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Laser-welded dissimilar steel-aluminum seams for automotive lightweight construction

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Abstract

By reducing vehicle weight, a significant increase in fuel efficiency and consequently a reduction in CO_2 emissions can be achieved. Currently a high interest in the production of hybrid weld seams between steel and aluminum exists. Previous methods as laser brazing are possible only by using fluxes and additional materials. Laser welding can be used to join steel and aluminum without the use of additives. With a low penetration depth increases in tensile strength can be achieved. Recent results from laser welded overlap seams show that there is no compromise in strength by decreasing penetration depth in the aluminum.

Keywords: laser; overlap welding; penetration depth; dissimilar materials; steel; aluminum

1. Motivation / State of the Art

The importance of lightweight construction due to economic reasons will increase continuously in the future. This can be made possible through the use of light weight metals or plastics. Mixed parts of steel and aluminum have the potential to reduce the weight of components, combined with adequate strength characteristics [1].

The difficulty is that intermetallic compounds are formed during the joining process of steel-aluminum. After the welding process, solidification of the molten aluminum and steel can form different superstructures and intermetallic compounds. The superstructures are FeAl and Fe_3Al. $FeAl_3$, Fe_2Al_5 and $FeAl_2$ are brittle intermetallic compounds of aluminum and iron [2]. In contrast to iron-rich joints, aluminum-rich joints show a brittle welding seam with a reduced strength. The maximum hardness range of welded steel is between 350 and 400 HV0.2, whereas hardness values of pure aluminum and iron are

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significantly lower. The intermetallic compound $FeAl_3$ exhibits a hardness range between 820 to 920 HV0.2. Furthermore, the intermetallic compound Fe_2Al_5 has a hardness of 1000 up to 1100 HV0.2.
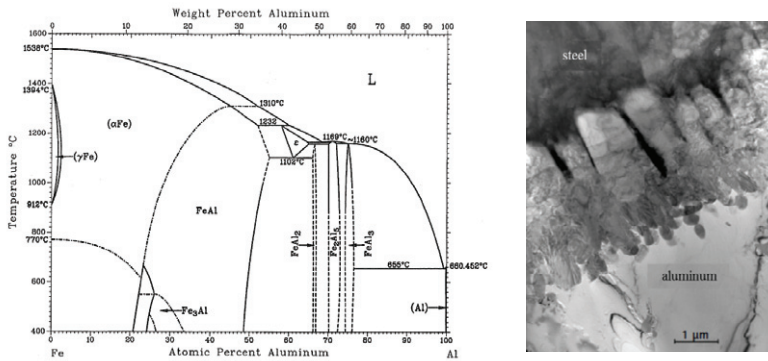

Fig. 1.   (a) Fe-Al binary phase diagram [3]; (b) TEM image of intermetallic layers [4]

Accordingly, by bonding aluminum and steel through the thermal joining process, brittleness and cracking result. Furthermore, compound formations occur at about 400 °C. Aluminum can be dissolved up to 18 at% in iron, but iron cannot be dissolved in aluminum (fig. 1a). To ensure high quality in a mixed weld seam of steel and aluminum, the width of the intermetallic layers (fig. 1b) has to be minimized [5, 6].

In addition, the dissimilar material properties cause further difficulties. A major challenge is the thermal bonding process due to the considerable difference between the melting temperatures of aluminum and steel. Furthermore, the unequal linear thermal expansion coefficient and the average thermal conductivity must be overcome to have successful joining of the two materials. The different electrochemical potential of the materials lead to an undesirable corrosion behavior. Due to the potential difference of 1.22 V a corrosion rate flows between the two metals [7]. To prevent a galvanic corrosion between steel and aluminum the weld seams should be free from electrolyte and/or exhibit an electrical isolation. After the joining process it is also possible to coat the workpieces with the cataphoretic painting process.

In order to produce steel-aluminum seams with sufficient mechanical properties, several methods and concepts have been developed and tested in the past. A proven technology for joining steel-aluminum is the reduced energy arc joining method. The resulting steel-aluminum hybrid structures have desirable properties. The cold metal transfer joining process (CMT) or the coldArc process is characterized by a low heat input. Due to the low heat input, the growth of intermetallic compounds is reduced.
The sheets are positioned in a butt joint, and welded using a soldering process. Zinc- and aluminum-based solders are used as filler materials. By using aluminum-based solders, intermetallic layers between 2-5 microns can be detected. Furthermore, using zinc-based solders, the growth of the intermetallic layers is more pronounced, and deviations up to 35 microns can be proved [8-10].

Other methods of producing steel-aluminum hybrid weld seams are electron beam welding and friction stir welding. The best results for the steel-aluminum hybrid welds using the electron beam process can be achieved with an intermediate layer of titanium. This serves as a diffusion barrier to suppress the intermetallic layers [11]. During the friction stir process, the flow stress of the material can be reduced, based on local heating, so the material can be shaped very easily. This allows the parts to be mixed

together and joined during the cooling phase [12].

In addition to the above joining methods, the use of lasers to join steel-aluminum dissimilar materials is possible. In the literature laser brazing and laser braze welding processes are often mentioned. A brazing process is different to a welding process by using a solder material whose melting temperature is lower than the base materials. The laser brazing process for the production of tailored hybrid blanks of the materials aluminum alloy AA6016-T4 and a deep-drawing steel DX56 + C and a non-corrosive flux using cesium for removing the oxide layer of aluminum was used [1, 13]. While additional material from zinc-based solders $ZnAl_2$ and $ZnAl_4$ were applied. To decrease the formation of intermetallic layers in a following transformation, the workpiece edges were not melted during the brazing process. By using a special working head, it is possible to increase the processing area with an oscillating laser beam and to increase the brazing speed up to 4 m/min. Tensile tests of the welded joints concluded a tensile strength between 70-80% due to the weaker material. Also draw ratios of 1.9 are shown. [13]

In addition to the thermal welding processes non-thermal techniques for the joining of steel-aluminum dissimilar compounds can be utilized. Therefore techniques such as bolting, riveting, clinching and punching rivets are available. The problem with these kinds of methods is the necessary two-sided accessibility of the workpieces. In comparison to the thermal joining processes it is not possible to produce joints over the entire length of a part, which results in a lower tensile strength. After the welding process a deformation in sheet metal workpieces is also not possible. A combination of mechanical and adhesive technical processes is becomingly utilized [14]. Joining by adhesive provides a wide range of material combinations. The disadvantage during the curing process is the need for component fixation.

2. Experimental work

For the welding process, an Nd:YAG laser with a maximum output power of 4 kW with two focus diameters of 600 and 1200 μm were used. To determine the optimal parameters with the highest tensile strength of the specimens, overlap seams with a focus position below the upper steel sheet were produced. Based on the optimal parameters, welds with a weld length of 200 mm were made in order to reach conclusions about the process stability.

In addition to the welding tests, an "online" spectral analysis was performed. For this purpose, the process illumination was coupled to a spectrometer via an optical waveguide. A serial interface for data transmission and accompanying software was used. For the data record, a relative density of radiation as a function of wavelength was identified. The position of the sheet metals for the investigation and the process window are shown in fig. 2.
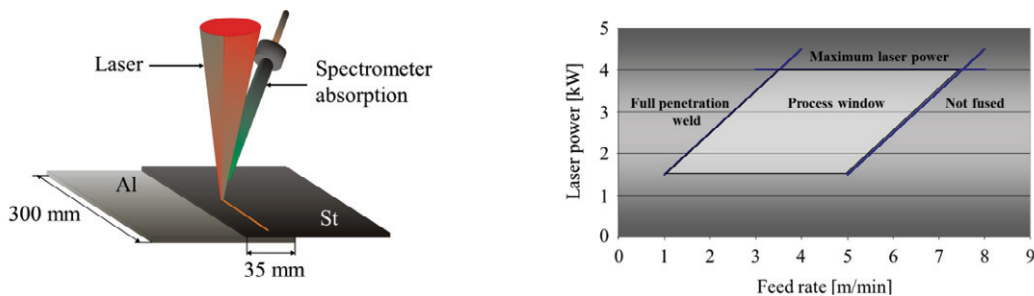

Fig. 2.   (a) experimental setup for welding; (b) determined process window

Two aluminum alloys EN AW-5128 with a thickness of 1.4 mm and EN AW-6016 with a thickness of 2.0 mm, and two steels H360LA in 1.0 mm thickness and 22MnB5 with an aluminum-silicon coating and without coating in 1.7 mm thickness were used as test materials.

The weld seams were made with a focus diameter of 600 μm and a laser power of 3 kW. The obvious reason for this is the high radiation intensity in the focus of the laser beam. The feed rate was varied from 3.75 m/min to 5 m/min. To reach more investigation results about the welding depth and joining width, a laser power of 4 kW and a focus diameter of 1200 μm with feed rates from 1.75 m/min to 2.88 m/min were used.

3. Results and Discussion

Tensile tests were performed to determine the maximum tensile shear strength. For the specimens welded with a focus diameter of 600 μm, maximum forces of 3.84 kN to 5.02 kN were used on the hybrid structures. For the focus diameter of 1200 μm, forces used were from 4.25 kN to 5.46 kN. The cause of failure is, on the one hand, a rupture of the welding seam within the steel sheet. On the other hand, a cause of failure is the unclip of the welding seam, due to a rupture between the intermetallic layer of steel and aluminum. The two break mechanisms are shown in fig. 3.
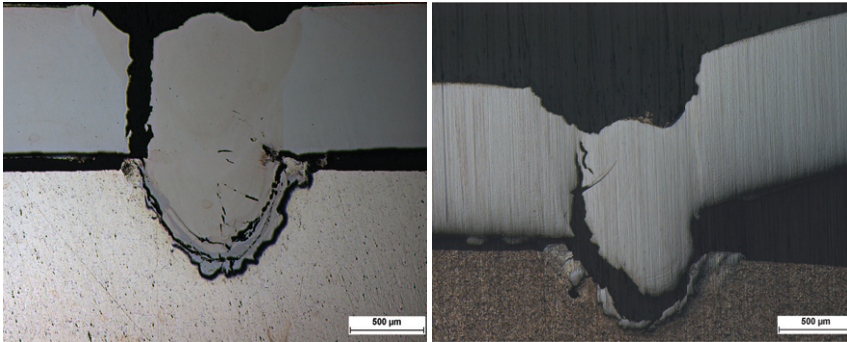

Fig. 3.   (a) unclip of the welding seam; (b) break of the welding seam within the steel sheet

The joining mechanism between the steel and aluminum sheet is similar to a tooth. The reduction of intermetallic brittle compounds is the challenge in joining steel and aluminum. As an indicator of the quantitative distribution of aluminum in the seam the welding depth is considered. A high welding depth results in an increasing mix of iron and aluminum, and of crack initiation. Furthermore, lower welding depths in the cross-section between the steel and aluminum are insufficient for high strength welds. Thus, there is an optimum for the welding depth. A small mixing of iron and aluminum implies high tensile shear strength of steel-aluminum compounds. In addition, a formation of intermetallic phases exists, which shows a very high hardness and low deformation capacity. Due to EDX analysis of brittle compounds, the structural formula FeAl at intermetallic layers was detected.

An almost homogeneous distribution of aluminum in the welding seam occurs due to the Marangoni flow. The direction of flow results from the temperature-dependent surface tension of the melt. In the upper welding seam, structures of Fe_3Al were detected.

Without a laser power control system, significant differences between the weld zones with regards to

the welding depths and joining width exist. In figure 4 an example of the weld seams of two steel on aluminum hybrid structures are shown. The weld seam on the right shows a slim weld seam. In contrast to the right welding seam the left welding seam shows a lower welding depth. An incongruent context occurs at the welding seam area. Important for the absorbable maximum forces is the size of the weld width. With an enlargement of the welding area which is limited by the focus diameter, higher maximum forces increases. An enlargement of the welding area is associated with a higher welding depth.
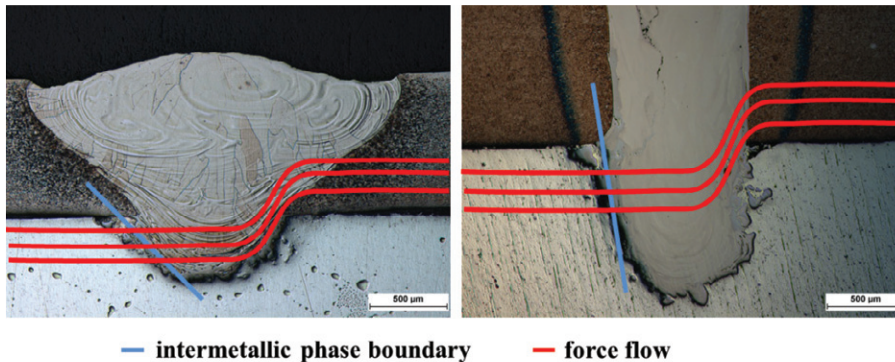

Fig. 4.　Weld seams and force flow of steel on aluminum hybrid structures produced with a focus diameter (a) of 1200 µm and (b) of 600 µm

A deeper welding depth results in a higher mixing of iron and aluminum, which formed brittle intermetallic phases. Steel and aluminum dissimilar compounds which are produced with a focus diameter of 1200 µm can increase higher maximum forces compounds than dissimilar compounds that are produced with a focus diameter of 600 µm.

Furthermore in figure 4 two examples of the welding zone and the force flow of steel on aluminum that were created with a focus diameter of 600 and 1200 µm are shown. In consideration to the force flow, welding seams which are produced with a various focus diameter, different forces exist. According to the literature [15] transverse forces perpendicular to the orientation of the intermetallic phases are unfavorable. Shear stresses that act parallel to the intermetallic phases are more favorable. The displayed force flow (red lines) run through the steel sheet over the weld seam in the aluminum sheet. The weak point of the intermetallic phases at the specimen that was produced with a focus diameter of 600 µm occurs approximately orthogonal to the force flow lines. An improvement by using a larger focus diameter can be achieved. A steel-aluminum dissimilar compound which was created with a focus diameter of 1200 µm is shown in fig. 5a. Due to the formation of a less slender but rather wide welding seam the angle between the intermetallic phase boundary and the force flow lines is increased. This results in an approximately parallel course of the force flow lines to the intermetallic phase boundary. This type of orientation is technically more load suitable.

Furthermore, regarding the surface appearance of the welding seam, the focal diameter carries a decisive influence. During the process, spits and deep seam collapse exist and the aluminum alloy that includes magnesium tends to outgas the magnesium. Thus, a part of the melting pool is ejected of the weld zone. Due to the evaporation the zinc layer of the steel sheet increases this effect. The steel-sided cross-sectional area becomes weakened and stress concentrations are formed in the welding seam.

Due to the use of a doubled focus diameter the surface appearance of the weld seam can be improved.

The weld surface shows a significantly lower seam collapse. Melt ejections due to the outgassing of magnesium or zinc occur only occasionally. The cross section of the steel sheet is weakened slightly. Geometrical notch of the seam collapse was obtained but was of less importance.

Laser-induced plasma spectroscopy shows that a quantitative distribution of aluminum within the molten pool can be determined. The characteristic spectral lines of aluminum can be clearly detected. The relative radiation density decreases with increasing penetration depth. These results enable a conceivable scheme build, generated by the data output of the spectrometer, to control the variable laser beam power. For this purpose a closed-loop control algorithm is under development. The proper intensities of the characteristic wavelength of aluminum are experimentally obtained for each material combination to be used as set points in the PID controller. Hence, the laser power is regulated in order to achieve the desired welding depth. This algorithm is implemented in a control and measure environment built in the system design software LabVIEW^{TM}. To achieve high flexibility and ease of use it includes a data acquisition program, a material combination management program and a database for additional user information. A real-time controller ensures the deterministic execution of the algorithm for high reliability and robustness, fig. 5.
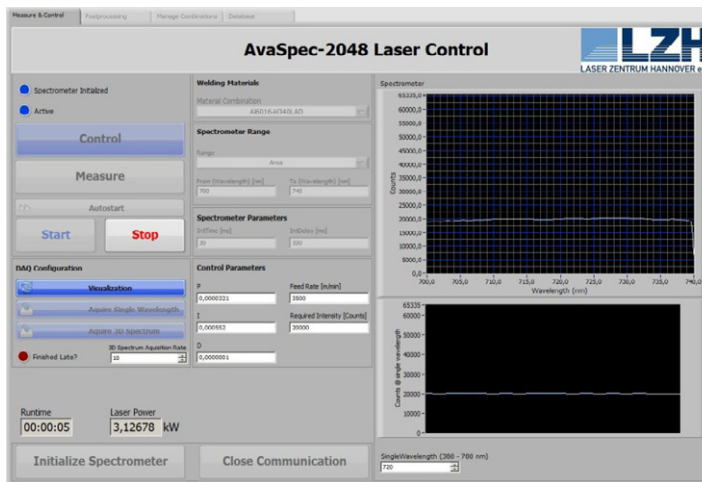

Fig. 5.   User interface for the real-time laser power control

The algorithm is automatically started and stopped by a digital high/low signal which is provided by the lasers CNC. Currently, a laser processing head with an integrated spectrometer for the acquisition of the process radiation is manufactured. A significant decrease of the fluctuations of the absolute values of the relative radiation density and a simultaneous increase of intensity is possible. Thus, repeatability of the experiments is demonstrated. Characteristic spectral lines of aluminum are shown in fig. 6.
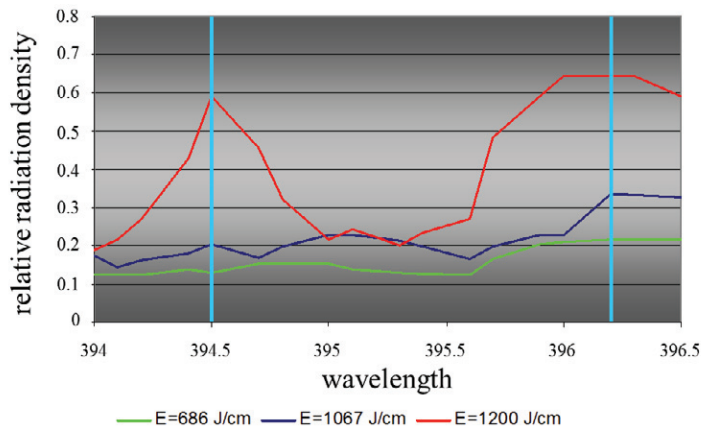
Fig. 6. Spectral analysis of aluminum during the laser process with a focus diameter of 1200 μm

The steel materials for mixed joints between steel and aluminum are suitable. The two aluminum-based materials show significant differences. The aluminum alloy EN AW-5182 is unsuitable for welding due to the high magnesium content. The outgassing of vaporized magnesium leads to high weld spatter. A reduction of this effect can be achieved by using a focus diameter of 1200 μm. The highest potential for a possible practical application is found for the mixed combination of steel H360LA and aluminum alloy EN AW-6016.

Acknowledgements

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