LASER-MIG HYBRID WELDING OF ALUMINIUM TO STEEL – EFFECT OF PROCESS PARAMETERS ON JOINT PROPERTIES

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ABSTRACT

Laser MIG hybrid welding was recently suggested as a feasible process for joining of aluminium to steel for both structural as well as tailored blank applications. To promote an understanding of the process and the effect of process parameters on joint properties, laser MIG hybrid welding experiments were performed to join aluminium alloy AA6016 to DC05 zinc-coated steel sheets, in the thickness range of 1 mm, in a butt joint configuration. Among the process parameters varied were laser power, MIG arc power, wire feed rate, welding speed and arc position relative to the abutting edges. By metallographic cross-sections and tensile tests, the effect of these process parameters on joint properties such as wetting length, intermetallic phase layer thickness and tensile strength could be elucidated. Based on these results, a process parameter envelope resulting in adequate and reproducible joint properties (sound weld bead, sufficient and regular wetting, thin intermetallic phase layer, tensile strength exceeding 180 MPa) was established. Within this parameter envelope, corrosion behaviour was rated not critical, and forming behaviour showed promising results.

IIW-Thesaurus keywords: Aluminium; Hybrid laser arc welding; Mechanical properties; Steels.

1 Introduction

In light-weight design, the use of hybrid structures from mixed materials such as aluminium and steel is currently widely discussed in order to achieve a loss of structural weight whilst maintaining or even improving structural performance. For thermal joining of aluminium to steel, a wide variety of processes was suggested in the past decades (see survey by Thomy ***et al.*** [1]).

The fundamental challenge lies with the formation of brittle intermetallic phases (such as Fe_2Al_5, $FeAl_3$), which may have a significant detrimental effect on the mechanical properties of the joints [2, 3]. As the formation of these phases is mainly driven by diffusion [4], the time-temperature cycle to which the joining zone is subjected during joining is of significant importance. Therefore, processes allowing precise control to potentially minimize heat input (by an optimization of process parameters) are required.

Aside from advanced arc-based processes (CMT- and ColdArc-process [5, 6]) with controlled heat input, mainly laser-based processes were considered with that aim in the past decade [7-10]. Although feasible joints with a static strength in the range of 170 MPa to 200 MPa and a phase layer thickness well below 10 µm were regularly obtained, limitations in processing speed, fit-up and clamping tolerances or process stability have so far often limited their practical use.

Most recently, the use of a hybrid welding process was suggested by Kreimeyer and Vollertsen to overcome some of these limitations, also aiming at improving wetting length and minimizing phase layer thickness [11]. In this process, which was developed further by the authors [12-17], a laser beam (CO_2, Nd:YAG, Yb-fibre or Yb:YAG) and a MIG arc operated in the pulsed mode are combined. In Figure 1, the process principle is depicted.

The aluminium and the steel sheets are arranged preferably in a butt joint configuration, also allowing a gap. The laser beam is positioned on the aluminium side. During joining, the edge of the aluminium sheet is molten, and together with the molten wire, the gap between the aluminium and the steel is bridged and the steel is wetted by the aluminium melt. The main task of the sub-process MIG welding is to create a large melt pool and to supply filler material to the melt pool, to influence the metallurgy of the weld and increase the melt volume further, thus contributing to improved wetting. The sub-process laser beam welding, which is operated in keyhole mode to supply the heat uniformly in the direction of depth, enables an increase in the welding speed by stabilizing the MIG

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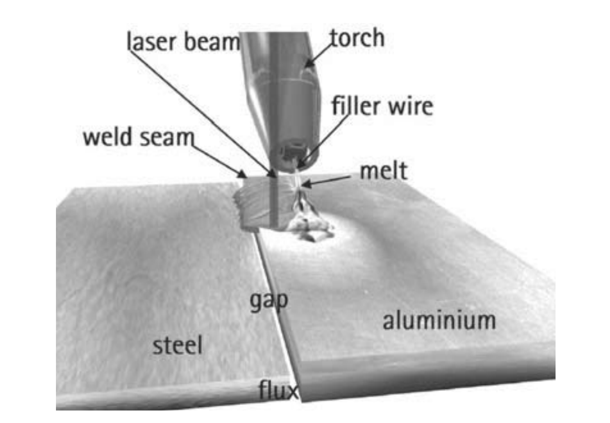


Figure 1 – Principle of the laser MIG hybrid joining process

arc, thus reducing heat input and, as a consequence, the negative effects of heat input such as excessive phase layer formation and distortion.

In general, the advantage of this process compared to most of the state-of-the-art laser-based processes is its ability of gap bridging of up to 1 mm [11]. Moreover, compared to arc-based joining processes, a higher processing speed, which is in excess of 6 m/min in thin-sheet applications, can be achieved [15].

Aside from the arc characteristics and pulse parameters, the governing parameters of this process are laser power, welding speed, MIG power, wire feed rate and the position of the MIG arc relative to the gap. All these parameters have to be optimized in view of both obtaining an adequate weld in the aluminium and a sufficient wetting of the steel with minimum intermetallic phase layer. Thus, the challenges of hybrid welding of aluminium are combined with the specific challenges of joining dissimilar materials. The effect of the governing parameters on process and properties will be discussed in the next sections. Moreover, the challenges associated with formability and corrosion of weldments produced within an optimized parameter envelope will be addressed.

2 Aim and scope of the investigations

The investigations reported and discussed in the following were aimed at contributing to an improved understanding of the effect of process parameters on joint properties in laser MIG hybrid welding of aluminium to steel and of the formability and corrosion behaviour of the joints. To this end, the governing process parameters in Nd:YAG laser MIG hybrid welding of aluminium to steel sheet material, in a butt joint configuration, were systematically varied, and the results were subjected to metallographic examinations and tensile testing. Based on an evaluation of phase layer thickness, wetting length and static strength, correlations between process parameters and process results were identified and used as a basis for developing a process parameter envelope. Within this process parameter envelope, specimens were produced and subjected to bend testing, hydromechanical deep-drawing and corrosion testing.

3 Experimental set-up, materials, methods and programme

3.1 Set-up

The laser MIG hybrid welding experiments were performed using a Trumpf HL 4006D lamp-pumped Nd:YAG laser, and a Dalex Vario MIG 400L(W)-B MIG power source (operating in pulsed mode) together with an Abicor Binzel MIG torch and an Abicor Binzel wire feeder. Both heat sources were combined in a hybrid welding head. The projection of the filler wire on sheet surface (approximately the arc foot point) was positioned 4 mm behind the laser spot; torch inclination was 35° to the laser beam. The laser spot was directed onto the aluminium sheet with focus on the sheet surface at a distance of 0.5 mm to the sheet edge. The distance of the arc foot point to sheet edge was among the parameters varied (see below). Shielding gas (argon) was fed through the MIG torch at a flow rate of 17 l/min.

3.2 Materials

The joining experiments were carried out on the material combination AA6016 T4 (thickness 1.15 mm) and DC05+ZE (1 mm). SG-AlSi 12 (diameter 1.2 mm) was used as filler wire. Prior to joining at zero gap conditions, the sheets were mechanically cut into strips; no further edge preparation was applied. The sheets were cleaned with alcohol; flux (Fontargen F400NH) was applied to the uncoated edge of the steel sheet primarily to break up oxide layers on the aluminium and support the wetting process.

3.3 Methods

Aside from evaluating seam surface quality and the results of static tensile tests, all welded specimens were subjected to metallographic analysis, quantifying the micro-geometrical parameters of the welds. In particular, wetting length and seam reinforcement on top and bottom were measured by optical microscopy (magnification 20x) (Figure 2).

Moreover, phase layer thickness (Al_5Fe_2) on the top, bottom and face side, was measured at three equally-distributed points and then the averages were measured by optical microscopy (magnification 1000x, molybdenum-based etchant).

The static tensile tests were carried out on the basis of DIN EN 895 and DIN EN 10002-1. For each parameter

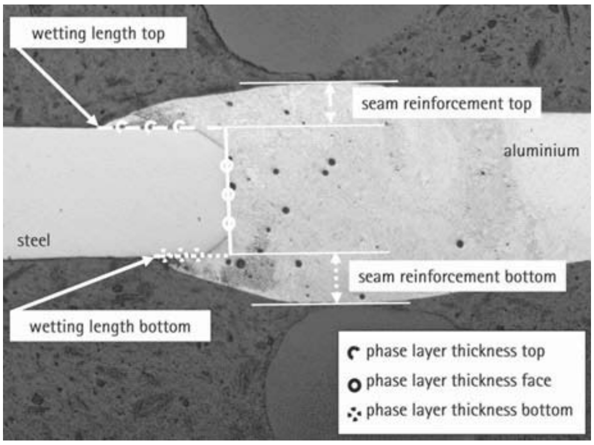


Figure 2 – Micro-geometrical parameters for seam assessment

setting three specimens (where available) were taken from one weld and tested to ultimate load without prior machining of the seam surface. Tensile strength was then calculated relating to the aluminium section.

For assessing formability, a non-standard longitudinal bend test (bending angle 180°, bend radius 10 mm) was applied. Subsequently, the specimens were inspected for transverse cracks and delaminations (using longitudinal cross-sections taken from the formed zone). Moreover, test specimens, produced by using an optimized parameter set, were subjected to hydromechanical deep-drawing at LFT Chair of Manufacturing Technology, University Erlangen-Nuremberg to produce demonstrator parts. These were then visually inspected for surface cracks.

Corrosion testing was performed at ISF Welding and Joining Institute, RWTH Aachen on test specimens produced by using an optimized parameter set. After cathodic dip coating (KTL) at standard conditions and parameters used in the automotive industry, and after applying a scratch pattern (one longitudinal and one transverse scratch in the coating in the weld zone), salt spray testing (10 cycles) was performed according to the automotive standard VDA 621 415. Aside from optical inspection of the specimen surfaces for rust, cross-sections were investigated for traces of intercrystalline corrosion.

3.4 Experimental programme

The experimental programme was designed to elucidate the effect of the governing parameters, laser power, MIG power (by varying current), welding speed, wire feed rate and position of the MIG arc relative to the aluminium sheet edge, on joint properties. Starting from basic parameter settings resulting in adequate joints (Table 1), the process parameters were varied individually whilst keeping all other parameters at the constant level of the basic parameter setting.

Table 1 – Basic parameter setting

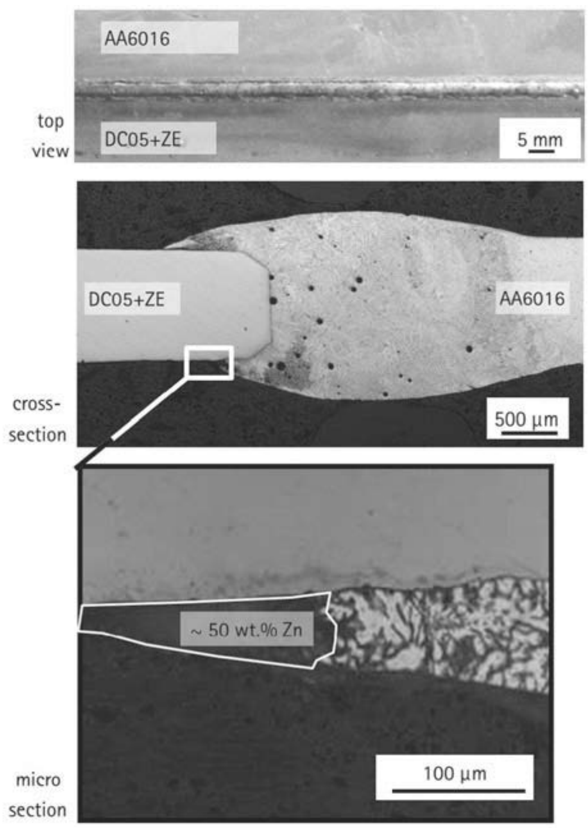
Parameter	Unit	Value
Laser power	W	2 400
MIG power	W	2 240
Welding speed	m/min	6
Wire feed rate	m/min	6.2
MIG position	mm	+1.5

Table 2 gives the parameter variations. Note that the MIG position is measured as distance of the projection of the filler wire (approximately the arc foot point) to the edge of the aluminium sheet, with negative values indicating a position on the steel sheet.

Moreover, to contribute to the development of a process parameter envelope based on an optimized parameter setting, a proportional parameter variation was performed, increasing welding speed whilst keeping constant:

Table 2 – Parameter variations

Parameter	Unit	Variation
Laser power	W	2 000/3 400
MIG power	W	2 100/3 800
Welding speed	m/min	5/7
Wire feed rate	m/min	4.2/8.2
MIG position	mm	-0.5/+3.5



(Laser power 2 400 W, MIG arc power 2 490 W, welding speed 6 m/min, wire feed rate 6.2 m/min, MIG position + 1.5 mm.)

Figure 3 – Top view, cross-section and micro section of a laser MIG hybrid welded aluminium-steel specimen

- total heat input per unit length,
- ratio of heat input by laser beam and by MIG arc,
- ratio of wire feed rate and welding speed.

Within this parameter envelope, and at an optimized parameter set, test specimens for assessing formability and corrosion behaviour were produced.

4 Results

4.1 General observations

Figure 3 gives the top view, the cross-section and a micro section of a typical aluminium-steel joint obtained by laser MIG hybrid welding using optimized parameter settings. A typical bottom view for the same welding parameters as in Figure 3 is given in Table 3 for a welding speed of 6 m/min.

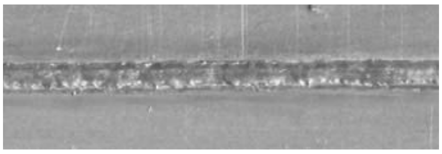
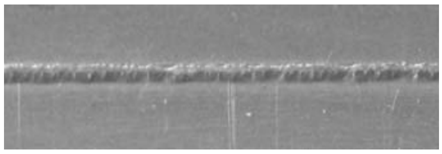
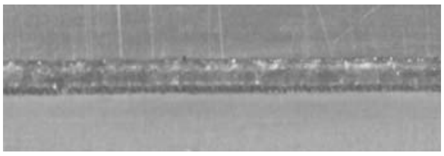
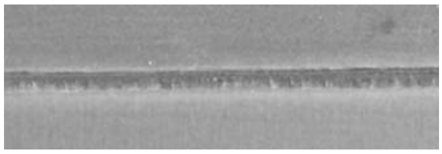
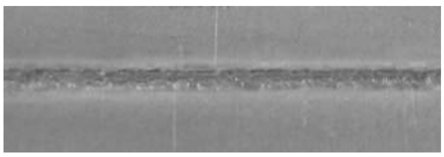
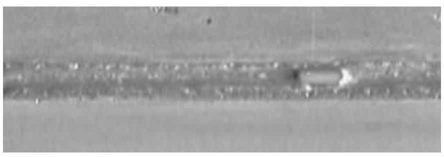
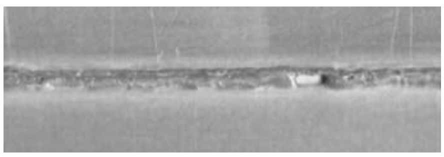
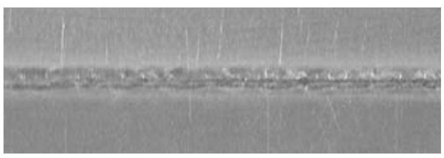
A brazed bond is created between the steel and the aluminium melt. It is obvious that the weld seam in the aluminium is smooth, and its width and the wetting length are fairly constant over the total seam length. In particular, no weld sagging, undercut or excessive spatter were observed. There was no melting of the steel sheet, and the weld showed only few small pores close to the face side of the steel sheet. Hot cracks were not found. The dark areas in the tip of the wetted zone were identified to be zinc-rich by means of EDX.

4.2 Effect of process parameters

In the following, the effects observed for a variation of laser power, MIG power, welding speed, wire feed rate and MIG position and of a proportional variation of welding speed (see above) will be reported.

Varying laser power between 2 000 W and 3 200 W at otherwise unchanged parameters, a slight trend towards an increase in intermetallic phase layer thickness on top, bottom and face side with increasing laser power was found (Figure 4), however, staying below approximately 4 µm. For a laser power of 3 400 W, a marked increase in phase layer thickness to 12 µm on the average at significant scatter was observed, and cracking occurred without external load. However, for all other laser powers, tensile strength remained well in the range of 180 MPa on the average, and seam reinforcement and wetting length (0.8 mm to 1.2 mm on the average) were also not affected significantly.

Table 3 – Influence of welding speed during proportional variation of process parameters

Welding speed [m/min]	Top side	Root side
5		
6		
7		
8		
9		

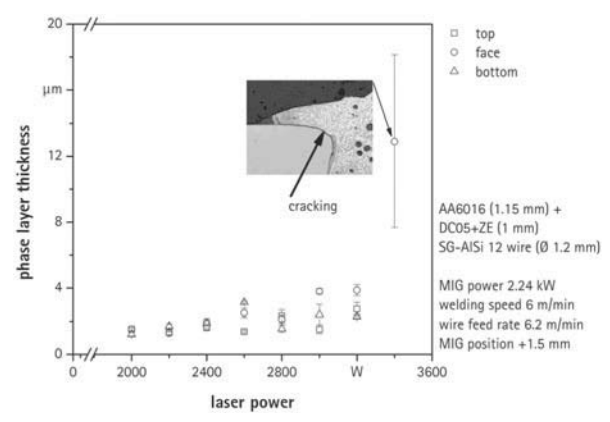


Figure 4 – Effect of laser power on phase layer thickness

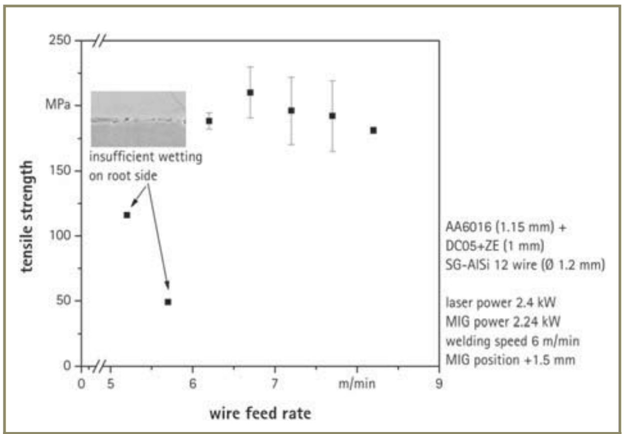


Figure 5 – Effect of wire feed rate on tensile strength

Comparable, but less pronounced results were found for the effect of MIG arc power. Again, the phase layer thickness was less than 4 µm for all arc powers. However, the regularity of the seam especially in view of wetting length (which was still in the range of 0.8 mm to 1.2 mm) deteriorated slightly, and scatter in the tensile tests increased with increasing MIG power. Above a MIG power of 3 200 W, average tensile strength was reduced from approximately 180 MPa for all other MIG powers to 150 MPa.

Welding speed at otherwise unchanged parameters (especially wire feed rate) had some influence on wetting behaviour. If welding speed was increased to more than approximately 6.5 m/min for a wire feed rate of 6.2 m/min, regular wetting at the bottom side no longer occurred. However phase layer thickness (<< 4 µm) in the areas wetted was not affected. In the case where regular wetting was obtained, tensile strength was again in the range of 180 MPa on the average.

At a welding speed of 6 m/min, wire feed rate was varied between 4.2 m/min and 8.2 m/min (Figure 5). Below a wire feed rate of 6.2 m/min, wetting was insufficient to non-existing. This had a detrimental effect on tensile strength, which was drastically reduced from conveniently more than 180 MPa to well below 120 MPa. In those areas where wetting occurred, phase layer thickness (<< 4 µm) was not affected by wire feed rate.

The position of the MIG arc relative to the sheet edges had a significant effect on both the micro-geometrical parameters such as phase layer thickness (Figure 6) and tensile strength (Figure 7).

The maximum phase layer thickness for the given processing conditions was obtained for the arc foot point (projection of the wire on the aluminium sheet) positioned at a distance of 0.5 mm from the aluminium sheet edge on the aluminium side. By increasing the distance of the arc from the sheet edge (still positioning on the aluminium sheet), phase layer thickness was decreased to about 50 %. This was associated with a decrease in wetting length (no regular wetting on root side of the steel sheet from a distance of 2 mm on) and an increase in seam reinforcement. Moving the arc position towards the aluminium resulted in a significant destabilization of the process, associated with significant variations in wetting length and occasional weld sagging. For these positions, tensile strength was reduced, and scatter in the data was increased (Figure 7).

In most cases, fracture occurred in the HAZ of the aluminium. In those cases, where fracture occurred at the

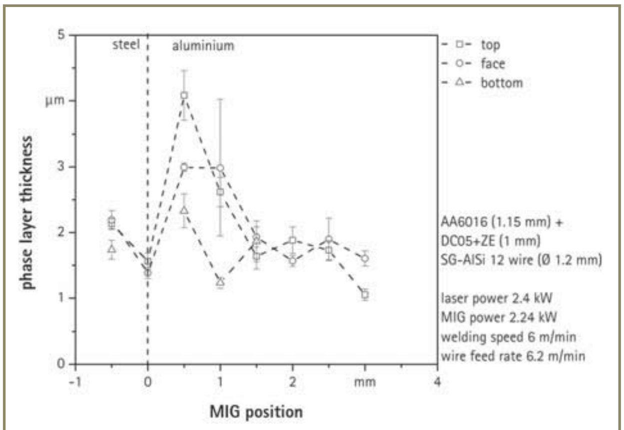


Figure 6 – Effect of MIG position relative to sheet edge on phase layer thickness

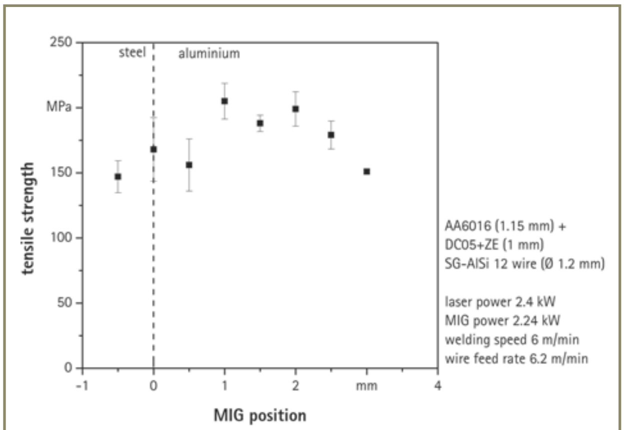
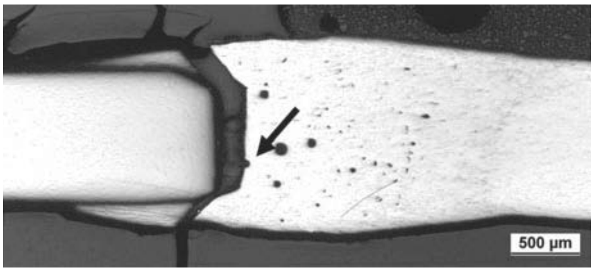


Figure 7 – Effect of MIG position relative to sheet edge on tensile strength



(Laser power 2 400 W, MIG arc power 2 490 W, welding speed 6 m/min, wire feed rate 6.2 m/min, MIG position + 1.5 mm.)

Figure 8 – Cross-section of a fractured laser MIG hybrid welded aluminium-steel specimen

interface zone, either a phase layer thickness in the range of 10 µm or above or a defect close to the interface zone was identified. In the latter case, fracture typically started at a small pore close to the interface zone and then deviated along the intermetallic phase layer (Figure 8).

4.3 Effect of proportional parameter variation

A proportional variation of parameters (when total heat input per unit length, ratio of heat input by laser beam and by MIG arc and ratio of wire feed rate and welding speed are kept constant at the value of an optimized parameter setting) yielded the results given in Table 3.

By evaluating the top and root side of the joints, very regular wetting was found up to a welding speed of 7 m/min. Moreover, a smooth root and regular wetting occurred. At 8 m/min, the process was less stable, resulting in the occasional formation of holes and large spatter at still fairly regular wetting and no significant undercut. At 9 m/min, the process became more stable again, and a smooth root was formed. However, significant undercut formed on the top side of the weld. Except for the instable processing conditions at 8 m/min (tensile strength approximately 150 MPa), which could not be traced back to any specific, systematic cause, tensile strength well exceeded 180 MPa on the average. Wetting length and seam reinforcement as well as phase layer thickness were not significantly affected (which was to be expected from the design of the parameter settings).

4.4 Process parameter envelope

Based on the above results and further experimental investigations, a process parameter envelope (Figure 9) yielding sufficient wetting (0.8 mm to 1.2 mm), a phase layer thickness of less than 4 µm and an average tensile strength in the range of 180 MPa to 220 MPa was developed as a function of welding speed, wire feed rate and heat input (calculated).

Below a heat input of 0.46 kJ/cm, wetting was insufficient, whereas exceeding a heat input of 0.57 kJ/cm resulted in an increased formation of intermetallic phases. The upper limit for the welding speed was set by the maximum laser power available. A decrease in welding speed significantly

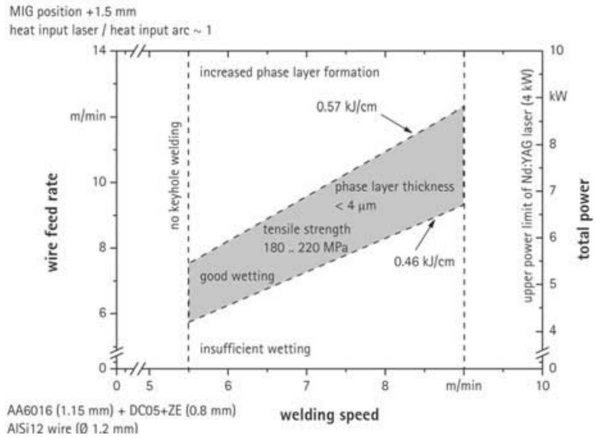


Figure 9 – Process parameter envelope for laser MIG hybrid welding of aluminium to steel

below 5 m/min resulted in a laser power less than 2 kW (to stay within the heat input boundaries), which resulted in an unwanted transition from keyhole welding mode to heat conduction welding mode. The distance of the MIG arc to the aluminium sheet edges was set to 1.5 mm on the aluminium side.

4.5 Formability

In general, specimens produced within the parameter envelope illustrated in Figure 9 exhibited a good formability in bend test. In particular, transverse cracking normally did not occur, and delaminations or cracks between the aluminium weld metal and the steel sheet surface were not observed (Figure 10).

In hydromechanical deep-drawing, the shape given in Figure 11 (length approximately 250 mm, width approximately 250 mm, height approximately 45 mm) was achieved applying a pressure of 65 bar. Aside from some slight transverse cracks in the weld metal in the zone of the edge radius of the die plate, no defects were observed. Increasing the pressure much further resulted in longitudinal cracks in the weld metal.

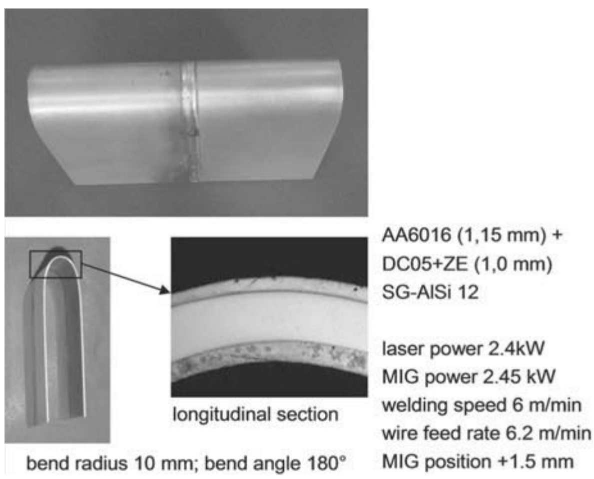


Figure 10 – Result of bend test produced within parameter envelope (Figure 9)

129

(Courtesy: LFT, Chair of Manufacturing Technology, University Erlangen-Nuremberg and BIAS.)

Figure 11 – Aluminium-steel tailored hybrid blank after hydromechanical deep drawing

4.6 Corrosion

After completion of the test cycles, only minimum traces of corrosion (red rust) were detected alongside the scratches in the coating (Figure 12). In cross-sections, no significant evidence of intercrystalline corrosion was found.

5 Discussion

All in all, the laser MIG hybrid welding process proved to be feasible for the production of aluminium-steel joints in the thin sheet range. Provided appropriate parameter settings were selected, smooth joints with a regular wetting (wetting length in the range of 0.8 mm to 1.2 mm), no melting of the steel sheet, an intermetallic phase layer thickness smaller than 4 µm and a tensile strength exceeding 180 MPa were obtained. In metallographic cross-sections, the welds did not show any hot cracking; however, they have some small pores, mostly close to the edge of the aluminium sheet. This was attributed to the use of flux on the face side, which can contain humidity and, as a consequence, be a source of hydrogen to the melt pool. Most recently, it was suggested by Güngör and Gerritsen [18] that such porosity in aluminium-steel braze welds may also be related to an evaporation of the zinc coating. This will require further research.

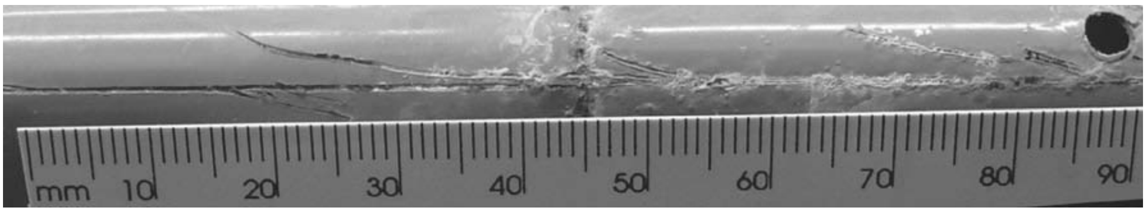
Coming to the individual process parameters, for a wide range of parameter settings for MIG power, welding speed and wire feed rate, no clear effect on phase layer thickness (which typically remained well below 4 µm) was observed. This was astonishing at first, because previous experience and the fact that phase layer formation is primarily driven by diffusion, hence being affected by cooling rate, led to the expectation that e.g. MIG power should have a significant influence (in case heat input is not constant). Yet, the lack of any compelling indications for an effect may be attributed to the fact that, contrary to other processes with a heat input normally significantly above 1 kJ/cm, the typical heat input for the laser MIG hybrid process is close to 0.5 kJ/cm, and phase layer thickness is much less than typically reported for higher heat input processes.

However, MIG arc position (Figure 6) and laser power (Figure 4) had some effect on phase layer thickness. The reason for this was that these two parameters are those with the greatest influence on the time-temperature cycle of the interfacial zone. There, cooling rate was increased for increasing laser power and a MIG position closer to the sheet edge (provided the process is not destabilized, as was the case for a position too close to the steel sheet). For excessive laser power, the steel sheet was partially molten, which resulted in the formation of larger intermetallic phase layers and the formation of cracks. This makes it advisable to restrict laser power and select a MIG arc position on the aluminium not too close to the sheet edge.

Wetting length in general, and also the regularity of wetting, was influenced by welding speed and wire feed rate (Figure 5). Basically, it was concluded that wire feed rate and welding speed should at least be in the same range to provide a sufficient amount of melt especially to the root area. If this was not the case and wetting was insufficient, tensile strength was drastically reduced (Figure 5).

Process stability was most affected by the MIG arc parameters. For an arc power exceeding approximately 3 200 W (and higher currents, consequently), the process was destabilized. This destabilization was partly attributed to an overheating of the wire and yielded a deterioration in the regularity of the seam especially in view of wetting length and an increase in the scatter in the tensile tests. This makes it advisable to limit the arc power to safely obtain an average tensile strength of 180 MPa or above.

Aside from its influence on phase layer formation, MIG arc position was of crucial importance for tensile strength (Figure 7) and wetting behaviour. If the MIG arc was



(Courtesy: ISF Welding and Joining Institute, RWTH Aachen.)

Figure 12 – Corrosion result after 10 cycles in salt-spray test; only minimal formation of red rust

positioned on the aluminium side too distant from the sheet edge, tensile strength was reduced. This was attributed to a significant decrease in wetting length and only irregular or absent wetting on the root side. If the MIG position was too close to the steel side, wetting became irregular, and tensile strength was also reduced. This was attributed to the fact that arc welding parameters were optimized for welding of aluminium, and a position of the arc too close to the steel side, with the instable root of the arc being irregularly rooted on the steel side, resulted in significant process instabilities such as arc deviations and spatter, which in turn results in irregular weld beads. Therefore, it is suggested to closely guide the arc process in an appropriate distance from the sheet edge (in this case 1 mm to 2 mm).

The proportional variation of parameters (keeping constant total heat input per unit length, the ratio of heat input by laser beam and by MIG arc and the ratio of wire feed rate and welding speed) yielded promising results. Joint properties were mostly in the expected range and provided a good starting point for further optimization. Such an optimization would have to focus mainly on the arc parameters, as a proportional variation for wire feed rate with welding speed may result in less than optimum conditions for the MIG arc (as e.g. in our work for a welding speed of 8 m/min, Table 3). In any case, the proportional parameter variation provides a helpful tool to further increase processing speed.

The parameter envelope developed, taking into account the above effects and restrictions, gives basic rules for adjusting the parameters to obtain appropriate joint properties (static strength exceeding 180 MPa, phase layer thickness below 4 µm and sufficient wetting), which equal or surpass those reported in literature, however at a significantly elevated speed of 6 m/min or higher.

Within this parameter envelope, forming behaviour of the specimens in bend test was not at all critical. However, if multi-axial stress was applied (in hydromechanical deep drawing), the results were less favourable. Whereas limiting the maximum pressure could suppress longitudinal cracking, transverse cracks were not completely avoided. Aside from the difference in stress condition compared to static tensile testing and bend testing, another explanation that the forming results were not yet completely satisfactory is assumed to lie in the fact that both tool and part design were not yet fully optimized. Consequently, the issue of formability should be dealt with in more detail in further research, focusing on both the forming process and the joint properties of the tailored hybrid blanks before forming. One means to address the latter aspect will be connected to the selection of filler wire with the aim of obtaining a more ductile weld metal.

Finally, the results of corrosion testing should have demonstrated that, provided appropriate coating is applied, excessive concerns often raised considering this issue should normally not be justified.

6 Conclusions

On the basis of experimental investigations into the effect of process parameters on joint properties in laser MIG hybrid welding of aluminium to steel in butt joint configuration, a process parameter envelope was established. Within this parameter envelope, joints with optimized properties (especially a tensile strength exceeding 180 MPa) equalling or surpassing typical properties obtained by other processes can be reproducibly produced at an elevated speed exceeding 6 m/min. Whereas corrosion behaviour of coated specimens produced within this envelope was rated not at all critical, the issue of formability will require further study. Aside from investigating and optimizing specimen behaviour under multi-axial stress, a special emphasis will have to be set on optimizing the forming process.

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