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Detecting and utilizing reflected radiation in laser beam brazing

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Abstract

Laser brazing of galvanized steel is a common application in the automotive industry thanks to excellent joint properties and well-engineered system technology. However, the application utilizes copper base filler material and solid state lasers for joining at a wavelength of about 1 µm resulting in high losses of reflected radiation. Since there are currently no thrifty alternatives to either the beam source or the filler material, it is desirable to make use of reflected and therefore yet unexploited radiation.

The state of the art process configuration for laser brazing features the laser beam impinging almost perpendicular to the joint and a leading filler wire supply. This contribution addresses an alternative process configuration, at which the laser beam was leading a steeply inclined filler wire. By this means, reflected radiation could be redirected onto the substrate to achieve a preheating of the joint. For process monitoring a total of two cameras were used: On the one hand, laser radiation monitoring (LRM) was achieved using a narrow-band filtered CMOS camera. On the other hand, high speed camera monitoring (HSM) was used to analyze the braze metal transition and the wetting. By synchronizing the respective image sequences from LRM and HSM, characteristics of the wetting process like the contour of the braze metal on the substrate could be transferred from the HSM images to the LRM images by numerical computing. Thereby, the part of the detected laser radiation that contributes to preheating of the substrate could be allocated and analyzed in terms of its geometrical shape and relative intensity. Ultimately, by utilizing reflected radiation for preheating a deep wetting of flange joints could be demonstrated and increased processing speeds could be attained.

Keywords: Joining; System Technology; Process Monitoring

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1. Introduction

Laser beam brazing is widely used to join zinc-coated skin-sheets in the automotive industry. In general, zinc-coated steels are a lower-cost alternative to aluminum when it comes to meeting anti-corrosion requirement as discussed by Bewilogua et al., 2009. In non-visible areas zinc-coated steels are normally welded, whereat certain measures must be taken to assure defect-free joining as Milberg and Trautmann, 2009 pointed out. However, skin-sheet joints are subjected to the highest standards in terms of joint appearance as for example Graudenz and Heitmanek, 2012 described. These high requirements are met by laser brazing using copper base filler materials, cf. Hanebuth, 1996.

As it was illustrated for welding of zinc-coated sheets by Bley et al., 2007, cost-efficient joining technologies are requested by the manufacturers. Wilden et al., 2010 discuss that brazing in general has advantages compared to welding regarding both cost-efficiency and resource-efficiency. Accordingly, a considerable number of approaches to improve laser beam brazing were introduced by researchers in recent years, concerning different aspects.

Two-beam brazing concepts were introduced aiming to improve the wetting and thereby to enhance the attainable processing speed by an extra preheating of the joint. Grimm et al, 2010 for example demonstrated a deep penetration of flange joints because of preheating resulting in long connection widths. Furthermore, attainable processing speeds of up to 8 m/min were demonstrated. To classify this, the state of art for laser brazing in the application reports reliable processing speeds of a maximum 4 m/min, according to Engelbrecht, 2009. Compact system-technology for two-beam brazing was introduced by Hoffmann et al, 2004 for example.

Despite the availability of two-beam processing heads, single-beam processing heads are still the most common system technology in today's manufacturing plants. Thereby, the OEMs rely on existing well-engineered solutions that come with the highest available degree of robustness (cf. Riedelsberger, 2006).

The latest trend in the field of laser brazing is the utilization of a very localized removal of the zinc-layer at the seam edges prior to the wetting. That is because manufacturers tend to prefer hot-dip galvanized steel sheets over electrogalvanized material due to lower costs, better corrosion resistance and world wide availability. However, hot-dip galvanized material facilitates the formation of imperfections like pores and spatter at laser brazing, which is presented by Heyn, 2003 for example. Moreover, the wetting is less consistent compared to electro-galvanized material resulting in higher reworking needs. By means of local zinc-layer removal at the seam edges those drawbacks can be overcome. This is achieved by trifocal laser brazing and brazing with a tailor-made beam intensity-profile, as presented by Reimann et al., 2016 and Luft and Baumann, 2016, respectively. Reimann et al., 2017 also demonstrated higher processing speeds by means of local zinc-layer removal. Therefore, laser brazing with localized zinc-layer removal also increases the cost-efficiency of laser brazing.

Another subject to cost-efficiency of laser-based joining processes in general is the energy-efficiency. In this regard, the efficiency of the beam source is decisive. Diode lasers are often referred to as efficient beam sources. Although not suitable for every application today, Luft, 2013 points out that diode lasers are well established for laser brazing. Nevertheless, the combination of IR laser radiation and copper based filler material inevitably results in high power losses due to reflections, see Dausinger, 1995. Therefore, redirecting and utilizing reflected radiation can increase the process efficiency.

This contribution shows how to detect and utilize reflected laser radiation in laser beam brazing. Experimental and numerical methods were used to analyze the braze metal transition and to quantify the intensity profile of the reflection on the substrate, respectively. In the end, the performance of the laser leading brazing concept is demonstrated for standard applications from the automotive industry.

2. Experimental

2.1. Material

The experiments address brazing of hot-dip galvanized and electrogalvanized steel grades DX54 Z100 and DC04 ZE75/75, respectively, using copper-base filler wire CuSi3Mn1. Sheet thickness was 0.75 mm and the filler wire diameter was 1.2 mm.

2.2. Set-Up

The process set-up used in this work aims to utilize reflected laser radiation for preheating. The idea, at which the laser beam is leading the filler wire at laser brazing, is illustrated in **Fig. 1 a** by means of the solid filler wire tip and the pilot laser, which is redirected from the wire onto the substrate. Thereby, the pilot laser becomes expanded because of the cylindrical shape of the filler wire. High-speed-camera monitoring (Fig. 1 b and c) of the brazing process points out the potential utilization of reflected radiation, ascribing an apparent melting of the substrate to the estimated beam bath of redirected radiation.

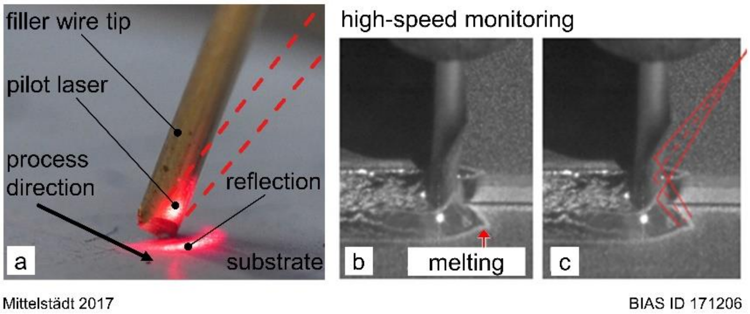


Fig. 1. Illustration of the process configuration.

For the experiments a solid-state disc laser Trumpf TruDisk 8002D was used. The process set-up along with the beam attributes is given in Fig. 2. The filler wire angle was set to 10 degree and laser beam angle was set to 30 degree. The laser beam had a focal diameter of 0.29 mm, resulting from the core diameter of the optical fiber cable of 200 µm and the ratio of the focal lengths of the collimation lens (200 mm) and the focusing lens (300 mm).

For monitoring of the brazing experiments a high definition high-speed-camera Phantom VEO 410 and a free configurable CMOS-camera DMK 23GP031 was used. The CMOS-camera was equipped with a set of neutral density filters (OD 3 and OD 1.3) and a narrow-band-pass filter (central wavelength 1030 nm; FWHM ±6 nm) that was chosen with respect to the wavelength of the processing disc laser (1030 nm). The framerate of the CMOS-camera was set to 200 Hz. The high-speed-camera was used synchronized with an illumination laser system Cavitar CAVILUX, where camera and laser source (808 nm wavelength) were designed for synchronous processing. Thereby, occurring process emissions can be filtered out. The framerate of the high-speed camera was set to 2 kHz.

To evaluate the geometry of the melting filler wire, the high-speed-camera was aligned in different angles (increment for angle γ was 10 degree) related to the process direction (cf. **Fig. 2)**. The observed geometry of the melting filler wire was used to compute the intensity profile of the reflected radiation on the substrate using MATLAB 2016b. The computation considers the measured intensity profile and attributes of the laser beam utilizing the MATLAB Laser Toolbox (cf. Römer and Huis in 't Veld, 2010).

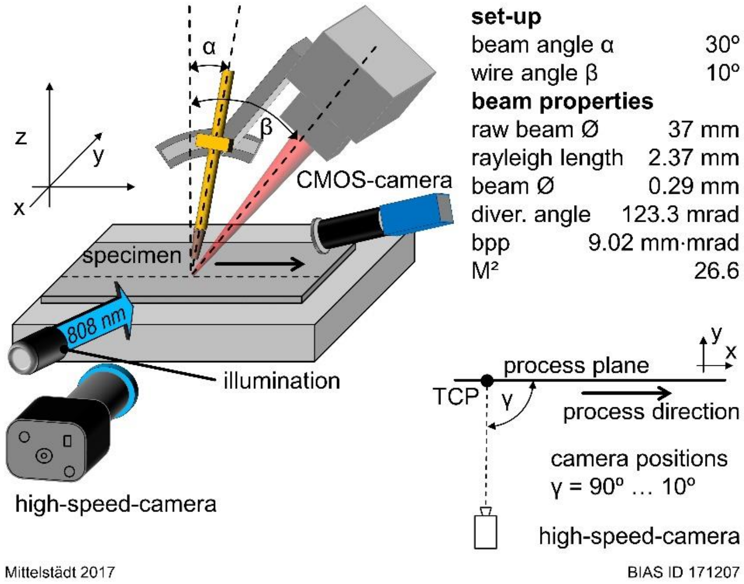


Fig. 2. Sketch of the experimental set-up

3. Results and discussion

3.1. Detecting reflected laser radiation used for preheating

During laser brazing process radiation occurs, which is emitted from the base material, the coating in the first place, and the braze metal. The overall process radiation spectrum was captured in a range between 339 nm and 1173 nm using optical spectroscopy and is illustrated in Fig. 3. Aside from the reflected laser radiation of 1030 nm, process radiation towards shorter wavelengths occurred over the entire measuring range. However, using a beam source emitting laser radiation at a different wavelength than 1030 nm, no reflections could be detected with the LRM-camera. Therefore, it can be concluded that with the applied filter concept using a laser-specific band-pass-filter and ND-filters is suitable to detect nothing but the reflected laser radiation from the process.

LRM grayscale-images indicate the process behavior in terms of the occurring laser reflections from the brazing process. Thereby, the LRM-images display the intensity distribution of the reflected radiation qualitatively.

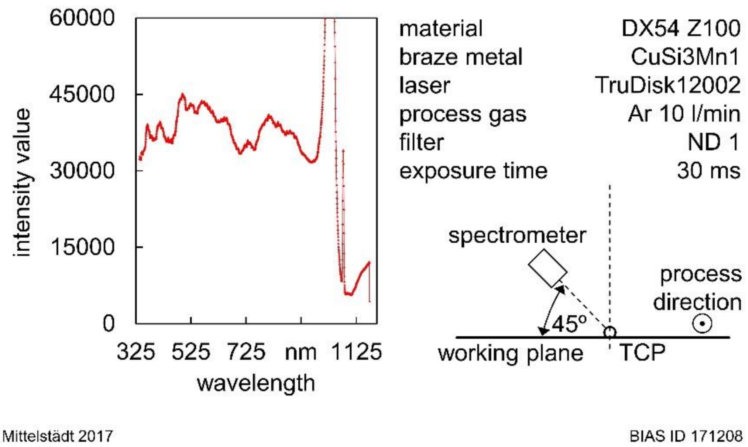


Fig. 3. Spectrum of the process radiation.

HSM of the process zone provides detailed knowledge about the braze metal transition. Thereby, the geometry of the melting filler wire and the wetting of the substrate are important process characteristics. The geometry of the melting filler wire significantly influences the shape of the reflected laser radiation from the process. The correlation is illustrated in Fig. 4, wherein the formation of the braze metal transition and the detected reflection are given starting from the laser beam impinging on the substrate with no filler wire interaction up to the formation of a stable brazing process.

The position of the footprint of the laser beam directly impinging on the substrate (no filler wire interaction) can be found in both image sequences (first image of each sequence in Fig. 4). It is indicated by the dashed yellow line in each image. The footprint of the laser beam is the only clear reference that can be found in the LRM-images. Hence, it is mandatory for correlating HSM and LRM.

The geometry of the melting filler wire and the position of the braze metal front on the substrate can only be found in the HSM-images. The position of the braze metal front (pink dashed line in **Fig. 4**) was determined in relation to the initial footprint of the laser beam in the HSM-images. In the depicted case the distance was 1.3 mm.

Considering the differing framerates of HSM (2 kHz) and LRM (200 Hz), every tenth high-speed-image was evaluated regarding the distance between braze metal front and initial footprint of the laser beam. The measured distances were applied for evaluating the LRM-images regarding detected radiation from the substrate. Thereby, the part of the detected radiation above the position of the braze metal front was cut off. The course of the seam edge was approximated with a square function (pink curve in Fig. 4) assuming symmetry of the seam.

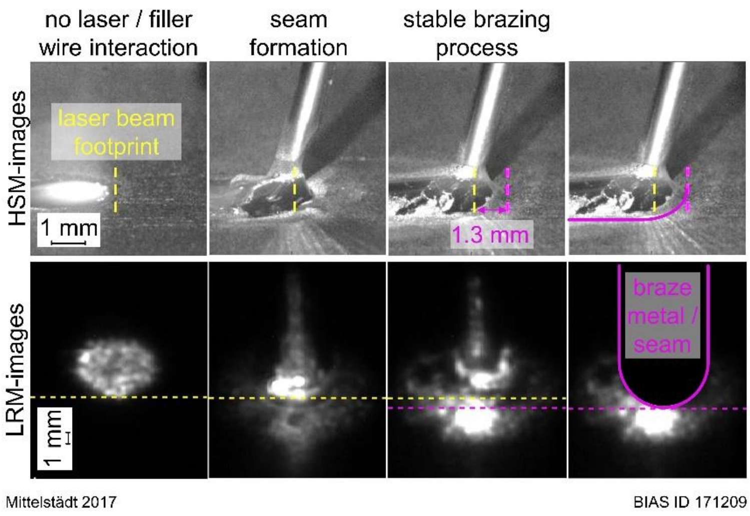


Fig. 4. Image sequence of synchronized LRM-images (upper sequence) and HSM-images (lower sequence).

The resulting intensity profile of the detected radiation coming from the substrate is given in Fig. 5 indicating the preheating capability of the reflected radiation qualitatively. The measurement shows a high-intensity part of the reflection in the center of the travel path directly at the braze metal front. Punctual measurement with a pyrometer in that area shows an average preheating temperature of 534 °C for the stationary process. In the surrounding areas the intensity of the reflection decreases rapidly. This observation could be due to the position of the LRM-camera, detecting directional reflected radiation from the center and diffuse reflected radiation from the edge regions of the processing zone. However, radiation from a wide area surrounding the seam could be detected indicating an also wide preheating. The cone-shaped geometry of the reflection could be ascribed to the initial round shape of the filler wire indicating that this form is conserved for some time within the laser/filler-wire-intersection zone.

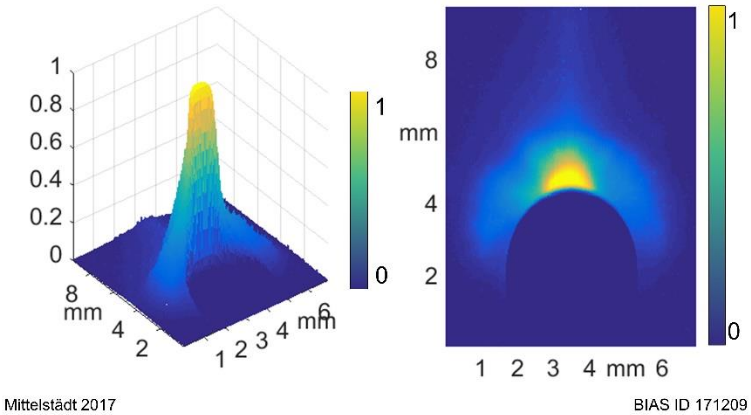


Fig. 5. Measured intensity profile of the reflected radiation from the substrate

To validate the detected intensity profile of the reflected radiation and provide further quantitative values, numerical modelling of the beam path was considered. Thereby, the in-process shape of the melting filler wire was detected from different angles (cf. Fig. 2) using HSM and image processing based on the canny edge detection method. An HSM-image that shows the geometry of the melting filler wire is given in Fig. 6 a. The detected geometry of the filler wire was used to interpolate a 3D-geometry-model of the filler wire, which is part of a ray-tracing model. The detected geometry is exemplified in Fig. 6 b, where it is highlighted by the pink curve. A profile of the resulting interpolated 3D wire model is depicted **Fig. 6 c** and Fig. 6 d.

The ray-tracing-model considers the intensity profile and beam attributes of the laser beam. Therefore, a beam measurement using a PRIMES high-power micro-spot-monitor was used. Furthermore, the model assumes an average absorptivity of the filler wire of 15.7 %, which leads to a temperature-rise of 1300 K of the filler-wire, which again is accordance with findings from Reimann et al., 2017. Thereby, overheating of the braze metal above its liquidus temperature is considered given the laser beam also impinges on already molten braze metal.

The results of the ray-tracing model are given in Fig. 6 e and Fig. 6 f. The numerically computed intensity profiles of the reflection also show the highest intensity in the center of the travel path right at the braze metal front, agreeing to the experimentally measured intensity profile. The intensity of the reflection also decreases in the surrounding areas, although not as rapidly as experimentally observed. This could be attributed to directed and diffuse occurring reflection in the experiment.

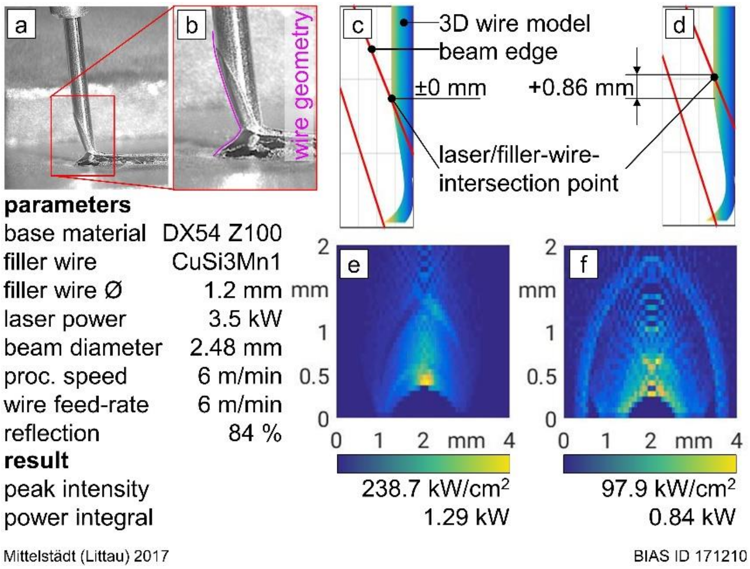


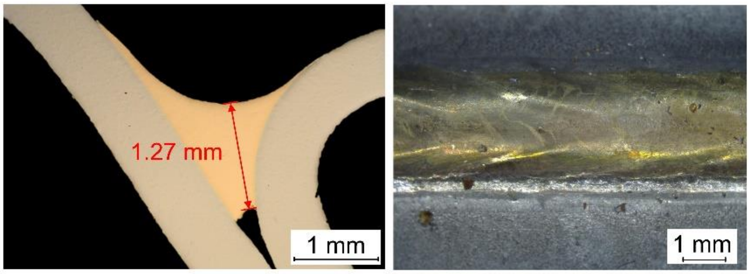
Fig. 6. Computed intensity profiles of the reflected laser radiation from the filler wire on the substrate for different laser/filler-wire-intersection points.

The shape and the quantity of the computed intensity profiles depends on the laser/filler-wire-intersection point. The laser/filler-wire-intersection point that were considered here are marked in Fig. 6 c and Fig. 6 d. In Fig. 6 c the laser beam and the filler wire intersect right where the geometry of the filler changes. In Fig. 6 d an offset of 0.86 mm between the geometry-change and the laser/filler-wire-intersection point is considered. In the former case the experimentally observed cone-shaped geometry of the reflection is missing in the computed intensity profile (Fig. 6 e). In the latter case, which results in the intensity profile illustrated in Fig. 6 e, the laser radiation is spread wider and therefore the peak intensity of the computed profile decreased from 238.7 kW/cm² to 97.9 kW/cm². Furthermore, the power integral decreased from 1.29 kW to 0.84 kW because more laser radiation was scattered relative to a lower laser/filler-wire-

intersection point. However, there is a slight discontinuity of the computed intensity occurring in Fig. 6 f indicating the intersection point was just too high, or the interpolated geometry of the modelled filler wire was not smooth enough.
All in all, the laser/filler-wire-intersection point does affect the rate of the laser power that is redirected onto the substrate and contributes to preheating. Considering LRM (Fig. 5) and the ray-tracing-analysis (Fig. 6) it can be assumed that a cylindrical part of the filler wire does affect the intensity profile of the reflection onto the substrate. Thereby, the computed intensity profiles given in Fig. 6 e and Fig. 6 f depict border-line cases of the actually utilizable reflected radiation. Therefore, a laser power between 0.84 kW and 1.29 kW could be used purposefully for preheating. That is between 24 % and 36.9 % of the expended laser power.

3.2. Fillet seam properties

To demonstrate the preheating capability of brazing in laser leading configuration flange joints and overlap joints were carried out. For flange joints a deep penetration of the grove of the joint could be determined metallographically, Fig. 7. This is comparable to two-beam laser brazing solutions, cf. Grimm et al, 2010. Moreover, high processing speeds along with excellent wetting as illustrated in Fig. 7 for brazing at 8 m/min is facilitated. The attainable processing speed and the excellent wetting demonstrate the potential of laser leading brazing. However, a deep penetration at this particular application is not necessarily desirable, since sheets with radii of 2 mm and more are common, which results in large joining gaps. Therefore, instead of deep penetration, gap bridging and a smooth transition between the sheets is often preferred, which is why preheating in this application is rather inhibiting. Nevertheless, joining sheets with small radii becomes feasible, providing more options construction-wise.



substrate	DX54 Z100 (0.75 mm)	brazing speed	8 m/min
braze metal	CuSi3Mn1 (Ø 1.2 mm)	wire feed rate	8 m/min
laser power	4.25 kW	beam angle	10°
beam diameter	2.48 mm	wire angle	30°
process gas	Argon (10 l/min)	sheet radius	1.5 mm

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Fig. 7. Seam appearance and respective cross-section for a 45°-flange joint.

An application that is more suitable for laser leading brazing is the lap joint, as illustrated in Fig. 8. Hence, the reflection-induced preheating leads to a reliable and robust wetting. In the depicted case the preheating contributed to a wetting length on the lower sheet of 2.46 mm, which is way more than the base material thickness of 1 mm. Furthermore, the top bead appearance shows a smooth seam edge on the lower sheet. Moreover, the wetting of the upper sheet was very good as the croos-sections shows a small reinforcement.

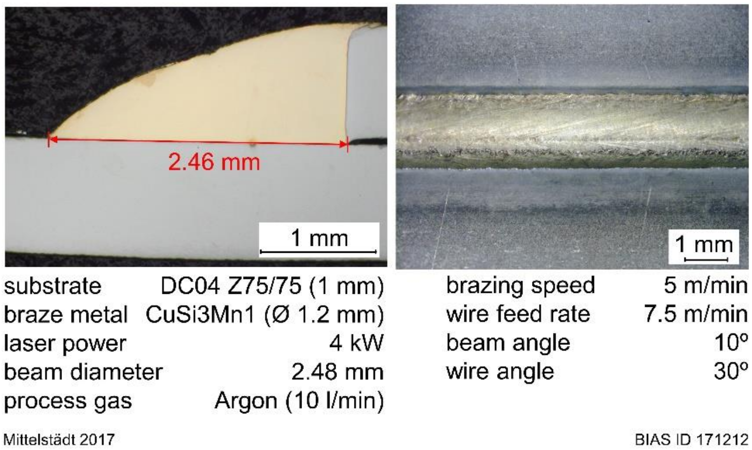

Fig. 8. Seam appearance and respective cross-section for a lap joint.

4. Conclusion

Laser brazing using copper-base filler material is a firmly established joining technology in today's automotive plants. Thereby, occurring reflected laser radiation and a resulting low process efficiency is tolerated because the joint requirements concerning seam quality in terms of a smooth wetting, low porosity and mechanical strength are mostly fulfilled. However, it is possible to make use of reflected radiation using laser brazing in laser leading configuration, which is desirable from an economical point of view.

A qualitative assessment of the reflections from a laser brazing process can be achieved by using a norrow-band-pass filtered standard CMOS-camera. In order to allocate the detected reflections to specific areas of the processing zone a synchronized high-speed camera can be used. Thereby, those parts of the detected reflections can be identified, which are coming from the substrate located right ahead of the braze metal front. This area of the processing zone is particularly interesting since the substrate is preheated there. Punctual measurement in that area shows a mean preheating temperature of 534 °C for the stationary process. Therefore, laser leading brazing facilitates a more efficient utilization of the expended laser power and resulting joint properties that are otherwise only reached by additional preheating measures or two-beam solutions, which result in overall higher system costs. The improvement in process efficiency could be classified exemplarily by means of a numerical ray-tracing approach to be in the range between 24 % and 36.9 %.

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