Development of a double beam process for joining aluminum and steel

Sascha Frank* 
Fraunhofer Institute for Production Technology IPT, Steinbachstr. 17, D-52074 Aachen, Germany

ABSTRACT

Multi-material structures pose an attractive option for overcoming some of the central challenges in lightweight design. An exceptionally high potential for creating cost-effective lightweight solutions is attributed to the combination of steel and aluminum. However, these materials are also particularly difficult to join due to their tendency to form intermetallic compounds (IMCs). The growth of these compounds is facilitated by high temperatures and long process times. Due to their high brittleness, IMCs can severely weaken a joint. Thus, it is only possible to create durable steel-aluminum joints when the formation of IMCs can be limited to a non-critical level.

To meet this goal, a new joining method has been designed. The method is based on the combination of a continuous wave (pw) and a pulsed laser (pw) source. Laser beams from both sources are superimposed in a common process zone. This makes it possible to apply the advantages of laser brazing to mixed-metal joints without requiring the use of chemical fluxes. The double beam technology was first tested in bead-on-plate experiments using different filler wire materials. Based on the results of these tests, a process for joining steel and aluminum in a double-flanged configuration is now being developed. The double flanged seams are joined using zinc- or aluminum-based filler wires. Microsections of selected seams show that it is possible to achieve good base material wetting while limiting the growth of IMCs to acceptable measures. In addition, the results of tensile tests show that high joint strengths can be achieved.

Keywords: multi material design, mixed metal joining, steel, aluminum, zinc, multiple laser beams, hybrid process, brazing

1. INTRODUCTION

The concept of multi material design is based on the premise that the combination of different materials makes it possible to combine the advantages and compensate the weaknesses of each individual material. For example, a high strength material may be selected for load bearing parts which ensure the structural integrity of a system, while a lower strength material with superior formability can be used to manufacture more complex components which are subject to lower mechanical loads. The selective placement of highly specialized, expensive materials also makes it possible to create especially cost-effective solutions.

Due to these advantages, multi-material structures are becoming increasingly important in many applications which were classically dominated by mono-material approaches, especially where lightweight design is of importance. A prime example for this is the automotive industry. In the year 1977, 74 % of a typical automobile consisted of medium- or high-strength steel and other ferrous materials, while only 3 % consisted of aluminum. By 2006, the amount of ferrous materials was already reduced to 63 %, while the amount of aluminum alloys had more than doubled to 8 %

While steel continues to be used intensively, the use of aluminum is increasing. This leads to an increased number of interfaces between both materials. However, the different properties of these metals not only mean that their combination can be highly beneficial, but also that they are particularly difficult to join. One of the central challenges when attempting to join these metals thermally is the formation of intermetallic compounds (IMCs). The growth of IMCs is facilitated by high temperatures and long process times. Being highly brittle, intermetallic compounds can severely reduce the strength of a joint. In order to achieve mechanically sound joints, it is necessary to limit their formation to a non-critical level. As a general guideline value, the thickness of the intermetallic layer should be limited to 10 µm.

*sascha.frank@ipt.fraunhofer.de; phone +49 241 8904 447; ipt.fraunhofer.de
Laser brazing is a joining method which is particularly well-suited for combining low process temperatures with high joining speeds and short process times. Currently, it is primarily applied for joining galvanized steel sheets in the automotive industry. As opposed to welding, the base material is not melted during a brazing process. Instead, the solid material is wet by a liquid filler material, minimizing thermal damage to the joining partners. This advantage is amplified by using the laser as a source of thermal energy, making it possible to concentrate the energy input on a small area. When brazing galvanized steel, the zinc coating of the steel facilitates the wetting process due to its low melting temperature. By contrast, the surface of aluminum alloys is typically covered by a very dense and thermally stable oxide layer. This oxide layer provides aluminum alloys with their corrosion-resistant properties, but also prevents liquid filler material from wetting the aluminum during the brazing process. For this reason, chemical fluxing agents must be used to destroy the aluminum’s highly resistant oxide layer. However, the use of fluxes entails disadvantages like a reduced seam quality or additional pre- and post-processing steps in addition to environmental and health concerns. To circumvent this, aluminum parts are often laser welded, exposing the joining partners to much higher thermal strain.

To offer a new alternative to these conventional approaches for joining aluminum, Fraunhofer IPT has developed a technology which makes it possible to perform a flux-free laser brazing process. This is achieved by introducing a second laser beam to the process, which is pulsed instead of continuous. In analogy to a standard laser brazing process, the continuous laser beam provides most of the required thermal energy. The additional pulsed laser is used to destroy the oxide layer of the aluminum, but only enacts a minor influence on the macroscopic thermal process field. Both laser beams act in a common process zone, creating a hybrid process. Shield gas is supplied to the process zone to support the decomposition of the oxide layer and counteract a renewed oxidization of the aluminum until the joining process is complete. A schematic illustration of the process principle is provided in figure 1. As illustrated by the additional 3D view, the pw laser beam is focused to a line, allowing it to act over the whole width of the seam. The cw laser is shaped to provide a circular spot, heating both the wire and the base materials.

By using an additional pulsed laser to destroy highly resistant oxides, the double beam process makes it possible to join aluminum at especially low temperatures without having to employ chemical fluxes. This advantage can be used, for example, to reduce thermal warping when joining especially thin-walled aluminum parts. It also provides a new approach for limiting the growth of intermetallic compounds when joining steel and aluminum.

2. PRELIMINARY WORK

One of the first development steps in creating a process for joining steel and aluminum consisted of examining different wire materials in bead on plate tests. For these initial tests, several commercially available aluminum- and zinc-based alloys were selected. The experiments showed that the double beam technology can also be used to process zinc-based wire materials, which also possess a high oxygen affinity. Good results were achieved in the bead on plate tests for the following wire materials: AlSi12, AlSi5, ZnAl15, ZnAl4 and ZnAl2.

Figure 1. Schematic illustration of the double beam process (left) and 3D image illustrating the different beam shapes and relative positioning (right)
A double-flanged joint configuration was selected as the first geometry for transferring these results to mixed-metal joints. To generate baseline parameters for initial experiments with the double beam process and to produce reference samples for comparison, the first experiments on double flanged seams were performed using a standard single beam configuration for laser brazing and non-corrosive chemical fluxes. Sample results from these experiments using AlSi12 wire material are shown in Figure 2. Unless stated otherwise, all experiments were conducted at a process speed of 0.7 m/min, using a wire diameter of 1.6 mm. As base materials, AlMgSi1 (EN AW-6082) aluminum alloy as well as DX51D+Z275 (1.0226) galvanized steel sheet were used. The thickness of the intermetallic layer was measured in cross-sections using an optical microscope, with multiple measurements being made on every cross-section. For each measurement series, the average (avg.) and maximum (max.) value is provided.

Figure 2. Steel-aluminum joints created using non-corrosive chemical flux and a single laser beam at different output powers

The results confirm that it is possible to limit the thickness of the intermetallic layer to values below 10 µm using chemical fluxes. The images also illustrate that an increase in laser power leads to increased amounts of intermetallic compounds. Furthermore, the cross-sections show large pores in every seam, with diameters ranging from 200 µm – 500 µm. All of the pores are in direct contact with the surface of the galvanized steel sheet, suggesting that they are caused by evaporating zinc. To test this theory, some of the pores were examined using a scanning electron microscope to perform EDS analysis.

Figure 3. Atomic distribution of elements across the surface of a pore
Figure 3 shows the results of an EDS line scan across the surface of a pore that was laid open in a cross-section. In order to achieve accurate results, the measurements were performed on surfaces which were not previously subjected to metallographic acid treatments. While the measurement shows increased amounts of zinc close to the galvanized material, the zinc concentration does not abruptly increase on the inside of the pore. On the other hand, the measurements show high amounts of oxygen and fluorine on the inside of the pore. Other measurements also showed high concentrations of potassium. Both fluorine and potassium are typical ingredients of chemical fluxes. This indicates that the pores were not caused by evaporating zinc, but instead originate from the flux. This provides additional motivation for developing a joining process that does not rely on chemical fluxes.

3. DOUBLE BEAM PROCESS DEVELOPMENT

After completing the preliminary bead on plate tests and flux-based experiments, the development of a double beam process for double flanged joints commenced. Two images depicting the successful transfer of the double beam technology to this configuration are shown in figure 4. Depicted on the left is an image that was extracted from a high speed video recording of the process. The image shows the process zone with the wire material entering from the right and the seam forming on the left. The wire material starts partially melting due to the thermal energy provided by the cw laser even before interacting with the pw beam. However, the wetting of both joining partners dramatically improves as soon as the material enters the area in which the pulsed laser is effective. The abruptness of the change also indicates that it is not caused by the thermal field of the process, but rather by a strictly localized interaction with the pulsed laser radiation. After exiting the process zone, the material then rapidly cools, creating a seam between the steel sheet depicted on the top and the aluminum material on the bottom of the image. In this case, AISi12 was used as a wire material.

![Figure 4. High speed camera image showing the process zone (left) and sample seam demonstrating the effect of the pulsed laser beam (right)](image)

The second image in figure 4 shows the surface of a seam where the pulsed laser was deactivated for a short distance in order to demonstrate its effect. The seam was created using AISi5 wire material. As the sample clearly shows, the joining process is disrupted as soon as the pulsed laser is deactivated. The cw laser by itself does not provide enough energy to fully melt the wire material and destroy the inhibitory oxide layer. Thus, the wetting process is interrupted. As soon as the pulsed laser is activated again, the process re-stabilizes and the seam continues. The image also shows that the double beam process makes it possible to achieve a very high surface quality.

The cross-section of a double flanged seam that was joined in the double beam process using AISi5 consumables is given in figure 5. The image shows that a predominantly concave seam surface with an almost tangential transition to the base material was achieved. The aluminum sheet is partially molten, leading to a welded connection on the aluminum side. The connection to the steel sheet is established without melting the base material, creating a brazed bond. In total, a hybrid braze-welded joint is formed. However, it has previously been shown that is also possible to use the double beam process for creating aluminum joints which are purely brazed. The seam exhibits only a very thin layer of intermetallic compounds in the contact area to the steel sheet, as the detail view of the cross-section shows. The thickness of the IMC layer was measured with a maximum value of 4.24 µm, which is well below the accepted guideline value of 10 µm. In
average, the thickness of the intermetallic layer was determined to be 3.20 µm. As with the other cross-sections presented after this one, these values are based on at least 9 separate measurements of the intermetallic layer per sample.

![Image of seam and cross-sectional view](image)

**Figure 5.** Cross-section of a hybrid steel-aluminum joint created in the double beam process

For most of the experimental work, DX51D+Z275 quality steel was used. This material was chosen due to its good availability and to approximate the galvanized steel sheets used in automotive applications. However, this steel quality is hot-dip galvanized and possesses a zinc coating of 137 g/m² on each surface, which is a significantly larger quantity of zinc than commonly applied on steel grades for automotive use. This means that a larger volume of zinc may evaporate during the joining process, potentially causing increased amounts of pores or spatter. For joining steel and aluminum, the presence of more zinc can also be advantageous, since it absorbs thermal energy and facilitates the wetting process. To show that the double beam method can also be used to join electrogalvanized steel with a lower coating strength, additional experiments were conducted using DC04+ZE75/75 (1.0338) steel with a coating of only 54 g/m².

![Image of seam and cross-sectional view](image)

**Figure 6.** Cross-section of a hybrid joint between aluminum and electrogalvanized steel

As shown in figure 6, the electrogalvanized material could also be joined successfully by braze-welding. The sample seam shows a smoother surface than the one depicted in figure 5 and displays good wetting and connection lengths on both sides of the seam. In addition, the thickness of the intermetallic phase layer is even lower than that of the previous sample, reaching a maximum value of 1.98 µm.

The cross-section provided in figure 7 shows that good results were also achieved using AlSi12. The etching of this cross-section reveals the microstructure more prominently, showing that the joint is also partially welded on the aluminum side. The seam possesses a good surface quality with a concave profile and near-tangential transition to the base material. The thickness of the intermetallic layer lies also well below 10 µm.
As a second category of filler materials, zinc-based alloys were examined. This group of materials offers the advantage of particularly low liquidus temperatures, ranging from 387°C for ZnAl4 to 450°C for ZnAl15. This makes it possible to achieve a larger difference between the melting temperature ranges of base and filler material, further reducing thermal damage to the base materials. Due to their similar nature, zinc-based filler materials exhibit a strong affinity towards the zinc coating of the steel sheet.

Figure 8 shows the cross-section of a seam where ZnAl2 was used as a filler material. As was already indicated by the results of the bead on plate tests, the use of zinc-based wire materials will lead to a larger contact angle and more convex seam shape. The detail view reveals a thin layer of intermetallic compounds, for which a maximum thickness of only 4.14 µm was measured. The contour of the AlMgSi1 sheet remains nearly entirely unchanged in the cross-sectional view, making it possible to classify this connection as brazed joint.

A comparison of the process parameters provided in figure 8 and figure 5 shows that the laser output power required for creating a sound joint is much lower for zinc-based consumables than it is for aluminum-based ones. The output power of the cw laser could be decreased by 500 W while other conditions such as the choice of base materials, wire diameter and process speed remained constant.

The images in figure 9 show a seam created using ZnAl4 consumables. While the solidus temperature is equal, ZnAl4 possesses a lower liquidus temperature than ZnAl2. Despite this fact, the output power of the cw laser had to be increased slightly to achieve a good seam quality. To compensate this, the wire feed rate was also increased. Still, the resulting seam displays a stronger melting of the aluminum sheet. The seam surface, however, is more convex and the contact angle to the base material is larger. Despite the increased aluminum content in the alloy and the higher energy input, the detail view reveals no clearly distinguishable intermetallic layer.
In Figure 10, a seam that was created using ZnAl15 is depicted. The seam displays a contact angle similar to that of ZnAl4, even though the filler material penetrates deeper into the gap between both joining partners. The cross-section shows only little thermal damage to the aluminum material. The thickness of the intermetallic layer was measured with an average value of 4.84 µm. However, the shape of this layer is highly irregular, as shown by the detail view. While some areas exhibit no intermetallic layer at all, other areas reveal intense local growth in excess of 10 µm. The irregular shape of the intermetallic layer is not only concentrated in the area shown in the detail view, but was also observed in different parts of the cross section. Other samples joined using ZnAl15 exhibit a similar behavior. This is attributed to the high aluminum content of the ZnAl15 alloy as well as its liquidus temperature of 450°C, which exceeds that of the other zinc-based alloys.

4. TENSILE TESTING

Figure 11 provides the results of tensile tests performed on samples which were joined using the double beam method and zinc-based wire materials. The tensile test samples consisted of strip specimen extracted from double flanged seams according to the recommendations of DIN EN ISO 6892-1. Each test series shown in the diagram encompassed at least 5 samples. The error bars represent the calculated standard deviation of each series. The tensile stress was calculated using the nominal cross-section on the steel side of the testing strip.

All of the samples represented by the diagram exhibited material failure in the base material on the aluminum side, close to the joint, as marked in the images of the two samples in figure 11. The location of the fracture suggests that the relatively high contact angle between the aluminum sheet and filler material may have led to a stress concentration, causing the fracture to originate at this point. This indicates a potential for further improvement. However, the results show that it is possible to use the double beam technology to create mixed-metal joints in which the strength of the joint exceeds that of the base material.
Of the materials tested in this series, ZnAl15 showed the highest ultimate tensile strength and also the highest elongation at fracture. The standard deviation for this test series is also particularly low, which indicates a highly stable process behavior. Despite the more pronounced tendency to form intermetallic compounds that was noted for this material, the relatively high sample elongation does not indicate brittle behavior. Still, the results show that a high joint strength can also be achieved using ZnAl2 or ZnAl4 as wire materials, which delivered better results in regard to the formation of intermetallic compounds.

5. SUMMARY AND OUTLOOK

A new approach for creating mixed-metal joints was presented in this paper. After introducing the process principle of the double beam technology, it was shown that this technology can successfully be used to create steel-aluminum mixed metal joints in a double-flanged configuration. Preliminary experiments using chemical fluxes confirmed the importance of minimizing the thermal heat input to counteract the growth of intermetallic compounds. These tests also revealed further disadvantages of using chemical fluxes to create mixed-metal joints. A comparison of the cross-sections provided in this paper shows that the amount and size of potential pores can be severely decreased by employing the double beam technology instead of a flux-based solution.
The cross-sections provided in this paper demonstrate that both aluminum-based as well as zinc-based filler materials can be used to achieve a sound joint quality. As was also shown, the results can successfully be transferred to electrogalvanized steel grades with a lower zinc coating thickness.

While the zinc-based alloys offer the advantage of particularly low solidus and liquidus temperatures, a superior surface quality and lower wetting angles could be achieved using aluminum-based alloys. As indicated by other sources, it is expected that the zinc-based alloys will also provide a higher tensile strength, while the aluminum-based wire materials may lead to a more ductile joint. To investigate the mechanical properties of the joints in greater detail, further tests are being prepared. Another current focus is the development of a double beam joining process for creating lap joints. A current result of the work on lap joints is shown in figure 12.

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