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Joining of Aluminum and Steel in Car Body Manufacturing

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Abstract

Zinc-coated steel sheets have been joined with aluminum samples in an overlapping as well as in a butt-joint configuration. A bi-metal-wire composed from aluminum and steel was used for additional welding experiments. An advantage of the laser-assisted bi-metal-wire welding is that the welding process is simplified since the primary joint between aluminium and steel exists already and laser welding occurs only between similar materials. FEM-simulations of the process were chosen to determine the ideal dimensions with respect to the formability of the bi-metal-wire. A prototype demonstrated the feasibility of the process.

Keywords: laser welding; intermetallic phases; FEM, IMP

1. Introduction

1.1. Laser welding of dissimilar metals

During the last years, the amount of steel used in car body manufacturing has decreased continuously. As a consequence, plastics and light metals have replaced many parts previously manufactured from steel.

Many different joining methods, like riveting, bonding and many others are in use to join such components of unequal composition. Due to its excellent properties, aluminum is one of most-used light metals in car body manufacturing. Unfortunately, laser assisted joining of aluminum and steel tends to the formation of brittle intermetallic phases. Nevertheless, laser joining methods have been examined during the last years at many different laser centers world-wide. It has been shown that laser joining of aluminum-steel components is possible if process parameters are chosen carefully [1], [2], [3].

Within the framework of a larger project, several different aluminum-steel joining techniques (like friction stir welding, delta spot welding, magnetic pulse welding and others) have been examined by our project group with respect to standards in car body manufacturing. Samples have been evaluated by means of metallographic

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specimens, corrosion resistance, strength, process reliability, varnishability and others. Within the framework of the paper presented here we will focus on laser assisted joining of aluminum and steel.

As a first step, zinc-coated steel sheets have been joined with aluminum samples in an overlap as well as in a butt-joint configuration. Additionally, a bi-metal-wire composed from aluminum and steel has been used for welding experiments. An advantage of the laser-assisted bi-metal-wire welding is that the welding process is simplified since the primary joint between aluminum and steel already exists and laser welding occurs only between similar materials.

FEM-simulations have been used to determine the ideal dimensions with respect to the formability of the bi-metal-wire. Coupled field FE analysis of the formability at welding temperatures showed the processing limits of bi-metal-wire welding. First experiments exposed that no modification of the primary joints between aluminum and steel appeared by subsequent laser welding. Results of tensile tests indicated that samples failed in the vicinity of the primary joint at the aluminum part of the bi-metal-wire. Nevertheless, a prototype demonstrated the feasibility of the process.

2. Experimental setup

As already mentioned, during joining of aluminum and steel at elevated temperatures intermetallic phases (IMP) will occur. As can be seen from the equilibrium diagram solubility of iron in aluminum is extremely narrow, even smallest amounts of iron yield to the formation of very brittle IMP's [1]. Nevertheless, joining of aluminum and steel has been examined at different laser centers world-wide [2], [3], [4], [5], [6], [7], [8]. Due to needs of the automotive industry, joining of zinc-coated sheet metals (DC01, H340 LAD, DX54D) with aluminum alloys from the 5xxx and 6xxx groups and pure aluminum (AW5754, AW6016, Al99.0) have been chosen for experiments. Materials thicknesses were 1 mm for steel samples and 1.5 mm for aluminum alloys, respectively. A 3 kW dc excited CO2 and a 3 kW lamp pumped Nd:YAG laser have been used for experiments. Temperature fields during laser processing have been recorded by means of thermocouples and temperature data have been used to adjust absorption parameters required for FE-simulations. Laser radiation was focused by a metallic mirror with a focal length of 150 mm in the case of the CO2-laser. Nd:YAG laser radiation was guided by means of a 600 µm fiber and focused by a lens with a focal length of 250 mm.

A clamping tool has been designed and used during the overlap welding experiments which allows to influence the heat flow away from the laser irradiated zone into the jig. By insertion of different backing block materials (i.e. copper, steel, aluminum or a water-cooled backing block) the heat removal rate from the aluminum-steel interface could be modified to a certain extent. It has been shown previously by Borrisutthekul et. al. that such backing block materials can influence the formation of brittle intermetallic phases [9].

Dimensions of the backing block were 120 x 20 x 12 mm. Well defined thermal contact between aluminum and steel was assured by compressing the workpieces together with an accurately defined force in overlap as well as in butt-joint configurations. A welding flux and argon as a shielding gas have been used during the experiments to increase wettability and protect welding zone against oxidation, respectively. Shielding gas was delivered by a lateral gas nozzle. Different gas supply positions have been examined (perpendicular to as well as in direction of the weld seam).

Samples have been laser welded in a butt-joint as well as in an overlap configuration. After laser welding, samples have been visually examined and tested with an electromechanical drawing apparatus (RMC 100, ±100 kN). Structural analysis as well as SEM and EDX measurements have been carried out on selected samples.

In a second step, bi-metal-wires have been designed to simplify the welding process between steel and aluminum. Laser welding of such bi-metal-wires with an already existing primary joint between aluminum and steel offer the possibility to eliminate problems related to the formation of IMPs since welding occurs only between similar materials. Within the framework of an additional project, laser assisted roll bonding of aluminum and steel wires has been examined, similar to the setup described by Nishimoto et al [10].

Unfortunately, due to process instabilities, only very short bonds between aluminum and steel could be produced and additional efforts will be necessary to stabilize the process. As a consequence, wires used for bi-metal-wire welding have been cut out from cladded bi-metal sheets delivered by an external supplier. Due to roll cladding process characteristics, almost no IMP's are generated at the primary joint between aluminum and steel. Since only certain roll cladded metal sheets were available, the cut-out bi-metal-wires were composed of pure aluminum Al99.0

and DC01 steel.

3. Results and discussion

3.1. Conventional laser welding

First experiments have been carried out with a 3kW CO2-laser. Since reproducibility of the process was very poor, subsequent experiments have been carried with a 3 kW Nd:YAG-laser in an overlap configuration. Following first orientating experiments, samples have been supported by backing blocks to achieve good thermal contact between aluminum and steel. By changing backing block materials it was possible to change the heat removal rate due to the different thermal properties of the materials (aluminum, copper, steel and a water cooled backing block) used.

As a consequence, results of shear strength measurements varied since growth rate of IMPS could be modified. To minimize influences of varying clamping forces, a pneumatic fixation applied a well defined force onto the samples. The amount of overlapping of the samples chosen for experiments was 1 mm and 1.5 mm, respectively. Lateral alignment of the focal spot of the laser has been kept constant at a distance of 0.5 mm measured from the edge of the samples. Line energies have been varied, ranging from 30 J/mm up to 130 J/mm. The focal position of the laser has been changed, ranging from 0 up to 40 mm defocus. Shielding gas (argon) flow rates (lateral nozzle) have been changed between 0 l/min and 40 l/min, respectively.

Figure 1(a) shows results of shear strength measurements of laser welded samples with different backing block materials. Best results have been achieved with copper as a backing block material. Due to changed geometrical conditions welding results with a water cooled backing block must be evaluated critically.

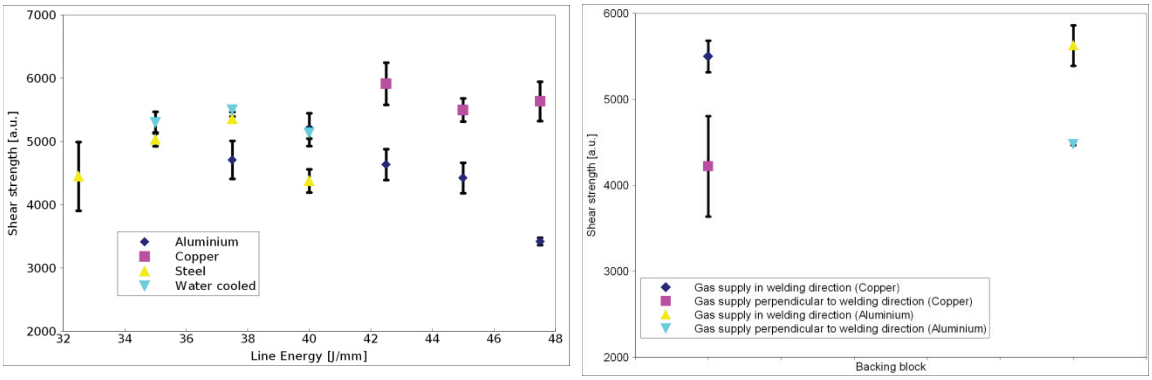

Figure 1. (a) Shear strength of aluminum-steel samples welded with different backing block materials; (b) Shear strength of aluminum-steel samples welded with gas supply in welding direction as wells as perpendicular to welding direction.

Due to the excellent thermal properties of copper, heat flow into the backing block causes a relatively fast temperature drop of the samples after welding. It is assumed that due to different cooling conditions following laser welding the growth of IMPs is influenced which, in turn influences shear strength. Additionally, the position of the gas supply (perpendicular to or in welding direction) influenced shear strength results, too. It is supposed that the position of the gas supply changes cooling conditions and growth of IMP’s, too see Figure 1(b).

The experiments so far have been performed without any welding flux and with an AlMg3-alloy. Since wettability of the samples in the overlap as well as in the butt-joint configuration was poor, subsequent experiments have been carried out with an additional welding flux and an AW-6016 alloy. Drawing experiments and micrographs of laser welded samples showed an increase of the shear strength and very uniform IMPs. Thickness of IMPs is well below 10 µm, see Figure 2. Compared to previous experiments, shear strength of laser welded aluminum-steel samples increased almost 3 times with an excellent reproducibility, see Figure 3.

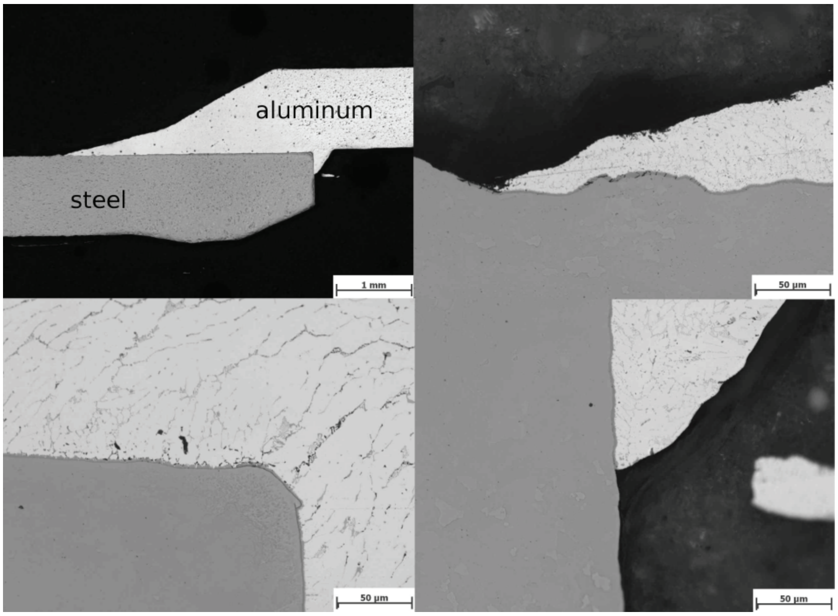

Figure 2. Cross sections of a laser welded aluminum-steel sample at different positions and magnifications. Steel sample remained unchanged without melting. Thickness of IMPs remains well below 10 µm. Nd:YAG-laser line energy was 80 J/mm with 40 mm defocus.

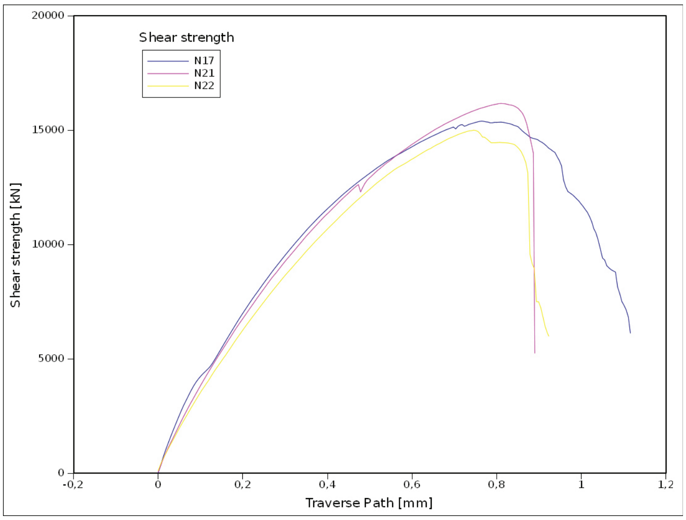

Figure 3. Shear strength of several laser welded aluminum-steel samples as shown in Figure 2.

Additionally, a butt-joint laser welding configuration has been examined, too. A well defined thermal contact between steel and aluminum samples has been achieved by a modified clamping device. From one side of the samples a pneumatic cylinder applies an accurately defined force during laser welding on the aluminum-steel interface. Again, line energies and focal positions have been varied during the experiments. Variations of the lateral position of the laser beam showed that an offset of 0.5 mm toward the aluminum sample was beneficial. Results of first butt-joint welding experiments showed very narrow IMP where thickness of the IMPs is well below 10 µm and almost uniform. Unfortunately, it was not possible to avoid cracks at the bottom of the weld seam. It was assumed that the crack was caused by the clamping device used for experiments.

As a consequence, the clamping device was modified to avoid unwanted stress after laser welding. Together with additional measures it was possible to avoid crack formation, see Figure 4. IMPs are very uniform along the whole circumference of the aluminum-steel interface.

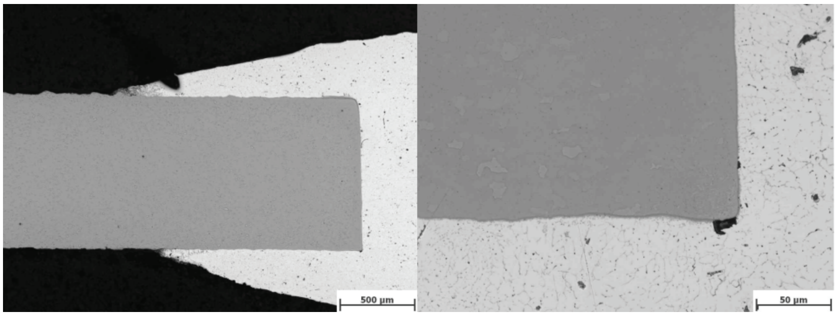

Figure 4. Cross sections of laser welded aluminum-steel samples in a butt-joint configuration. Thickness of IMP's remains well below 10 µm. Nd:YAG laser line energy was 130 J/mm and 10 mm defocus, 10 l/min Ar shielding gas, lateral nozzle.

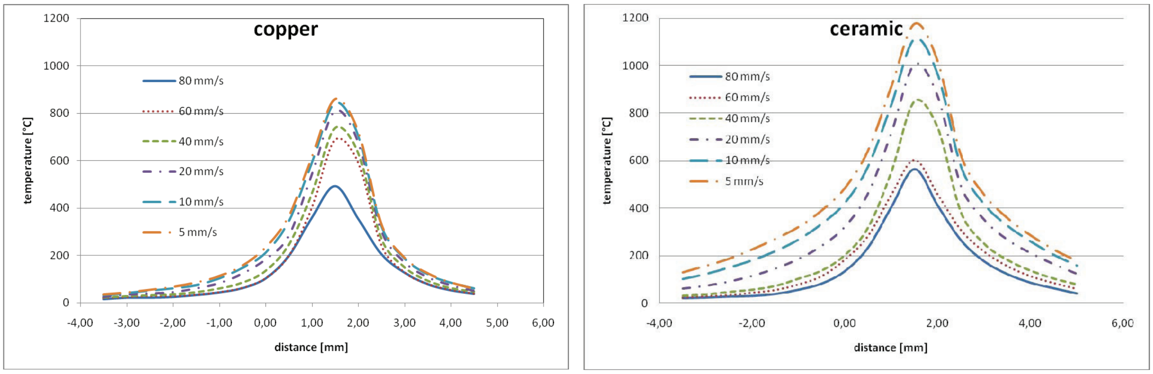

Figure 5. Calculated temperatures at the aluminum-steel- interface for different welding velocities, perfect thermal contact at different distances from the overlapping region and (a) copper as a backing block material; (b) ceramic backing block.

Shear strength measurements showed again very good reproducibility of the process. As already mentioned, experiments have been supported by means of FE-simulations. Heat removal through different backing block materials has been simulated and compared to experimental results. Data achieved by thermocouple measurements have been used to adjust absorption parameters used for FE-simulations. Line energies have been changed and the temperatures at the steel-aluminum interface have been calculated, see Figure 5. It was assumed that laser parameters should be chosen in such a way that temperatures at the aluminum-steel interface remained below vaporization temperature of zinc but above melting point of aluminum. Comparisons between experimental results and FE-simulations showed good agreement.

As can be seen from Figure 5(b), temperatures increase very fast in the case of a ceramic backing block material due to its excellent insulating properties. As a consequence, it is difficult to keep the temperatures at the aluminum-steel-interface within the desired range, whereas copper as a backing block material allows a much wider range of welding velocities.

3.2. Bi-metal-wire laser welding

Bi-metal-wires composed from aluminum and steel with a primary joint between both materials have been used for subsequent experiments. By using a bi-metal-wire it would be possible to shift problematic aluminum-steel laser welding away from production lines to supply lines [11]. Bi-metal-wires could be supplied and in succession at an aluminum-steel welding production line only welding between similar materials will be required. Within the framework of an additional project laser assisted roll bonding of aluminum and steel wires has been examined. Due to process instabilities wires with very short bonds between aluminum and steel could be produced, see Figure 7(a).

As a consequence, bi-metal-wires used for subsequent experiments have been cutted out from cladded bi-metal sheets delivered by an external supplier. All bi-metal-wire welding experiments have been performed in a butt-joint configuration. Within a first step, the wire was welded to one material and in a second step the remaining interface has been welded. In any case, laser welding occured only between similar materials (aluminum-aluminum and steel-steel). At the beginning the influence of subsequent laser welding on the primary joint of bi-metal-wires has been analyzed. FE-simulations indicate that the primary joint between steel and aluminum remains unchanged if minimal wire dimensions are not under-run.

Additional simulations should help to evaluate the possibility of using a conventional wire-feeder to deliver the bi-metal-wire to the welding zone, see Figure 6(b). Simulation results indicate that deformations due to bending together with elevated temperatures at the laser irradiated zone can cause debonding of the aluminum-steel interface since material properties will be exceeded, see Figure 6(a).

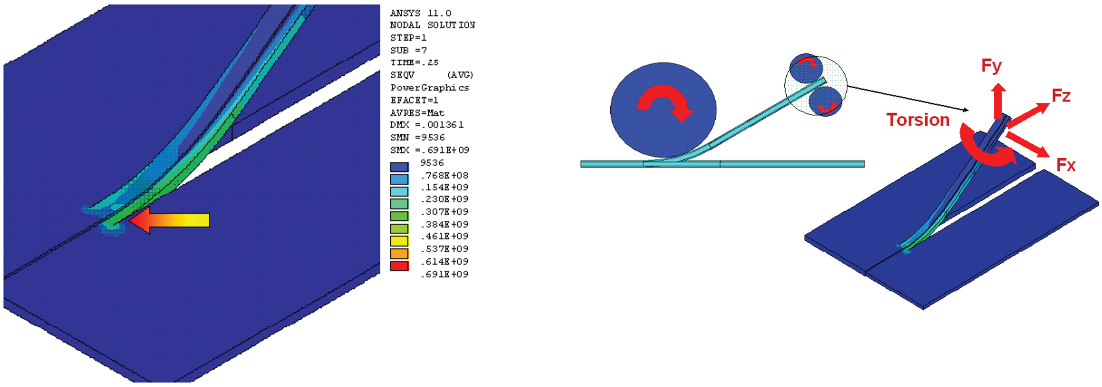

Figure 6. (a) FE-simulation of the interface region between bi-metal-wire and the aluminum-steel sample. Simulation shows von Mises stress at the laser irradiated zone. (b) Setup used for calculations. Bi-metal-wire is delivered by a conventional wire feeding system with a wire bending radius of 30 mm.

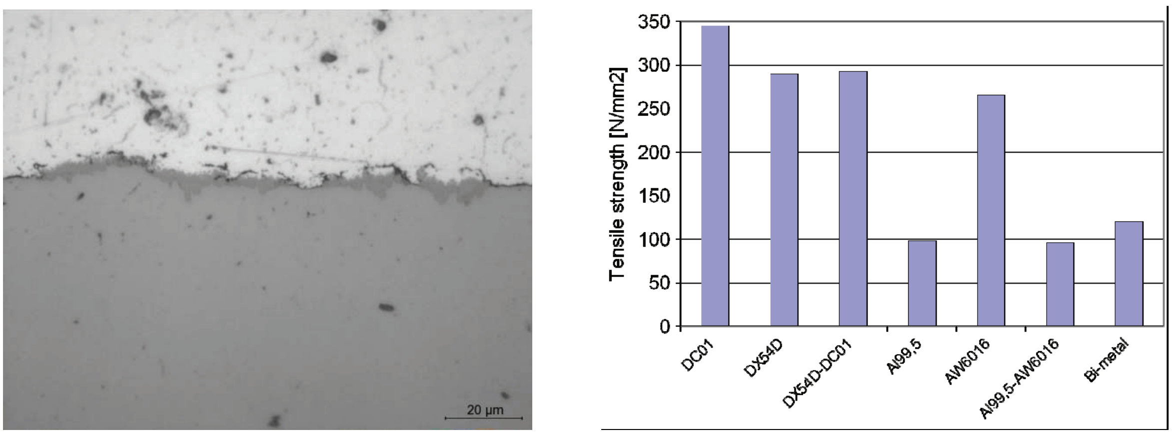

Figure 7. (a) Micrograph of the aluminum-steel interface of a bimetal-wire produced by laser assisted roll bonding. IMPs and several small cracks are visible. (b) Results of tensile tests of bi-metal-wire laser welded samples. Bi-metal-wire laser welded samples have been compared to steel-steel and aluminum-aluminum laser welds. The tensile strength of bi-metal-wire samples increased slightly in comparison to Al99.0.

Nevertheless, it was possible to produce laser welded bi-metal-wire samples. Results of tensile tests are shown in Figure 7 where a comparison between steel-steel and aluminum-aluminum and bi-metal-wire laser welded samples is given. Tensile strength of bi-metal-wire laser welded samples is slightly higher compared to pure aluminum laser welded samples which is caused by alloying pure aluminum with AW6016. Following the tensile tests, bi-metal-wire welded samples were subject of a bending test. Bending parameters have been chosen in such a way that bending radius and angle were comparable to parts used for car body manufacturing. No cracks or debonding of the aluminum-steel interface occured.

4. Conclusions

Experimental results indicate that laser welding of aluminum-steel samples produces well defined and narrow IMPs with thicknesses well below 10 µm. Butt-joint as well as overlap laser welding configurations show good reproducibility. Cooling cycle after laser welding influences growth of IMPs and a good agreement between experimental results and FE-simulations of the temperature at the steel-aluminum interface could be achieved. Shear strength measurements of laser welded aluminum-steel samples in a butt-joint as well as in an overlap configuration showed excellent results and reproducibility.

A bi-metal-wire has been used for further research on aluminum-steel welding. Dimensions of the bi-metal-wire have been chosen in accordance to FE-simulations to achieve a good compromise between formability and heat resistance of the wire. Coupled field FE-analysis showed that conventional wire feeding systems are not suitable for transporting a bi-metal-wire since deformations will cause debonding of the wire. Development of a simple production process of steel-aluminum wires remains a challenging task for future experiments. Nevertheless, a prototype demonstrated the feasibility of the bi-metal-wire laser welding process.

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