areas in the LRM image appear.

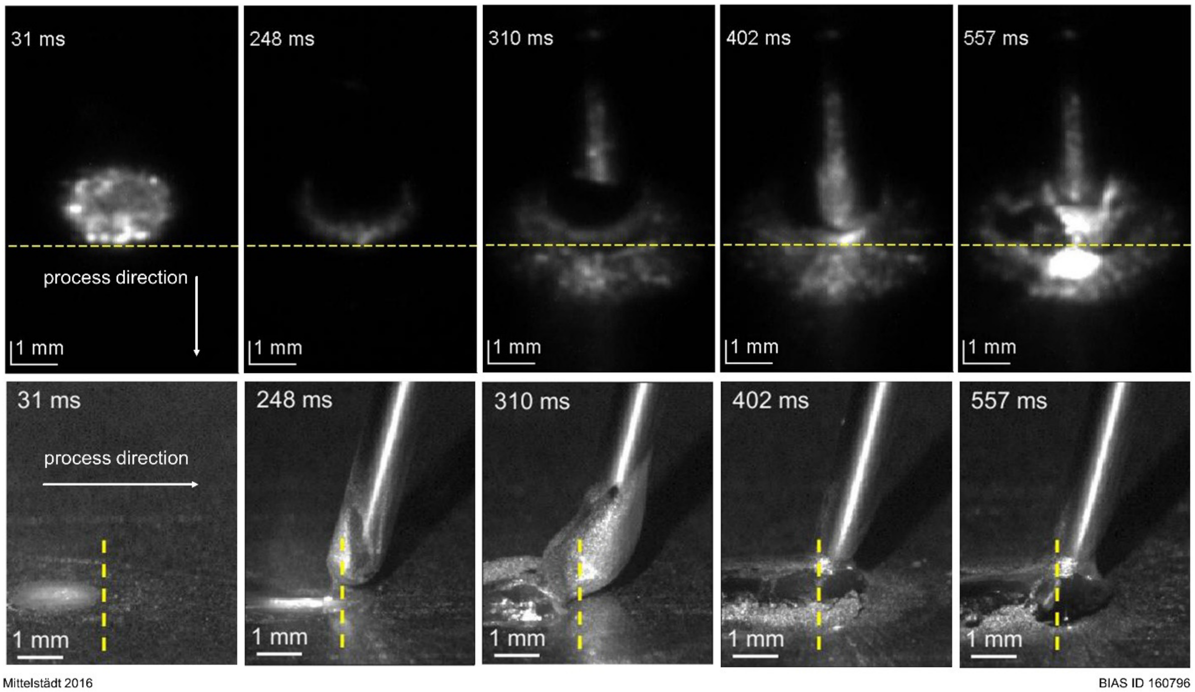

Fig. 5. Synchronized picture sequences of the laser radiation monitoring (top) and the high-speed video monitoring (bottom) for bead-on-palte laser brazing. Parameters: DX54 Z100 (0.75 mm); CuSi3Mn1 (Ø = 1.2 mm); brazing speed = 1.5 m/min; filler wire feed rate = 3m/min; laser power = 2 kW; focus position = +20 mm; shielding gas Argon 15 l/min.

In order to investigate process behavior and characteristics, the shape of the gray-scale images from LRM were analysed, Fig. 6 and Fig. 7. To evaluate the reflected shares of the laser radiation that contribute to the wetting of the substrate, the length and width of the reflected laser radiation is considered for the process in stable condition.

The length of the reflected laser radiation is given as the distance from the edge of the detected reflection (solid red line) related to the initial laser incidence point (dashed line) in Fig. 6. It can be seen, that laser radiation shares can be detected on the substrate an average 3.10 mm prior to where the laser beam originally impinged with the course of the detected length not being regular, but consistently over 2.55 mm throughout the process. The peaks in the detected length and its unbalanced course can be related to the periodic wetting that can be seen in HSM.

The width of the detected radiation is illustrated in Fig. 7. As mentioned before, the width of the detected laser radiation exeeds the initially observed reflection on the bare substrate and beam diameter, respectively. Compared to the length of the reflected laser radiation shares the detected width is more even. The average of the width of the detected refelection is 4.11 mm. That exeeds the width of the seam (3.42 mm), but is less than the width of the visibly influenced area around the seam (cf. Fig. 4 a).

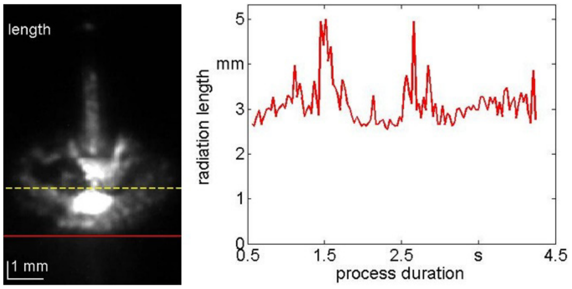

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Fig. 6. Course of the detected length of the reflected laser radiation given over the process duration (stable condition).

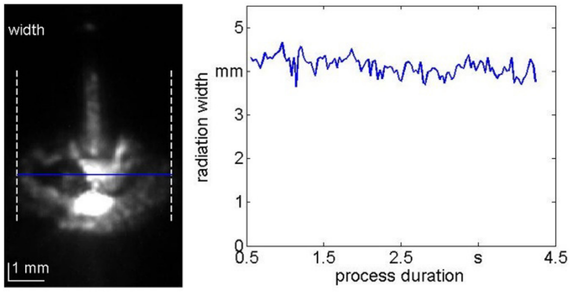

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Fig. 7. Course of the detected width of the reflected laser radiation given over the process duration (stable condition).

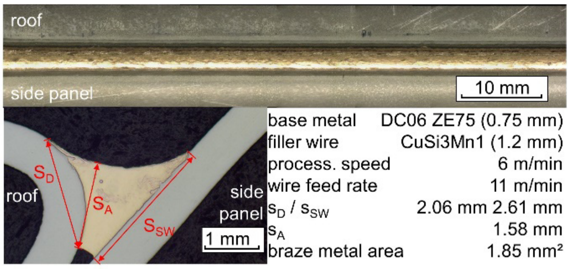
4.3. Laser brazing of fillet joints

To increase the energy-related process efficiency for laser brazing, joining experiments with respect to industrial conditions were perfomed. Therefore, the processing speed was increased to 6 m/min, lowering the energy input per length and reducing the thermal load on the joining partners and their respective coatings.

The resulting seam appearance for laser brazing of the roof to the side panel joint is illustrated in the top of Fig. 8. At the high processing speed of 6 m/min, a high melting rate of the braze metal and a correspondingly high filler wire feed rate is required, to achieve the requested connection width for this joint. In this case a filler wire feed rate of 11 m/min was chosen. Therefore, it was necessary to inrease the laser power to 5.5 kW as well, in order to obtain the high required melting rate. The focus position was set to +13 mm, resulting in a beam diameter of 1.63 mm, also contributing to the high melting rate of the filler wire. The high energy required the use of shielding gas.

In metallographic examination (Fig. 8 bottom) a slight melting of the substrate could be seen. However, pores could not be found in cross-sections. As far as the connection width is concerned, the filler metal deeply penetrated the joint, resulting in large connection widths to either panel ($S_D = 2.06$ mm and $S_{SW} = 2.61$ mm) with the minimum connection width (S_A) being 1.58 mm, which is 2.1 times the sheet thickness.

Furthermore a 100 mm long section from the joint was analyzed using X-ray computer tomography (XCT), see Fig. 9. Thereby a total number of 16 pores with a diameter of 100 μm to 180 μm could be found, at which no prefered location could be determined (see Fig. 9 a and b). Moreover it could be found by XCT-analysis that the wetted area of the grove of the joint was not uniform along the course of the seam. This is illustrated by Fig. 9 c and Fig. 9 d, showing two different planes from the XCT-analysis with differing gap fillings, which can be seen by the wetting of the side panel in either picture (right sheet). Moreover it could be proven by XCT- analysis that no wetting failures occurred.



base metal	DC06 ZE75 (0.75 mm)
filler wire	CuSi3Mn1 (1.2 mm)
process. speed	6 m/min
wire feed rate	11 m/min
s_D / s_{SW}	2.06 mm 2.61 mm
s_A	1.58 mm
braze metal area	1.85 mm²

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Fig. 8. Overview of the seam appearance (top); cross-section of the joint. Parameters: laser power = 5.5 kW; focus position = +13 mm; process gas: Ar 15 l/min.

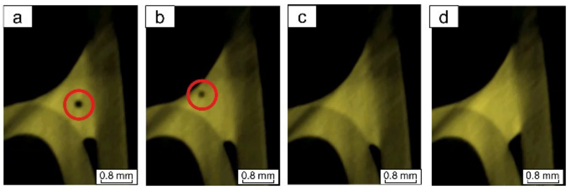

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Fig. 9. Four different planes from X-ray computer tomography analysis of the roof to side panel joint. Illustration of detected pores (a,b) and differing braze metal penetration of the grove of the joint (c,d).

5. Discussion

LRM shows, that the substrate is illuminated and therefore most likely preheated at a close distance to the wetting. This instance might very well be challenging temperature measurement, since the region of interest is very small and high temperature gradients are expected this close to the copper melt.

Considering the seam appearance for bead-on-plate laser brazing it can be seen, that the course of the seam edges and the seam width, appear to be even, but not straight. Since wetting is highly influenced by the temperature, this might either be due to slight irregularities in the braze metal temperature, or the substrate temperature. Reflected shares of the laser radiation could be detected prior to the wetting and next to the seam edges, which both contributes to an improved wetting. The laser radiation monitoring (LRM) indicates temperature variations of the surface of the substrate due to varying illumination by reflected radiation from the braze metal. Therefore, the generated temperature field of the substrate could be changing to some extend during the wetting.

Another point that has to be addressed in this context is the dynamic behavior of the braze metal. The varying shape of the reflection of the laser radiation onto the substrate can most probably be related to a periodic wetting and constantly changing shape of the braze metal, which can be seen in high-speed process monitoring. This agrees with the findings from Grimm 2012, suggesting the wetting takes place periodically. However, to perform a frequency analysis of the constitutional change of the detected shape of the reflection, increasing the frame rate of the camera will be necessary. A successful correlation of LRM and the wetting frequency could be a key step to improve laser brazing, since LRM can be applied easily at low costs and the wetting frequency is decicive for seam quality, but usually complex metrology is required to detect it.

Laser brazing of fillet joints in laser leading configuration proved the industrial applicability of the approach, although slight melting of the substrate was found. However is was demonstrated, that brazing with a laser beam diameter (1.6 mm) in the range of the filler wire diameter (1.2 mm) is feasible. Normally the applied beam diameter is about two times the diameter of the filler wire to achieve a sufficient (pre-)heating and prevent the occurrence of wetting failures (cf. Heitmanek et al. 2014). Considering gap filling of the braze metal achieved with the presented approach and the completed wetting confirmed by X-ray computer tomography (XCT) analysis, the intended preheating appears to be promising, which is improving the wetting significantly.

The resulting mimimum connection width measured in the cross-section was 2.1 times the sheet thickness. Typically a minimum connection width of only 1.2 times the sheet thickness is required. According to Heitmanek et al. (2014) even less is acceptable. Therefore, a reduction of the filler wire feed rate of 11 m/min, which was applied in the experiments, might be possible or even recommendable. Furthermore an increased processing speed of 6 m/min could be denmonstrated, overcoming the limits of conventional laser brazing.

6. Conclusion

It could be demonstrated that laser brazing of galvanized steels using copper base filler matrial is feasible in laser leading process configuration. Stable processing could be achieved for both bead-on-plate experiments as well as for laser brazing of fillet joints as demonstrated by brazing the roof to side-panel structure, which represets a common application for laser brazing in the automotive industry. In the latter case it was shown, that the processing speed could be increased to 6 m/min.

Reflected laser radiation could be detected using a filtered standard monochrome CMOS-camera. By this means it could be shown that otherwise/conventionally unexploited laser radiation shares, which are reflected by the braze metal, can be purposefully redirected onto the substrate prior to the wetting for brazing in laser leading configuration. Therefore, brazing in laser leading configuration has clear benefits concerning (pre-)heating of the substrate compared with the conventional process configuration with the filler wire shadowing parts of the joint. Process monitoring shows that both wire deposition and wetting of the substrate are taking place rather dynamic or with a periodic behavior, than being completely uniform.

It is illustrated by means of X-ray computed tomography of fillet joints, that appropriate preheating is achieved resulting in deep braze metal penetration with no connection failures occurring, overall improving the connection and indicating further potential of the investigated approach.

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