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Two-beam laser brazing of thin sheet steel for automotive industry using Cu-base filler material

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Abstract

This work shows the potential of two-beam laser brazing for joining both Zn-coated steel and 22MnB5. Brazing of Zn-coated steel sheets using Cu-Si filler wire is already state of the art in car manufacturing. New press-hardened steels like 22MnB5 are more and more used in automotive industry, offering high potential to save costs and improve structural properties (reduced weight / higher stiffness). However, for joining of these ultra-high strength steels investigations are mandatory. In this paper, a novel approach using a two-beam laser brazing process and Cu-base filler material is presented. The use of Cu-base filler material leads to a reduced heat input, compared to currently applied welding processes, which may result in benefits concerning distortion, post processing and tensile strength of the joint. Reliable processing at desired high speeds is attained by means of laser-preheating. High feed rates prevent significant diffusion of copper into the base material.

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Keywords: Laser beam brazing; Laser preheating; 22MnB5; Cu-base filler wire

1. Motivation

Novel lightweight design concepts introduced ultra-high strength steels (UHSS) like 22MnB5 to the industry. The superior mechanical properties of these materials result from a press-hardening process which combines forming and quenching leading to a more efficient process chain as it was discussed by Göschel et al. (2011).

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However the coating of UHSS, typically hot dip aluminized (AlSi), is a drawback to the state of the art joining techniques as e. g. Kim et al. (2011) found that the coating can substantially add to the reduction of the strength of laser welded lap joints.

Another challenge pointed out by Neugebauer et al. (2009) is that the strength of press-hardened UHSS is lowered in consequence of thermal joining processes. An answer to this challenge might be the substitution of welding by brazing. As Wilden et al. (2009) suggest, that there is great potential concerning process efficiency and joint properties meaning a reduced thermal load as well as class-A seam appearance. Further on investigations by Sevin et al. (2009) demonstrate superior joint strength for brazing high strength steel using Cu-base filler wire. However for brazing of AlSi-coated 22MnB5 further investigation is required.

As presented by Hornig (2006) laser beam brazing is a state of the art technology in the automotive industry, whereas an evolution of the technique is required to extend the field of application. Novel joining solutions like two-beam laser brazing, which was presented by Hoffmann et al. (2004), show excellent gap compensation as well as an advanced accessibility of the joining area. Additionally investigations by Grimm et al. (2010) demonstrate high achievable processing speed.

2. Aim and Approach

This work shows the potential of two-beam laser brazing of thin sheet steels using Cu-base filler material. One objective of this work is to avoid penetration of copper into the base material along grain boundaries often referred to as liquid metal embrittlement. This is reached by high processing speeds resulting in a reduced energy input and interaction time. Hereby the field of application for brazing using Cu-base filler material shall be enhanced.

Consequently two-beam laser brazing of press-hardened 22MnB5 is investigated. To meet the advanced mechanical properties of this material high strength Cu-base filler material is used to gain the highest possible joint strength.

3. Experimental

Nomenclature

1 (index)	-	Preheating laser beam
2 (index)	-	Brazing laser beam
b	in mm	Wetting length of the lower sheet
BPP	in mm*mrad	Beam parameter product
d_0	in µm	Fiber core diameter
d_f	in mm	Focus diameter
Δf	in mm	Focal position
M	-	Magnification
P_L	in kW	Laser power
v_L	in m/min	Processing speed
v_D	in m/min	Wire feeding rate
α	in °	Angle of preheating laser beam
β	in °	Angle of brazing laser beam
γ	in °	Angle of the wire axis
λ	in nm	Wave length of laser radiation

3.1. Material

In this work fillet welds on lap joints of thin sheet steels are investigated and assessed with respect to SEP 1220 (2011). The sheet samples were mechanically cut from blanks. Dimensions of the sheets and the length of the overlap (16 mm) have been selected as in accordance with the guideline. Properties of the investigated materials are given in table 1.

Table 1. Properties of the investigated materials according to ThyssenKrupp Steel AG (2013 / 2014) and Berkenhoff GmbH (2009).

Material	Thickness / diameter	Dimensions	Coating thickness	Melting range	Tensile strength
22MnB5 AS150	1.5 mm	200 mm x 100 mm	25 µm	-	1500 MPa
DC04 ZE 75/75	1 mm	200 mm x 100 mm	7,5 µm	-	270 MPa – 350 MPa
CuSi3Mn1	1.2 mm	-	-	965 °C – 1035 °C	350 MPa
CuSn6	1.2 mm	-	-	900 °C – 1040 °C	349 MPa
CuMn13Al8	1.2 mm	-	-	945 °C – 985 °C	900 MPa

3.2. Set-up

The set-up used for processing is illustrated in figure 1, basically consisting of a leading laser beam which is preheating the fusion zone, a filler wire supply and a trailing laser beam designated to melt the filler wire. Experiments were carried out using two separate solid-state laser devices by Trumpf. This allowed to adjust the laser power for preheating and wire melting independently. To support the wetting in the fusion zone a wide and homogenous temperature field on the sheet surface is intended. This was accomplished due to a wide preheating laser spot featuring a top hat intensity profile which is achieved within the beam waist of multimode laser devices. Therefore the laser optics in the light path of the preheating laser beam were selected to achieve a high magnification. In this case the ratio of focal lengths lead to a magnification of $M_1 = 7$ resulting in a focus diameter of 4.2 mm with the fiber core diameter of the feeding fiber being 600 µm. Characteristics of the laser beams are listed in table 2. A close-up illustration of the processing zone is given in figure 1a specifically showing the arrangement of laser beams and filler wire. The geometrical arrangement, especially the steep inclination of the wire axis, was selected to enable processing of complex shaped parts with small radii. Furthermore the preheating laser beam impinged right in front of the wire tip, ensuring maximal efficiency of the preheating process. Moreover the brazing laser beam was situated on the filler wire tip keeping the majority of the radiation away from the workpiece. Further on the processing head was not additionally inclined towards the fillet of the joint. As shielding gas Argon (20 l/min) was used.

Table 2. Characteristics of the laser beams.

Preheating laser beam		Brazing laser beam	
Beam source	Trumpf HL 4006 D	Beam source	Trumpf TruDisk 8002
Maximum power	4 kW	Maximum power	8 kW
wave length	$\lambda_1 = 1064$ nm	wave length	$\lambda_2 = 1030$ nm
fiber core diameter	$d_{0,1} = 600$µm	fiber core diameter	$d_{0,2} = 600$µm
Magnification	$M_1 = 7$	Magnification	$M_2 = 1$
Focus-diameter	$d_{f,1} = 4.2$ mm	Focus-diameter	$d_{f,2} = 600$ µm
Beam parameter product	$BPP_1 = 28$ mm*mrad	Beam parameter product	$BPP_2 = 28$ mm*mrad

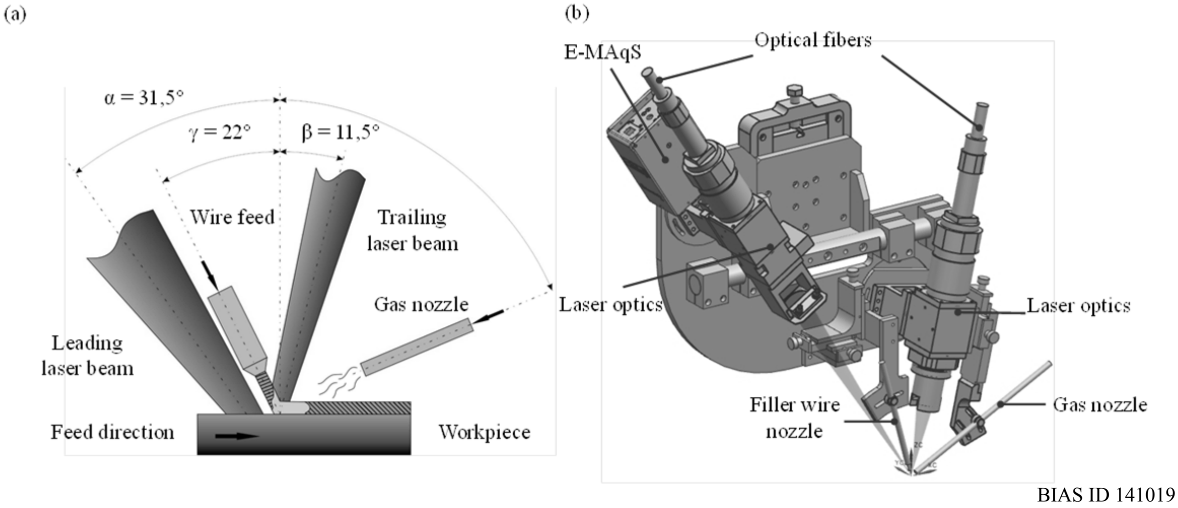

Fig. 1. Set-up used for experiments (a) Close-up illustration; (b) Two-beam processing head.

Additionally the processing head depicted in figure 1b featured a CCD-camera based temperature measuring system E-MAqS developed by Fraunhofer IWS, which was mounted to the preheating laser optics. Detection took place coaxially with the light path of the preheating laser beam via selective optical components guiding radiation at a specific wavelength (740 nm), which was emitted from the workpiece, to the camera. The measuring instrumentation allowed to detect the temperature on the sheet surface caused by the preheating process in the range of 800 °C to 1450 °C.

3.3. Procedure

First brazing of electrolytic galvanized DC04 sheets using CuSi3Mn1 filler wire was investigated. Subsequently investigations aimed on joining hot dip aluminized press-hardened 22MnB5 sheets. Therefore CuSn6 filler wire was used and, with respect to the advanced mechanical properties of the base material, a high strength copper alloy CuMn13Al8 was introduced to attain a superior joint strength. The characterization of the joints was done metallographically based on cross-sections and by quasi-static tensile shear testing. The microscopic inspection of the seams focused on measuring geometric properties of the joints. Furthermore the braze/steel interface of the joint was investigated. Additionally the influence of the process heat on the high strength base material was identified by means of hardness profiles along the cross-sections. All testing was performed with respect to SEP 1220 (2011).

4. Results and discussion

4.1. Two-beam laser brazing of DC04

Joining DC04 sheets with CuSi3Mn1 filler wire could be achieved up to a brazing speed of 5 m/min producing class-A seam surfaces. A joint obtained with two-beam laser brazing is presented in figure 2. Microscopic analysis of the cross-sections showed no melting of the base material (figure 2b). Furthermore no penetration of braze material into the base metal along the grain boundaries at the interface neither to the lower sheet (figure 2c), nor to the upper sheet (figure 2d) could be detected. However, the base material adjacent to the joint showed newly formed globulitic microstructure.

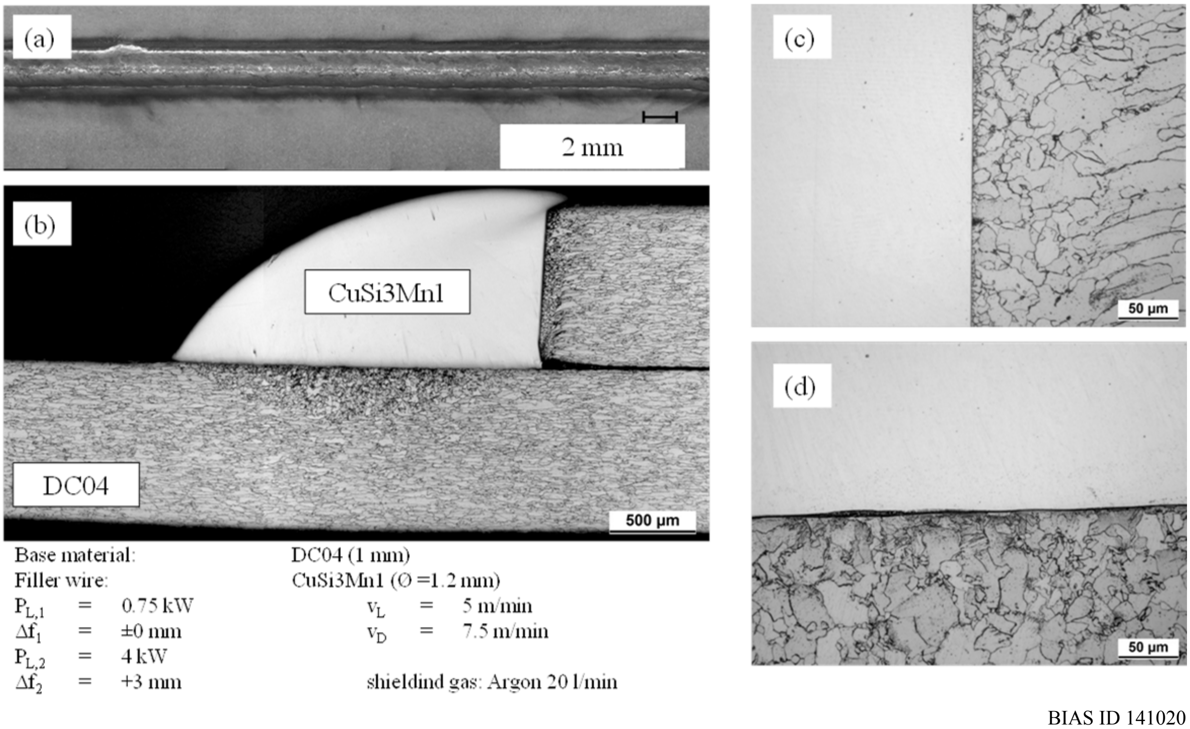

Fig. 2. Joint obtained for brazing DC04 (1 mm) with CuSi3Mn1 (Ø = 1.2 mm) filler wire (a) Top bead appearance of the weld seam; (b) Macro-section of the joint; (c) Micro-section at the transition to the upper sheet (d) Micro-section at the transition to the lower sheet.

Further investigations revealed that a variation of the preheating laser power had a significant effect on the properties of both the base material and the geometry of the seam. In particular the wetting of the lower sheet was increased for enhanced preheating laser power. The effect is depicted in figure 3 comparing cross-sections showing a wetting length of 2.15 mm brazed with 0.5 kW preheating laser power and a wetting length of 2.56 mm brazed with 1.5 kW preheating laser power, respectively. Due to higher surface temperatures prevailing at increased preheating laser power the wetting is improved.

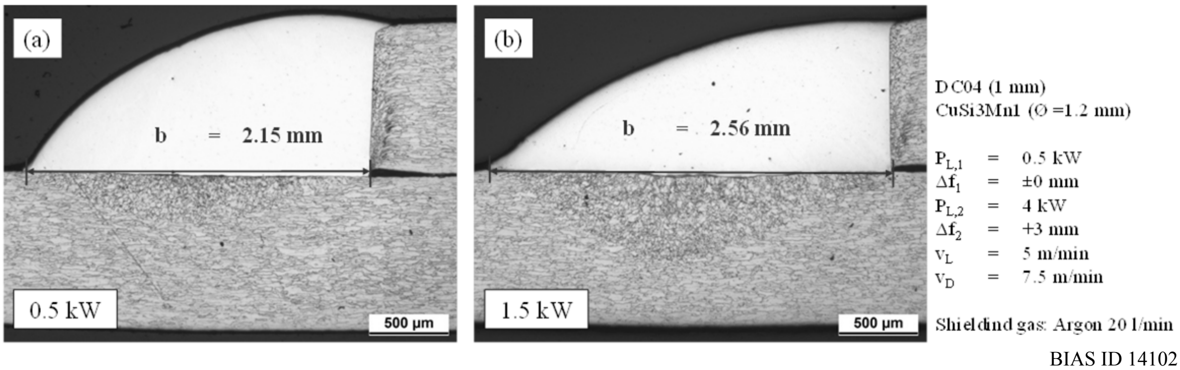

Fig. 3. Comparison between cross-sections of specimens brazed with varied preheating laser power; (a) 0.5 kW preheating laser power; (b) 1.5 kW preheating laser power.

Aside from the increasing thermal load, slight melting of the base material occurred for a preheating laser power of 1.5 kW. The effect is shown in figure 4. Furthermore a wider intermetallic compound layer could be found for 1.5 kW preheating laser power. Brittle intermetallic compound layers can lower the strength of the joint as they lower ductility and aid crack formation and propagation, which could result in early joint failure. In this case a preheating laser power of 1.25 kW should not be exceeded.

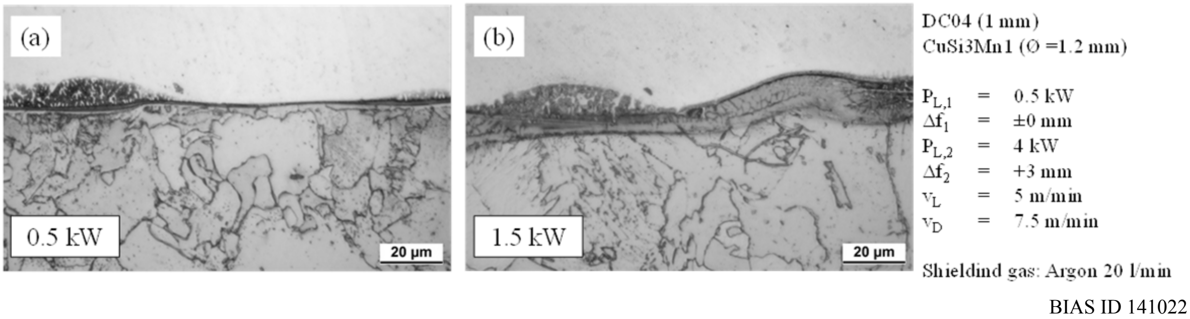

Fig. 4. Micro-sections of the interface between Base material and braze metal; (a) 0.5 kW preheating laser power; (b) 0.5 kW preheating laser power.

A gap of 0.8 mm could be compensated without any parameter adjustment, see figure 5. However the cross-section in figure 5b shows a slight melting of the upper sheet. This is because the heat conduction is constrained due to the presence of a joining gap, while no other process parameter was changed. Nevertheless the failure in quasi-static tensile shear testing occurred in the base material for all tested specimens. The results of the quasi-static tensile shears test are exemplarily presented in figure 6 for technical zero gap conditions and a gap of 0.8 mm, respectively.

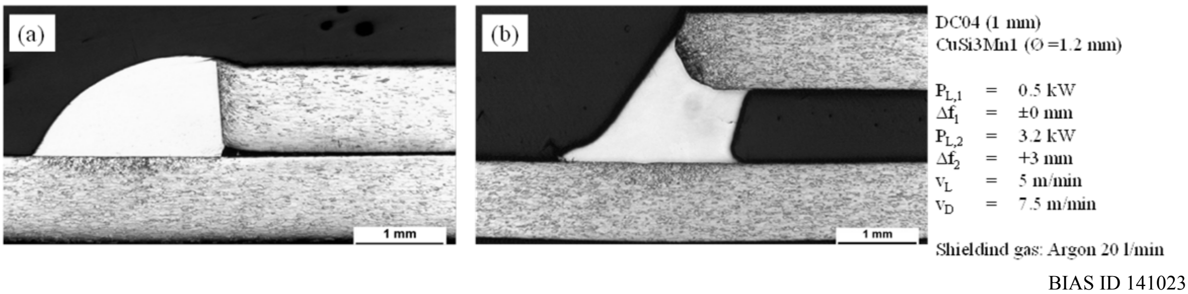

Fig. 5. Cross-sections taken from the specimen evaluated in quasi-static tensile shear test (a) 0 mm gap (b) 0.8 mm gap.

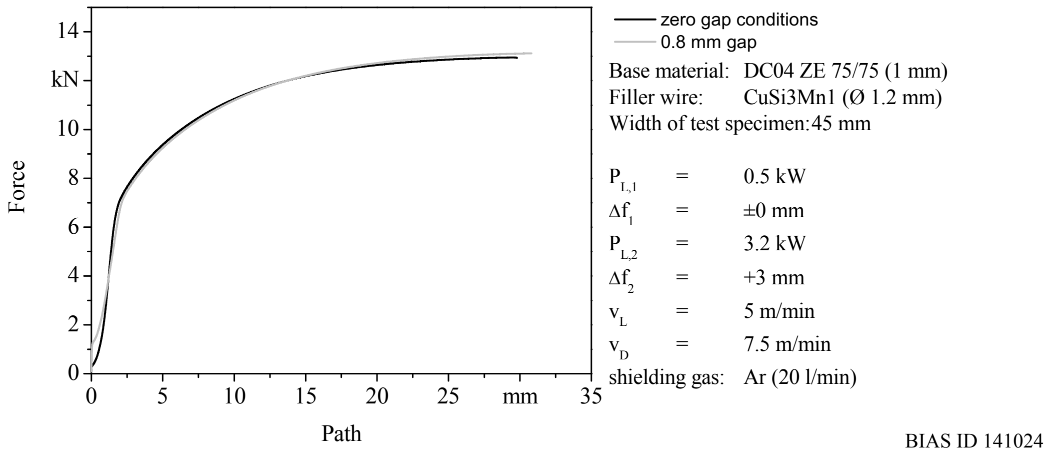

Fig. 6. Results of quasi-static tensile shear test at 0 mm gap and 0.8 mm gap.

4.2. Two-beam laser brazing of 22MnB5

The effect of the preheating on the base material was investigated preliminary to joining experiments. The effect of laser preheating on 22MnB5 for a surface temperature of 900 °C which is the solidus temperature of the CuSn6 braze metal is presented in figure 7. The cross-section taken from the sample shows a distinct heat affected zone (HAZ) (see figure 7a). The hardness profile depicted in figure 7b was measured 200 µm underneath the surface. It shows a significant loss of hardness in the HAZ as a result of laser preheating to the solidus temperature of the CuSn6 filler material. Therefore it is obvious, that thermal damage of the base material cannot fully be avoided. Furthermore the AlSi-coating was unaffected by the preheating process.

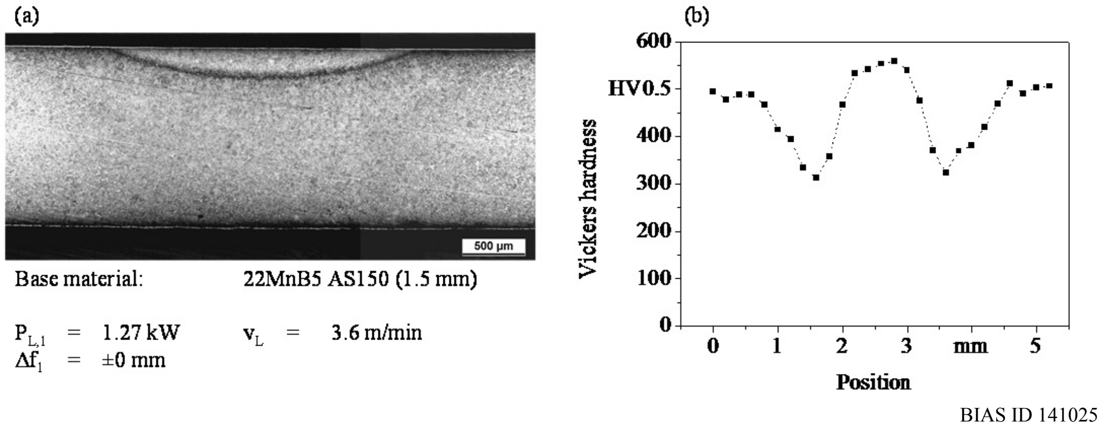

Fig. 7. (a) Cross-sections from specimen preheated to 900°C surface temperature; (b) related hardness profile of the cross-section.

Brazing experiments of the hot dip aluminized press-hardened 22MnB5 sheets showed that the AlSi-coating was impeding the joining process causing insufficient wetting of the lower sheet by the braze metal. The effect is shown in figure 8 for brazing with CuSn6 filler wire. Looking at the shape of the HAZ it seems probable that the temperature closer to the grove of the fillet was lower than the temperature towards the edge of the seam. This is because the AlSi-coating was inhibiting the wetting and constraining further heat input by the braze metal. The complete wetting of the edge of the upper sheet could be achieved because it was uncoated. This was due to the previously executed cutting process leaving a bare metallic surface. All in all no homogenous processing using the CuSn6 filler wire could be achieved.

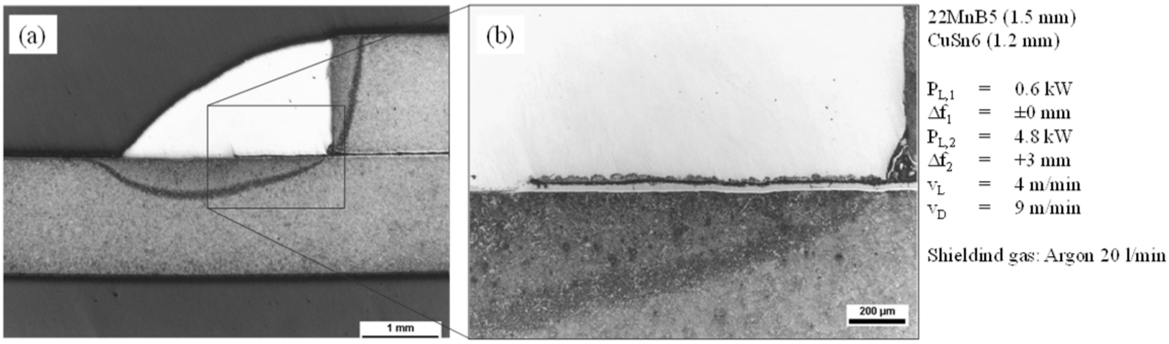

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Fig. 8. Cross-section showing incomplete wetting because of the high temperature resistant coating (a) Macro-section of the joint; (b) Micro-section of the interface between base material and braze metal.

For brazing experiments using the CuMn13Al8 filler wire, homogenous class-A seams could be attained. A processing speed of 4 m/min was achieved. However, for a complete wetting by the braze metal local melting of the base material was inevitable (figure 9). This could be prevented by adjusting the intensity profile of the preheating laser beam keeping the highest surface temperature underneath the melting temperature of the base material. It is noticeable that complete wetting was achieved with only 0.6 kW preheating laser power. Reflecting that 1.27 kW were required to heat the sheet surface to 900 °C at a comparable processing speed (cf. figure 7) the surface temperature required for a complete wetting is significantly lower than 900 °C. Therefore it is not necessary to preheat the surface to the operating temperature of the braze metal (cf. table 2)). The measured hardness profile related to the cross-section in figure 9b reveals a loss of hardness of the base material, similar to the effect of the preheating at 900 °C. Therefore it seems probable that the filler wire is overheated by the brazing laser beam when coming into contact with the sheet surface providing the rest of the energy needed for the wetting resulting in a similar influence on the base material. However the lowest hardness of the joint could be measured in the filler material.

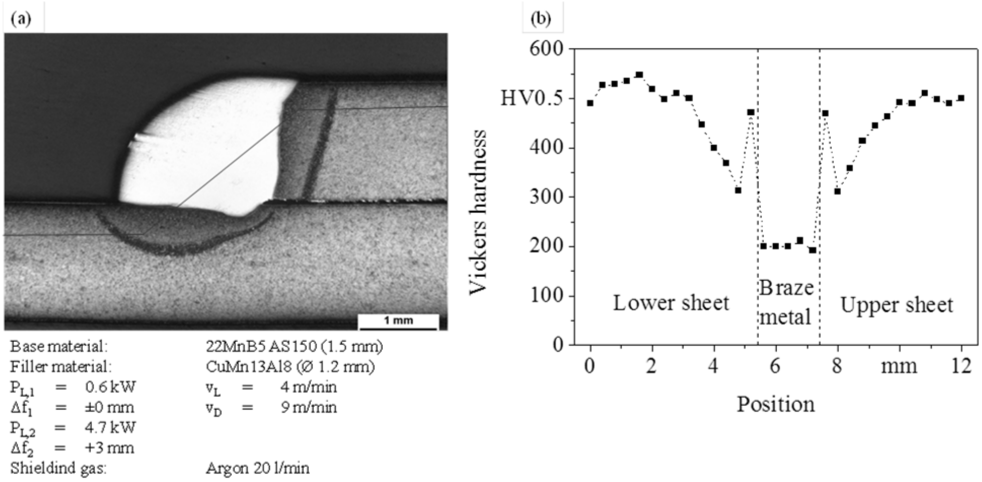

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Fig. 9. Cross-section showing of the lap joint between 22MnB5 sheets using CuMn13Al8 filler wire.

The failure of all the specimens investigated in quasi-static tensile shear test occurred in the seam at the transition to the upper sheet of the joint. A gap of up to 0.8 mm between the sheets could be compensated with constant parameters. The highest joint strength of 35.1 kN was measured for zero gap conditions with the joint strength decreasing for an increasing gap. The results are illustrated in figure 10. It is most likely that failure occurred due to a concentration of the mechanical stress at the grove of the fillet with the effect being amplified for larger gaps.

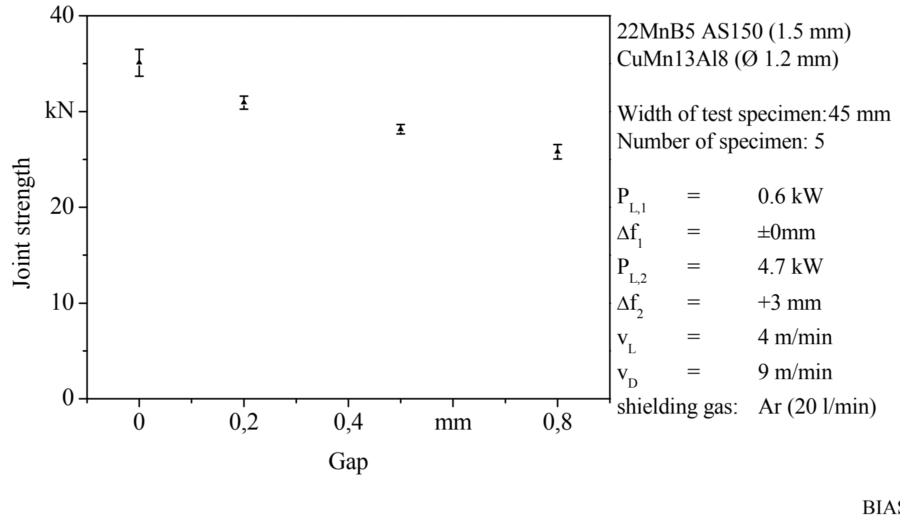

Fig. 10. Joint strength of 22MnB5 lap joints for a variation of the gap between the sheets.

Generally for brazing lap joints, gaps between the sheets can be used to increase the joint strength by filling the gap with braze metal thanks to the capillary effect as demonstrated by Sevim et al. (2009). However, in the presented experiments an enhancement of the joint strength could not be achieved. The authors assume that this is because the AlSi-coating impeded a wetting in between the sheets, considering that the preheating laser beam could not activate the surface.

Nevertheless the highest measured joint strength was 35.1 kN which is equivalent to 523.49 MPa with respect to the minimal measured side length of the seam, although an attainable joint strength of 900 MPa for the filler wire is specified by the manufacturer. Aside from the fact that stress concentration in the grove of the fillet is inevitable for lap joints which is lowering the ultimate strength, process-related alloying of the filler material has to be considered. Because of a slight melting of the base material a dilution of Fe into the braze metal is inevitable. Therefore an excessive formation of brittle intermetallic compounds could lower the strength of the joint. Furthermore the remainder of the AlSi-coating has to be considered since the presence of intermetallic phases is a well-known constraint joining 22MnB5. However it could not be clarified by optical microscopy what happened to the AlSi-coating at the interface between braze metal and the base material. Hence further investigations using WDS or EDS is necessary to clarify the remainder of the AlSi-coating.

5. Conclusion

For two-beam laser brazing of DC04 using CuSi3Mn1 filler wire class-A surfaces could be attained up to a process speed of 5 m/min, avoiding significant diffusion. Furthermore the excellent gap bridging capabilities of two-beam laser brazing could be demonstrated.

Experiments aiming at press-hardened 22MnB5 thin sheet steel demonstrated that two-beam laser brazing is feasible. However the AlSi-coating of the sheets is inhibiting wetting. Hence an activation of the sheet surface by means of preheating is mandatory to allow wetting by the braze metal. This may also explain, why filling the gap with braze metal was not observed, since an activation of the surface in-between the sheets could not be achieved.

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