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Influence of aluminum coating and diffusion affecting additives on dissimilar laser joining of steel and aluminum

J. P. Bergmann[a], M. Stambke[a*], S. Schmidt[b]

[a]*Department of Production Technology, Ilmenau University of Technology, Neuhaus 1, D-98693 Ilmenau, Germany*
[b]*Gelenkwellenwerk Stadtilm GmbH, Weimarische Str. 62, D-99326 Stadtilm, Germany*

Abstract

Steel as well as aluminum play an essential role for multi-material construction in the field of lightweight design. However, the thermal metallurgical joining of these materials is difficult due to their different physical properties and the formation of intermetallic phases. This paper describes investigations on laser joining of aluminum plated steel with aluminum. Furthermore examinations with additives acting as diffusion barriers were carried out. The results indicate that the aluminum coating is advantageous for the joint. The growth of intermetallic phases can be reduced by application of carbon and tungsten to the steel sheet tip.

Keywords: laser joining; steel; aluminum; diffusion barrier; intermetallic phase

1. Motivation / State of the Art

Over the past years, developments in different industrial sectors show the tendency to multi material design in order to reduce the weight of engineering constructions. The use of various materials offers the possibility to adapt material properties to the specific local requirements regarding stress situation and other requirements. One example for the application of these design principles is the field of light weight design. Engineering constructions like car or aircraft bodies have to fulfill diverse requirements at different positions in terms of strength and ductility. This demand in connection with the need for preferably light constructions

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* Corresponding author. Tel.: +49-3677-69-3867 ; fax: +49-3677-69-1660 .
E-mail address: martin.stambke@tu-ilmenau.de .

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can only be handled by adapting the materials characteristics to the local stress situation which in consequence leads to a mix of various materials. For current applications primary different types of steel and aluminum are used in order produce lightweight design constructions. Due to the fundamental differences regarding the physical and metallurgical properties of these materials, new approaches in joining technologies have to be investigated. Most of the current applications use cold joining processes like clinching, screwing or adhesive bonding. Other joining processes are for example diffusion bonding, resistance spot welding and hybrid process combinations. [1], [2]

Difficulties particularly occur with high temperature joining techniques, for example laser welding, TIG welding and brazing as well. Besides the differences of the thermal expansion coefficient and solidus temperature the major challenges for the application of thermal joining processes are the metallurgical properties of aluminum and steel. Due to the limited solubility of iron in aluminum and reverse intermetallic phases are formed. Up to approx. 23 At.-% aluminum dissolves well in iron whereas there is only a very low solubility of iron in aluminum of much less than 1 At.-%. If the solid state solubility is exceeded, brittle intermetallic phases with the structure Fe_xAl_y are formed. Especially the stable phases with high aluminum content, like $FeAl_2$, Fe_2Al_5 and $FeAl_3$ have a very high micro hardness up to more than 1000 HV. [3] This leads to very brittle welding seams which influences the performance characteristics negatively. The formation of intermetallic phases is driven by the mechanisms of diffusion, in which temperature and time are the major influencing variables, according to the Fick´s laws. In consequence, a suitable time-temperature regime can limit the growth of intermetallic phases.

Because of its concentrated energy input, high heat up and cool down rates can be achieved using a laser as energy source for joining processes. Due to the short interaction time between the laser beam and the base material a favorable time-temperature regime is obtained, that can lead to very small layers of intermetallic phases. Disadvantageous is the low amount of laser energy that is absorbed by the aluminum joining partner. In [3] Radscheit showed the possibility for process-reliable joints between steel and aluminum by laser joining using a 2 kW Nd:YAG laser. In order to remove the oxide layer flux was used and in some trials AlSi12 was used as filler material. The phase layer thickness was reproducibly reduced below 10 µm which lead to a strength of the overlap joint that was close to the aluminum base material. The authors of [4] presented a method to join aluminum and steel sheets in butt joint configuration using high power lasers. The laser beam was positioned on the aluminum. Due to deep penetration welding the aluminum sheet was molten completely while the steel was heated simultaneously. In combination with filler material this lead to good wetting of the zinc coated steel sheet. Very high welding speeds of up to 7800 mm/min were obtained using a CO_2 or Nd:YAG laser with an output power of several kilowatt. In consequence the thickness of the intermetallic phase layer was reduced below 2 µm. In [5] a combined joining / reshape process is presented. A defocused laser beam heats the overlap between steel on the top and aluminum at the bottom. The aluminum sheet is molten and by simultaneously applying a mechanical force the steel sheet is pressed into the aluminum. By using this method, very narrow phase layers of less than 1 µm thickness were achieved. The experiments in [6] were carried out by using a diode pumped Nd:YAG laser with an output power of 4.4 kW and different aluminum and zinc based filler materials and zinc coated steel sheets. By using a beam splitter in order to preheat the material, the wetting of the steel was improved. As a result the strength of the joining was very high but the same time the formability was limited when zinc based filler materials was used. As opposed to, welds with good formability were produced by using aluminum based filler materials.

2. Experimental procedure

The experiments presented in this paper contribute to evaluate the influence of an aluminum coating on steel sheets as well as potential diffusion barriers on the laser joining process of steel with aluminum. The experimental setup is shown in figure 1. As laser source a ROFIN 2.5 kW CO_2 laser with a focus diameter of 0,4 mm was used. In order to ensure the sufficient melt off of the filler material, the focus position was adjusted 5 mm above the sheet surface resulting in spot diameter of 0,68 mm on the sheet surface. The laser beam was positioned directly at the edge of the aluminum base material in order to avoid the melting of the steel sheet, which would favor the formation of brittle intermetallic phases. The angle between the metal sheets and the filler material supply was set to 20° with an initial distance of 1 mm. The upper side of the seam was covered by argon as shielding with a gas flow of 10 l/min.

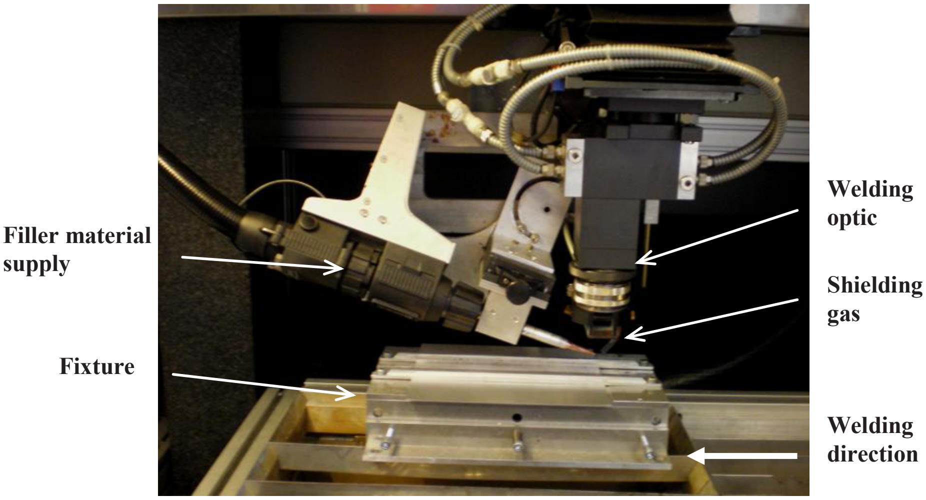

Fig. 1. Experimental setup

To examine the influence of different process parameters on the mechanical properties of the joining as well as on the formation of intermetallic phases the laser power/intensity and the feed rate were varied according to table 1. To derive the effects of the process parameters and their interaction the experimental plan was prepared by design of experiments (DoE).

Table 1. Varied process parameters

Laser power (W)	Intensity (W/mm^2)	Feed rate (mm/min)
1875	~ 5160	2250
2000	~ 5505	2500
2125	~ 5850	2750

All used materials are application-relevant aluminum and steel alloys. In order to investigate the influence of different coatings on the three different base materials were used as listed in table 2. The metallographic investigation of the aluminum plated DC 03 showed no detectable intermetallic phases. AlSi12 was used as wire filler material with a diameter of 1 mm. It was constantly supplied at a feeding rate of 3 m/min.

Table 2. Base material

	Sheet thickness (mm)	Coating	Coating thickness (µm)
EN AW-6016 T4	1,15	-	-
DC 01	1	-	-
DX 51 D+Z	1	hot zinc dipped	22
DC03 Al 99,0	1	aluminum plated	41

As shown in chapter 1 the formation of brittle intermetallic phases is driven by diffusion of iron into aluminum and reverse. Several elements, like titanium nitride, tantalum or tantalum nitride, are promising to inhibit atom movement and are already in use for example as coatings for milling tools. The experiments presented in this paper were carried out with carbon in form of a graphite block and tungsten, which was used in form of a paste made of tungsten powder and thixotropic oil. Both were applied to the tip of the steel sheet.

The mechanical characterization of the aluminum steel joint was performed by tensile test according to DIN EN ISO 4136. Three tensile specimens were cut out of the 200 mm long joining sample in order to investigate the start, middle and end of the seam. The testing speed was set to 10 mm/min with a free clamping length of 95 mm. A metallographic investigation of the joining zone was performed in order to examine the structure of the joining in terms of wetting and connection to the steel base material. Special attention was paid to the thickness of the intermetallic layers. The measurement was performed at cross sectional micrographs and with the help of evaluation software at three points at the steel sheet edge.

3. Results and Discussion

3.1. Influence of base material coatings

The experiments carried out with uncoated DC 01 steel were not successful. Despite the variation of several process parameters it was not possible to produce a joint between EN AW-6016 and uncoated steel DC 01. This is caused by the insufficient wetting of DC 01 with filler material. Using the zinc coated DX 51 steel better results were achieved. The wetting of the steel could be improved. Although the process was adjusted, the bonding between steel and aluminum is still poor as it can be seen in figure 2.

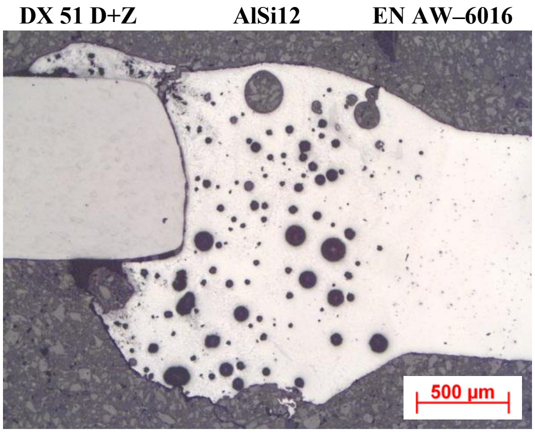

Fig. 2. Cross section of EN AW-6016 joined with zinc coated DX 51 D+Z

Especially at the uncoated edge of the steel sheet, no continuous bonding between the base material DX 51 and the filler material AlSi12 can be observed. Furthermore the joining seam shows a high porosity that is mainly caused by the interaction of the molten material with the surrounding atmosphere. In course of the experiments the gas shielding was improved but due to the experimental setup it was not possible to integrate argon shielding for the seam root side. In consequence the formation of pores could not be avoided completely. As shown in figure 3 the seam geometry can be significantly improved by using aluminum plated DC 03 steel. Compared to figure 2 the laser intensity was the same while the feed rate was reduced from 3500 mm/min to 2250 mm/min. There is a good connection between the Al 99,0 layer and the joining seam. Especially at the uncoated tip of the steel sheet, the formation of intermetallic phases can be observed. The phase layer at the front side of the steel sheet has a cambered shape with a maximum thickness in the middle of the joining zone. This characteristic shape can be observed in all trials and is caused by the low cooling rate in the middle of the seam. This area is exposed to a high temperature for longer time period which favors diffusion and thus the formation of intermetallic phases. At the transition to the original aluminum plating the phase layer becomes thinner. Because of the good wetting and seam formation, all following investigations were carried out using Al 99,0 plated DC 03 steel.

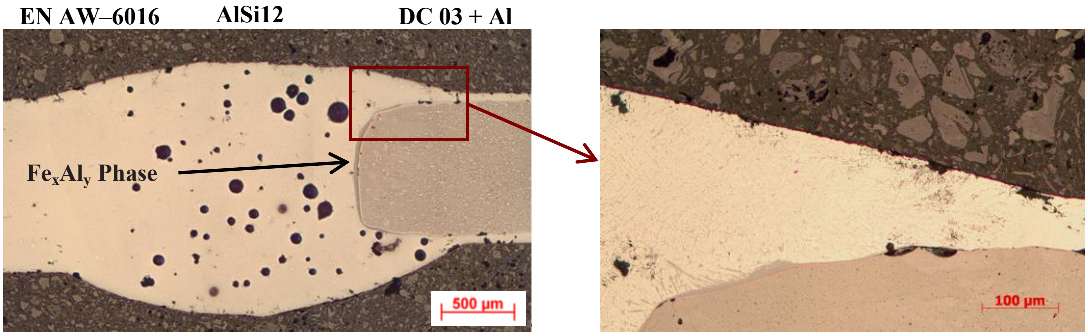

Fig. 3. Seam formation of aluminum steel hybrid joint with AlSi12 filler material

3.2. Influence of process parameters

The experimental investigation of laser power and feed rate was performed in order to study the influence of the time-temperature regime on the formation of intermetallic phases and thus the properties of the joining. The results indicate that a lower energy input per unit length also reduces the thickness of the intermetallic phase layer. At constant intensity of 5160 W/mm^2 an increase of the feed rate from 2250 mm/min to 2750 mm/min reduces the layer thickness from approx. 34 µm to approx. 16 µm. The same effect can be observed with the other intensity levels as it is illustrated in figure 4. The relatively large standard deviation has to be justified with the irregular thickness distribution of the phase layers as it was discussed in the previous paragraph. The thinnest phase layer was measured using the highest feed rate and intensity. This indicates clearly that the energy input per unit length has a significant influence on the growth of intermetallic phases. The higher the energy input the more diffusion processes take place and in consequence the intermetallic phase layer becomes thicker. These results are equivalent to the findings in [4] and show the importance of high intensities to achieve high feed rates and thus high heat up and cool down rates in order to limit the growth of intermetallic phases.

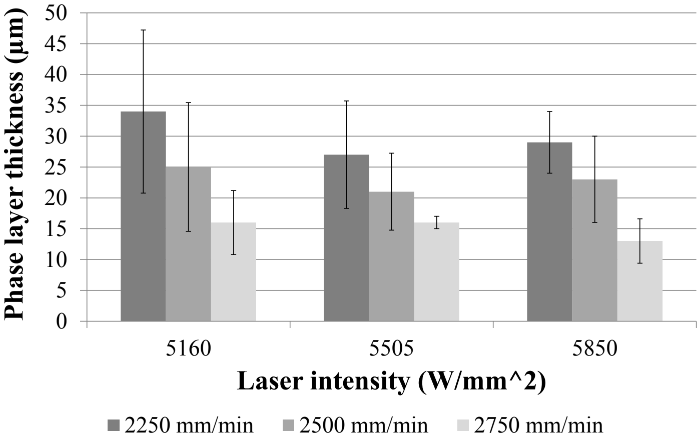

Fig. 4. Intermetallic phase layer thickness in dependence of laser intensity and feed rate

The mechanical characterization showed no tensile elastic limit as well as no contraction. That indicates a brittle fraction behavior and thus the presence of intermetallic phases. The fracture occurs within the joining zone as it is illustrated in figure 5. The highest tensile strength achieved was 135 N/mm^2 at an intensity of 5850 W/mm^2 and a feed rate of 2750 mm/min. The overall trend regarding the correlation of the tensile strength with the energy input is not as clear as for the phase layer thickness discussed previously. Besides the formation of phase layers, the morphology of the joining seams has to be considered as well, in terms of tensile strength. A hotter melt is advantageous for the wetting of the steel sheet and the melting of the filler material but at the same time it promotes the growth of intermetallic phases. It has to be pointed out that all results show a big variation. Reason for this is the formation of pores due to unintentional interaction of the molten material with the surrounding atmosphere. However, this aggravates general conclusions but a trend at least for the growth of the intermetallic phase layers is visible.

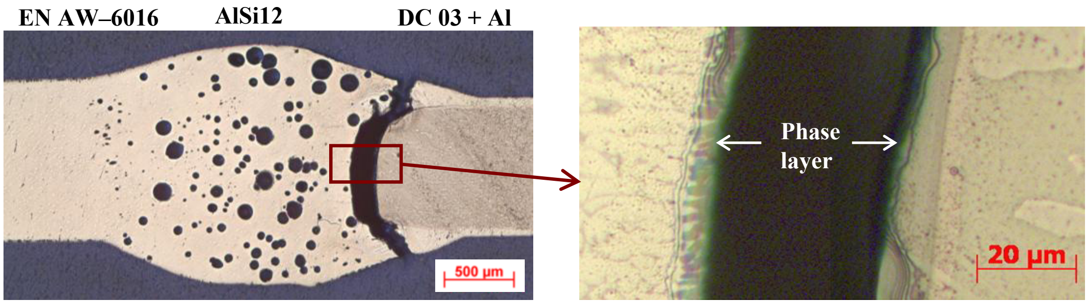

Fig. 5. Fracture behavior

3.3. Influence of diffusion barriers

Besides others carbon and tungsten are the most promising additives that can act as diffusion barrier because of their simple processing. The approach was on the one side to use the high affinity of iron to carbon in order to avoid Fe_xAl_y intermetallics. On the other side tungsten should form a high temperature barrier for diffusion of iron in aluminum and vice versa.

An intensity of 5505 W/mm^2 and a feed rate of 2500 mm/min were used to produce aluminum steel hybrid joints for the investigation of diffusion barriers. All other process parameters remained the same as in the trials before. In order to ensure a good comparability a reference joint using equal parameters was manufactured. Referring to figure 6 the growth of intermetallic phases was at least partially limited by the application of carbon and tungsten to the tip of the steel sheet. The measurement shows that the layer thickness in an average decreased from 23 µm for the untreated samples to 14 µm for the carbon treated specimens. When tungsten was applied to steel edge the layer thickness was more than halved to 11 µm. Due to the oil in which the tungsten powder is supplied the formation of big pores can be observed.

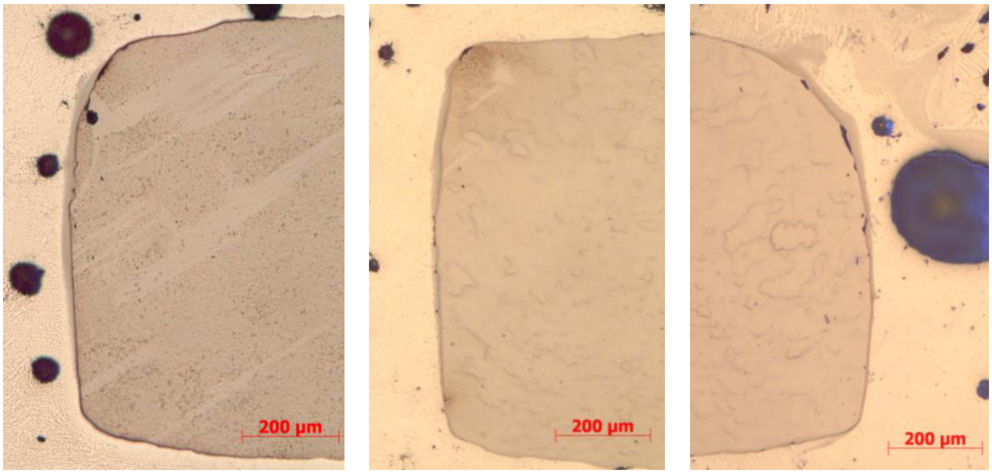

Fig. 6. Formation of intermetallic phase layers at aluminum steel hybrid joint with AlSi12 filler material and; (a) without diffusion barrier; (b) carbon and; (c) tungsten as diffusion barrier

Although the reduction of the intermetallic phase layer thickness is a significant improvement the mechanical properties, listed in table 3, of the joint were not improved. This suggests that the phase layer thickness is still above a critical level.

Table 3. Comparison of joining properties

Diffusion barrier	Tensile strength - max. (N/mm^2)	Cross head travel - max. (mm)	Intermetallic layer thickness (µm)
Reference joint	128	1,3	23
Carbon	117	1,0	14
Tungsten	111	1,0	11

A detailed picture of the joining zone manufactured with carbon is shown in figure 7. An effect that occurs only when carbon is applied to the steel sheet is the growth of the intermetallic phases into the steel. Steel shows a significantly better solubility of aluminum as vice versa and the phases with low aluminum content have less hardness. This is one possible explanation for the slightly better mechanical properties of the carbon treated specimen compared to tungsten as diffusion barrier although the layer is slightly thicker. The diffusion affecting elements are not applied as pure materials. Residues of binder materials and oil evaporate during the joining process. The resulting bonding defects can be observed in figure 6 and 7. These defects are another reason for the lower tensile strength of the joints manufactured with additives.

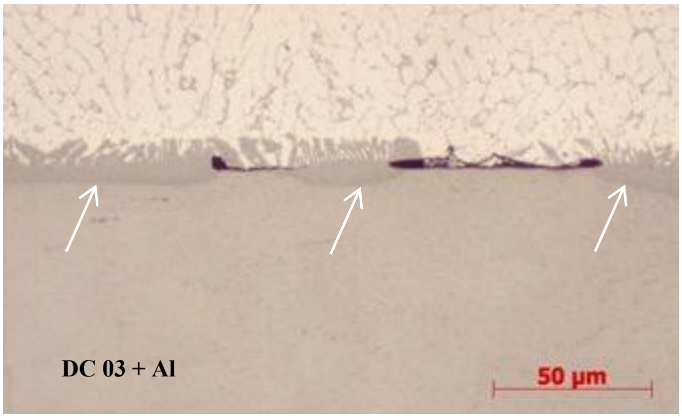

Fig. 7. Intermetallic phase layer of carbon treated steel aluminum hybrid joint

4. Summary

The experiments presented in this paper show the potential of aluminum plated steel for the laser based manufacturing of aluminum steel hybrid joints as well as the possibility to reduce the thickness of the intermetallic phase layer by the application of diffusion affecting additives. The comparison of uncoated DC 01, hot zinc dipped DX 51 D+Z and DC 03 plated with Al 99,0 showed the significantly better wetting and bonding of aluminum plated base material with the filler material AlSi12. The investigation of the main process parameters laser power/intensity and feed rate indicate a connection of the formation of intermetallic phases to energy input per unit length. A correlation of these parameters to the mechanical properties of the joining suggests the presumption that the joining conditions to achieve high tensile strengths favor the formation of intermetallic phases. However, further investigations are necessary in order to clarify this. Tungsten and carbon were applied to joining zone in order to inhibit the growth of intermetallic phases. Both additives offer the possibility to reduce the thickness of the phase layer up to more than 50 %. Despite these results the mechanical properties could not be improved compared to an untreated reference joint. The application of carbon into the joining zone leads to a reversal of the growth direction of the phase layer into the steel joining partner. This is assumed as beneficial for the joint.

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