

Innovative Joining Technologies for Multi-Material Lightweight Car Body Structures

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0. Introduction

For joining similar materials with high processing speed and focused energy input the laser beam welding has already been established in the automotive lightweight construction. But furthermore, as a result of rising demands on innovative lightweight concepts, joining of dissimilar materials is becoming more and more interesting (Figure 1).

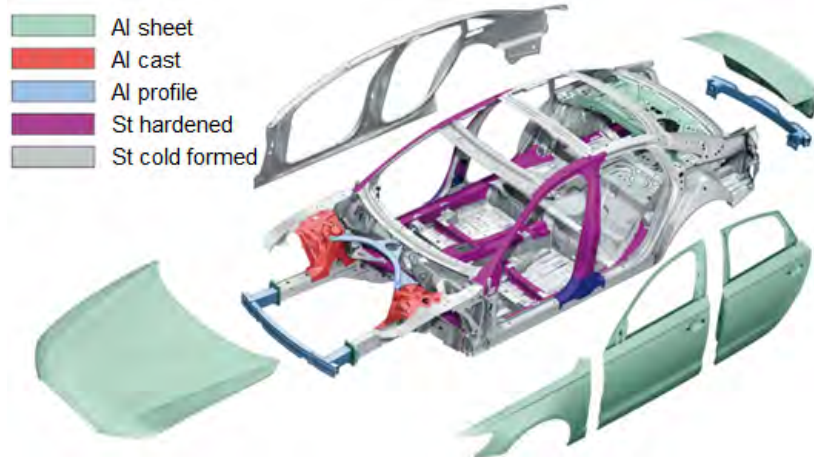


Figure 1: Audi A6 multi-material car body structure [1]

Especially for crash relevant car body components, multi-material joints have to ensure good deformability and strength properties. Hence, using thermal joining technologies the prevention of pronounced intermetallic phase formations in conjunction with reduced ductility is essential. The advantages of laser beam welding opens up new technological approaches in order to meet these requirements. Therefore Fraunhofer IWS developed basically 2 new laser-based joining technologies, especially for highly deformable hybrid components in car body applications.

1. Motivation and Challenge

In the present, different materials are already used for car body structures. According to the overall component load and specific demands, appropriate materials are applicative for complete component assemblies (Figure 1). So far, for example, aluminum doors and strut domes already have been joined with the steel-intensive body in white (BIW), mainly by mechanical joining technologies [2]. Components of the BIW are often oversized because the general component properties are not sufficiently adapted to the local acting loads. Therefore a new approach is the realization of load-adapted material combinations like aluminum and steel within structural body components by multi-material joints. Using different materials with diverse strength and density properties increases the lightweight potential significantly. Figure 2 shows the general intention of load-adapted material combinations to achieve essential weight reductions.

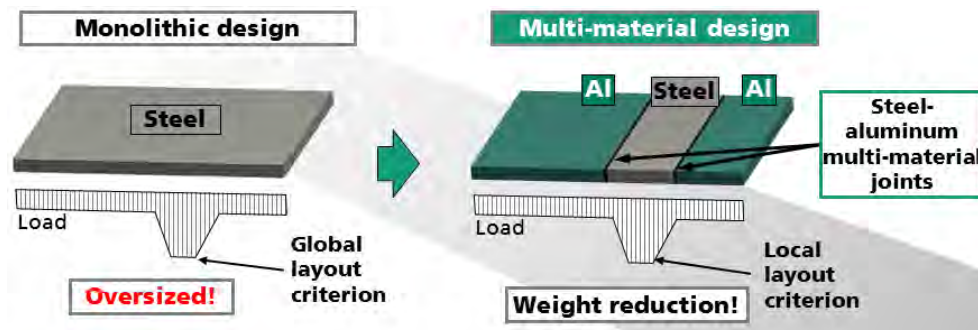


Figure 2: Lightweight design by load-adapted material application

To reach the goal of an optimum load-adapted multi-material component design, innovative joining technologies which are suitable for series production must be developed. Previously, joining of dissimilar materials of body structures was mainly realized by mechanical joining technologies. In addition, thermal joining technologies like laser beam soldering, which are typically used for roof seams are also appropriate for joining dissimilar materials. According to the state of the art, Table 1 gives an overview of the general characteristics of adequate joining technologies for hybrid components.

Table 1: Characterization of appropriate joining technologies for hybrid components [3 - 6]

Mechanical joining technologies punch riveting ¹ , clinching ¹ , direct screw joining	Thermal joining technologies laser beam soldering, friction stir welding, cold-metal-transfer
<ul style="list-style-type: none"> + No thermal interactions + Chemical separation - Joining flanges necessary - Punctual connections (differential construction) - High joining forces (Limit: high-strength steels) - Accessibility to both sides 	<ul style="list-style-type: none"> + Integral design + Low joining forces (laser soldering, CMT) + High surface quality - Intermetallic phase formations - Low process speed - Limited joining design (butt joint or flanged seam)

¹in conjunction with adhesive bond, if necessary

The joining technologies characterized in Table 1 lead to restricted lightweight potential. Particularly for deformable crash components intermetallic phase formations have to be prevented and redundant joining flanges are undesirable. The general objectives for the intended new laser based joining technologies can be formulated as follows:

Table 2: General objectives and challenges of the new laser based joining technology for hybrid components

Objectives and challenges Laser joining process	<ul style="list-style-type: none"> + Integral component design + No intermetallic phase formations + Joining of materials with highly diverse strength properties + Flexible joint designs + High process speed and reproducibility
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2. Laser joined multi-material products

The production of hybrid components with good mechanical properties requires completely new joining approaches, especially for the laser application. Therefore basically 2 new laser-based joining technologies, especially for highly deformable hybrid components in car body applications have been developed. Both technologies are explained below.

2.1. Steel-aluminum web-slot joints by selected laser melting

For the realization of a direct joining process, especially of hybrid T-joints a controlled laser remote process has been combined with a new integral construction approach. The formation of intermetallic phases can be avoided by a selective melting process. This includes a highly controlled laser remote process to perform a selective melting only of the low melting material. Specifically, the joint design of the aluminum side needs to be adapted. To meet this objective a laser-compatible web-slot construction design for T-joints, as shown in Figure 3 has been developed.

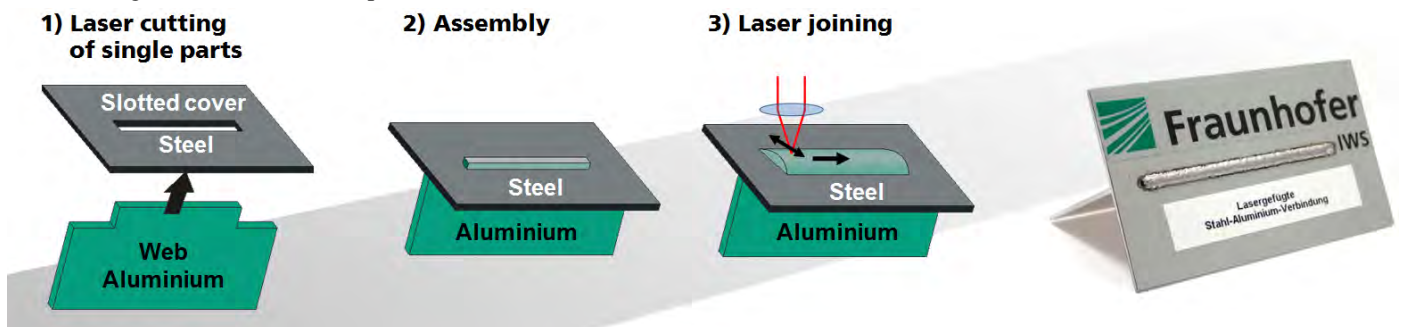


Figure 3: Process sequence for laser joined web-slot design (left), Laser joined web-slot demonstrator part (right)

As shown in Figure 3 basically 3 process steps are required for the direct laser joining process:

- (1) Laser cutting of the single sheet metal components (Al-web / Steel-cover)
- (2) Assembly by sticking the web through the slotted cover (form fit)
- (3) Selective laser melting of the low melting web material (aluminium)

The new web-slot construction design allows producing hybrid T-joints with remarkable mechanical properties. Hence, the characteristics of this technology might be the key in order to solve existing challenges in the automotive lightweight construction:

- 1-step thermal joining of steel-aluminum T-joints is possible
- Semi-integral design / Elimination of joining flanges
- Combination of joining mechanisms (form fit + metallic bond)
- No negative influence of intermetallic phases

By an optimizing of the laser remote process different joint geometries can be realized. Basically the scanning width and the laser power have been adjusted in order to melt only the aluminum side (Figure 4, left). Furthermore the optimization of the laser process allows the shaping also of both sided aluminum form fit (Figure 4, right). Metallurgical analysis show exclusively at the boundary area between steel and aluminium small and uncritical intermetallic phases. Within the strenght-relevant “laser rivet head” no critical iron-content was detected.

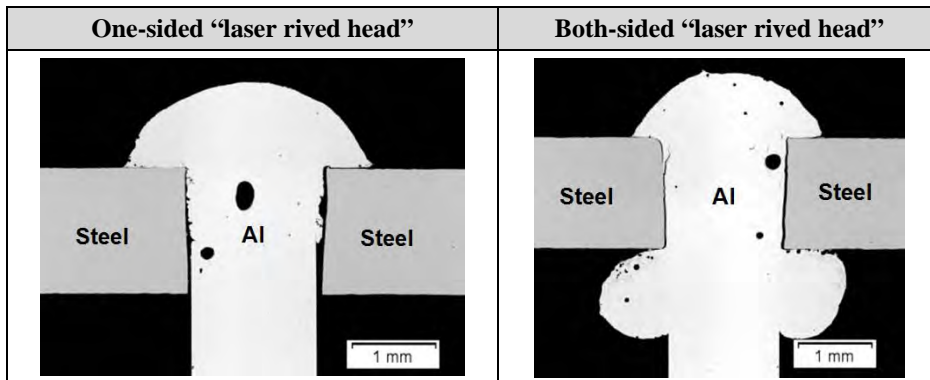


Figure 4: Laser joined hybrid web-slot corner joint geometries

2.2. Steel-aluminum products using laser induction roll plated (LIRP) Transition Joints

2.2.1. Production and design of hybrid Transition Joints

For the production of multi-material metallic strips a special laser induction roll plating (LIRP) process has been developed (e.g. [7]). In order to avoid the negative influence of brittle intermetallic phases, it combines a roll-bonding and a thermal joining process. Basically the 2 different material strips, like steel and aluminum, are inductively preheated and subsequently heated up to the joining temperature by a special shaped laser spot. The laser spot is focused to the joining gap just in front of the rolling process (Figure 5). By controlling the laser energy input besides the rolling forces, the optimum joint characteristics can be designed. The basic challenge is the limitation of intermetallic phases under 10 μm thickness in order to avoid a mechanical property decrease [8]. Therefore the developed LIRP-process ensures a thickness of intermetallic phases of less than 1 μm . With a LIRP-process speed of 4-20 m/min the technology is effectively suitable for series production. Hence, using optimum joining parameters, continuous bimetal strips with very high ductility properties in combination with a high joint strength can be realized time- and cost-efficiently.

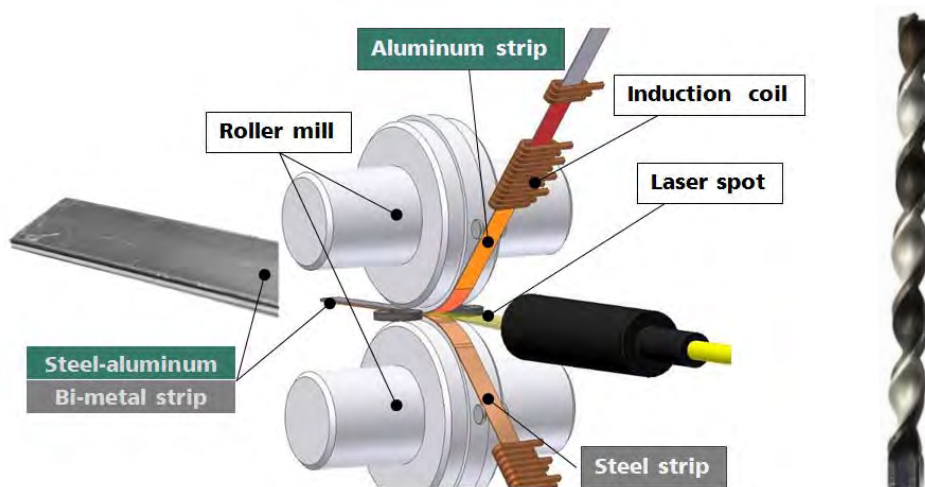

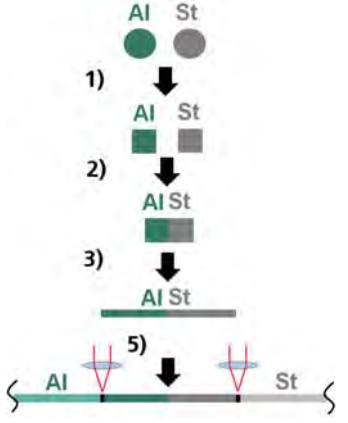


Figure 5: Illustrated LIRP-process (left), twisted steel-aluminum strip (right), demonstrating the high ductility without delamination

The metallurgical challenge for welding dissimilar materials like steel and aluminum can be solved by using these bimetal strips as Transition Joints. The comparatively simple joining of similar material combinations (steel-steel respectively al-al-joints) completes the hybrid joints, using laser beam welding or resistance spot welding. In order to realize customized designs for specific joint applications, flexible strip designs have to be generated. The production process, especially of laser butt welded components using hybrid Transition Joints requires several sequences. The amount of operation processes preferentially depends on the desired joint geometry and joining technology. Table 3 gives an overview about the necessary process flow, exemplarily for the laser welding of hybrid butt joints.

Table 3: Process flow of laser butt welded components using hybrid Transition Joints (made of wires)

Process step	Operation	Process flow visualization
Transition Joint production 	1) Roll forming (by using wire) 2) Laser induction roll plating 3) Cold rolling 4) Edge preparation (milling)	
Laser beam welding	5) Two welding processes - Steel-Steel side - Aluminum-Aluminum side	

As already mentioned, it is essential to generate flexible joint designs in order to meet the huge matrix of joining technologies and joint shapes in automotive production by now. Subsequently three different joint designs, which are particularly established in automotive production, were considered (Figure 6). With this selection the majority of demands for flat joints can be covered.

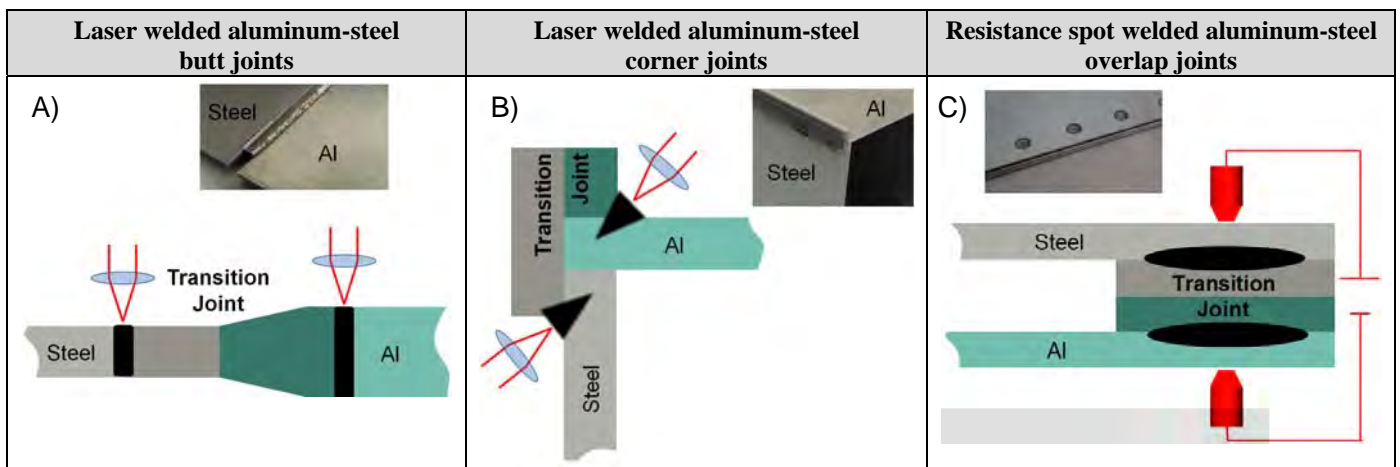


Figure 6: Laser welded hybrid butt joint A), laser welded hybrid corner joint B), spot welded hybrid overlap flange C)

Following the design selection the production process has been realized. Using aluminum and steel wires or thin profiles for the LIRP-process, flat strip designs especially for laser welded butt joints can be generated. The production process requires additional rolling sequences after the LIRP-process. As a result thin bi-metal strips with the sheet metal thickness of the joining partners can be realized. Especially for electromobility applications aluminum-copper combinations have been researched (Figure 7 A).

Bi-metal strips made of single metallic strips can achieve high joint widths. The joining area can cover the complete strip width (app. 22 mm). This design is particularly suitable for the resistance spot welding process of overlap flanges (Figure 7 C). Due to lateral offset of the single strips in combination with an adapted rolling process, overlap or corner joint configurations especially for laser welding are also feasible (Figure 7 B). Specifically, it means that the joining area covers only a defined area of the bi-metal strip. Single material flanges for overlap welding are located right and left of the joint zone.

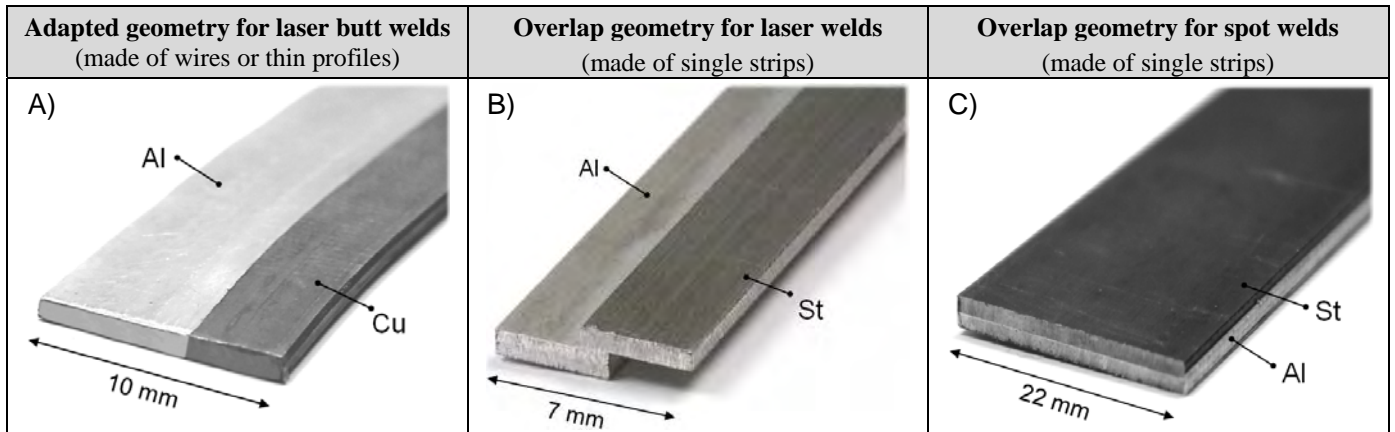


Figure 7: Customized Transition Joint geometries for laser welding A), B) and resistance spot welding C)

The advantages of the approach, using LIRP-products as Transition Joints to realize hybrid components, can be characterized as follows:

- Thermal joining of steel-aluminum hybrid joints is possible
- Avoiding intermetallic phase formations
- Integral or differential component design is possible
- Flexible joint designs (butt joints, T-joints, overlap joints)

2.2.2. Laser welded multi-material products

In order to characterize the metallurgical properties of the weld seam but also of the heat affected transition zone, metallographic examinations were performed. For the research work primarily a deep drawing steel (DC04) and a 5xxx aluminum alloy (AlMg3) has been selected. Through scanning electron microscopic studies of the transition zone, it was possible to detect a thin intermetallic phase zone with an uncritical width lower than $1\ \mu\text{m}$ (Figure 8, left). Hence, the laser welding process does not influence the metallurgical properties of the Transition Joint. In addition a heat treatment according to cathaphoretic coating (app. $180\ \text{°C}$, 30 min) has been tested. The analysis of SEM images showed definitively no intermetallic phase growth and thus no influence of tempering on the transition zone, too [9].

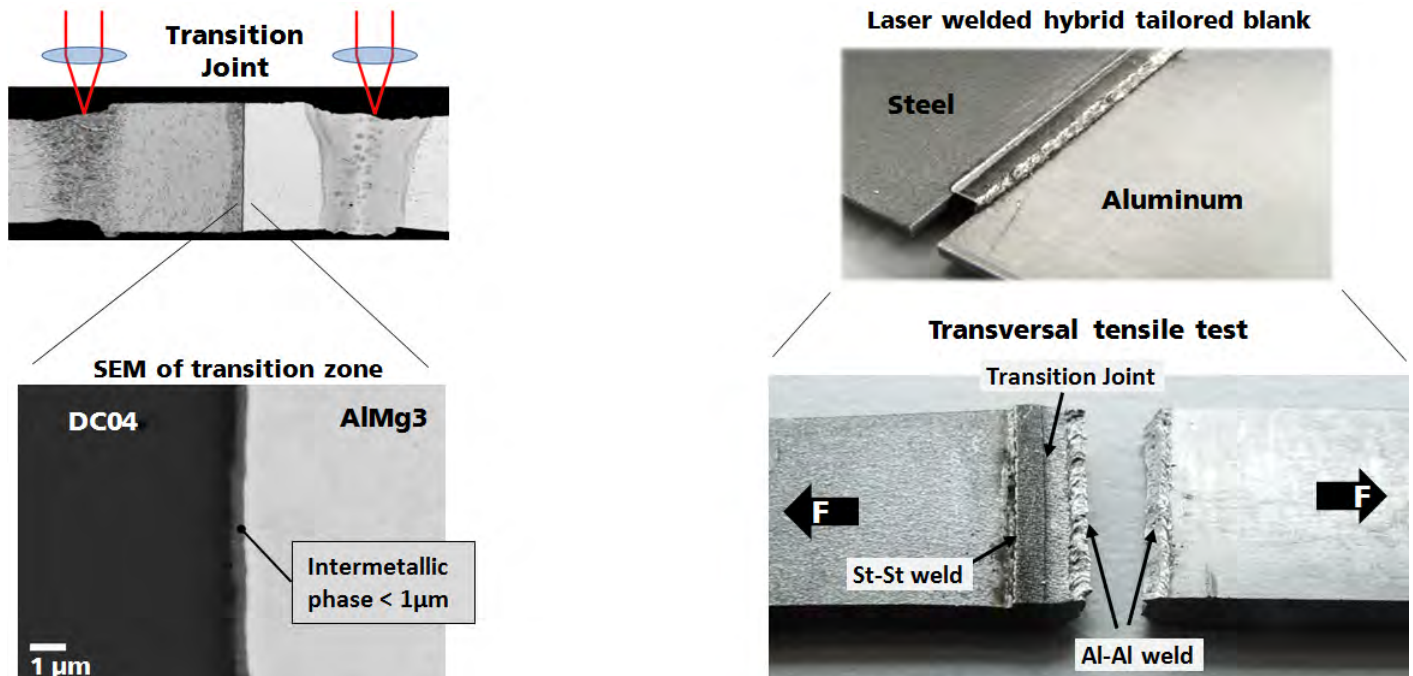


Figure 8: SEM of a laser welded Transition Joint (left), mechanical testing of hybrid components (right)

For estimating a possible modification of strength and ductility by the tempering process, the hardness distribution (HV 0.1) across the laser welded hybrid butt joints has been measured. The test results are summarized in in Table 4. In addition, tensile tests have been performed (Figure 8, right). The mechanical test results show that the critical damage zone is not situated at the transition zone. The fracture of the test specimens typically occurs at the weld zone of the aluminum side (Figure 8, right).

Table 4: Metallographic characterization of laser welded hybrid butt joints

Steel weld zone (DC04)	Transition Joint	Aluminum weld zone (AlMg3)
<ul style="list-style-type: none"> - Hardness increase (material dependent) 	<ul style="list-style-type: none"> - Uncritical thin intermetallic zone < 1 μm - No influence of welding heat and tempering (cataphoretic coating: app. 180 °C, 30 min) - Low hardness increase (fine grained steel micro structure) → No brittle behavior expected 	<ul style="list-style-type: none"> - No hardness increase (typical for Al 5000) - Critical damage zone under tensile stress

Prototypes of steel-aluminum tailored blanks in the size of 300 x 300 mm have been produced. In order to demonstrate the excellent formability of laser welded hybrid butt joints, deep drawing tests have been performed. Even at high forming ratios no joining zone failures occurred (Figure 9).

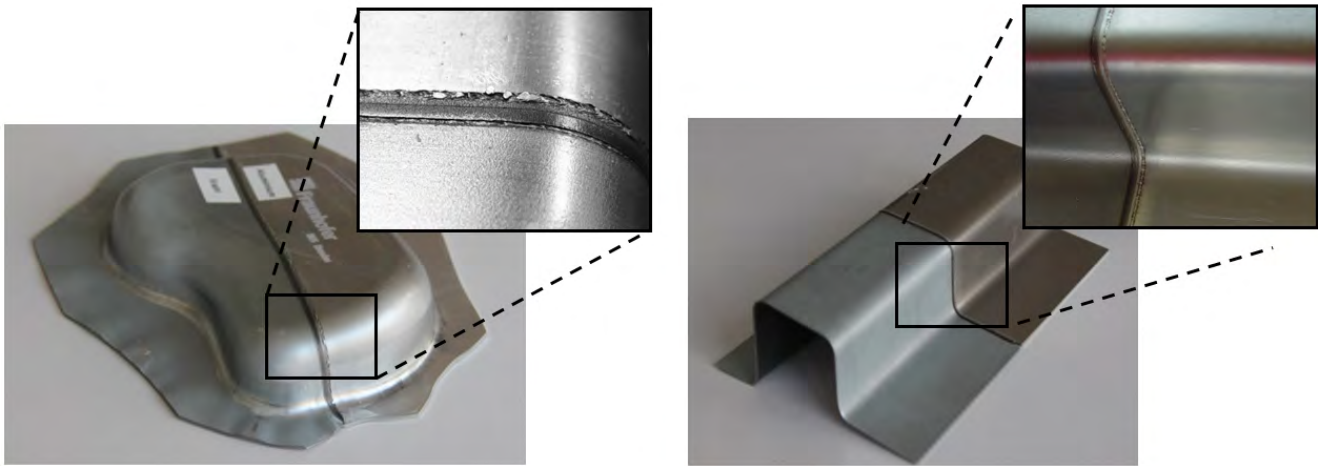


Figure 9: Deep Drawn steel-aluminum tailored blanks

2.2.3. Spot welded multi-material products

The main joining technology for the steel-intensive BIW-components presently is the resistance spot welding process. Therefore this joining technology also has been researched for realizing multi-material joints. Once again, the deep drawing steel (DC04) and the 5xxx aluminum alloy (AlMg3) have been selected. Basically a standard Transition Joint geometry with high joint width is reasonable to use (Figure 7 C). According to the actual joining materials the resistance spot welding process must be adjusted. Basically it is possible to minimize the thermal influence of the spot welding process to the transition zone by adjusting the process parameters (Figure 10 A). As a result of the welding process optimization, a spot welded steel-aluminum hybrid joint, consisting of two single weld nuggets (St-St and Al-Al), was achieved. A failure critical structure of the steel-aluminum transition zone can be prevented. Hence, the tensile test results indicate that the critical damage zone is located in the aluminum base metal (plug failure). The transition zone typically did not fail (Figure 10 B). Also the peeling tension test also shows this failure behavior of the base metal (Figure 10 C).

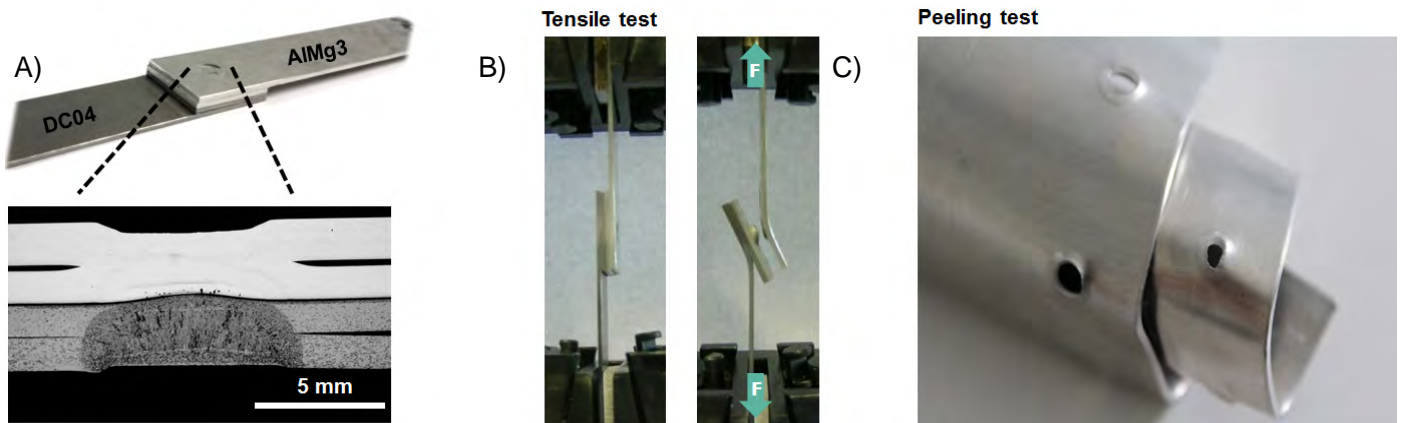


Figure 10: SEM of spot welded aluminum-steel test specimen A), tensile test B) and peeled sample C)

In order to bridge the gap between cost and time consuming generation of completely new joining technologies and the objective of implementing dissimilar lightweight materials, this technology could be the key. The conventional spot welding process especially of BIW-components could be retained. Only the implementation of the Transition Joint and the adjustment of spot welding process must be considered for an effective production of hybrid tailored blanks or body structures (Figure 11). However, an increased thickness of the joining zone has to be considered.

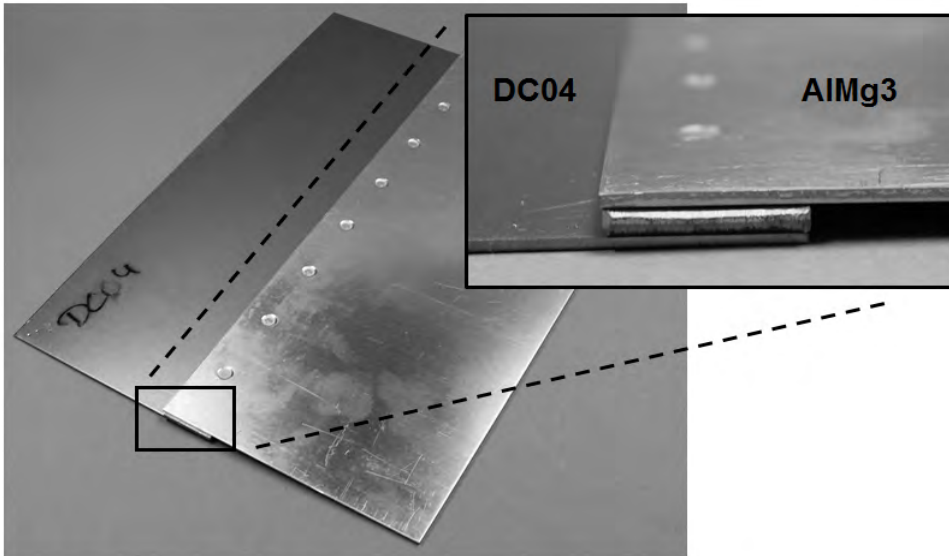


Figure 11: Resistance spot welded steel-aluminum tailored blank

3. Hybrid automotive crash components

The BIW-structure predominantly is made of monolithic steel-intensive components. Hence, structures are often oversized because the overall component properties are not sufficiently adapted to the local acting loads. In order to demonstrate the lightweight potential by using adapted materials, the research work has been focused on the front bumper structure (Figure 12, left). Through FE-simulations the characteristic load situation of the usual box profile can be analyzed (Figure 12, right). Particularly the cover plate, which is located at bottom side of the crash profile, is subjected to very low loads right next to the high stressed deformation zone. Because of this characteristic nonhomogeneous load situation, a new multi-material design could be beneficial in term of mass distribution and total component weight reduction.

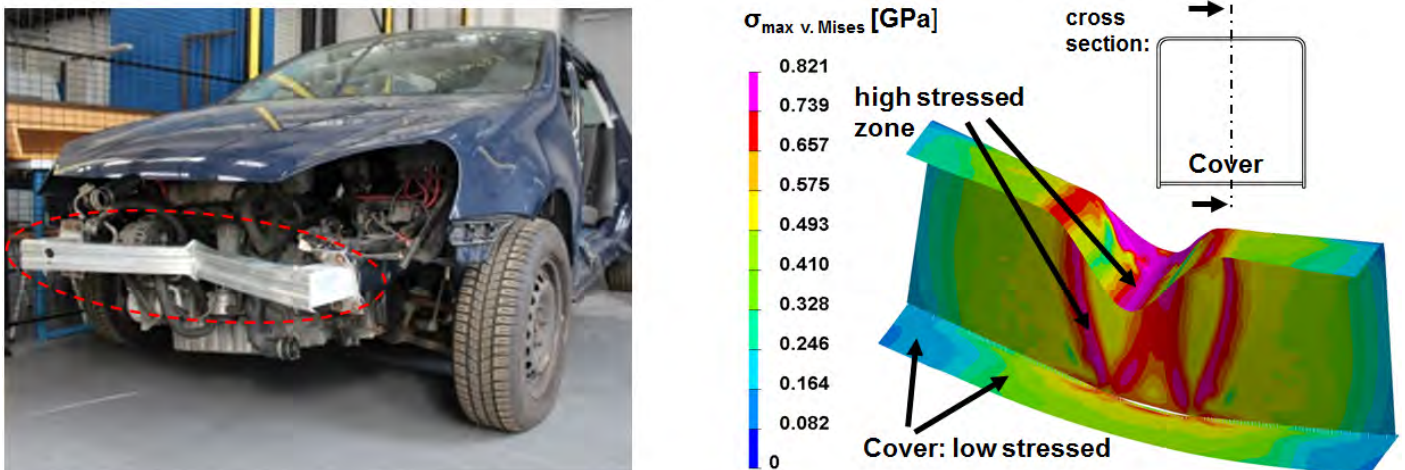


Figure 12: Pole impact test of an automotive bumper structure (left, TU Bergakademie Freiberg), crash simulation: nonhomogeneous stress distribution of the bumper crash profile (right)

3.2. Laser joined hybrid bumper structures

For components like rocker panels, chassis beams and bumpers it is state of the art to perform resistance spot welds, typical with 20 mm overlap flanges for welding. To meet the conventional dimensions for structural car body components, a spot welded steel-steel reference crash profile in the size of 80 x 80 x 900 mm with 20 mm overlap flanges has been defined. Considering the 2 new laser joining technologies (web-slot / Transition Joint) according to the reference dimensions, two laser welded hybrid structures were developed. Due to these new laser technologies, the overlap flanges can be eliminated and the component weight can be reduced by app. 20 % (Figure 13 B). For an additional weight reduction, the low stress loaded steel cover sheet was replaced by an aluminum sheet, which leads to a further weight decrease of 10 % (Figure 13 C).

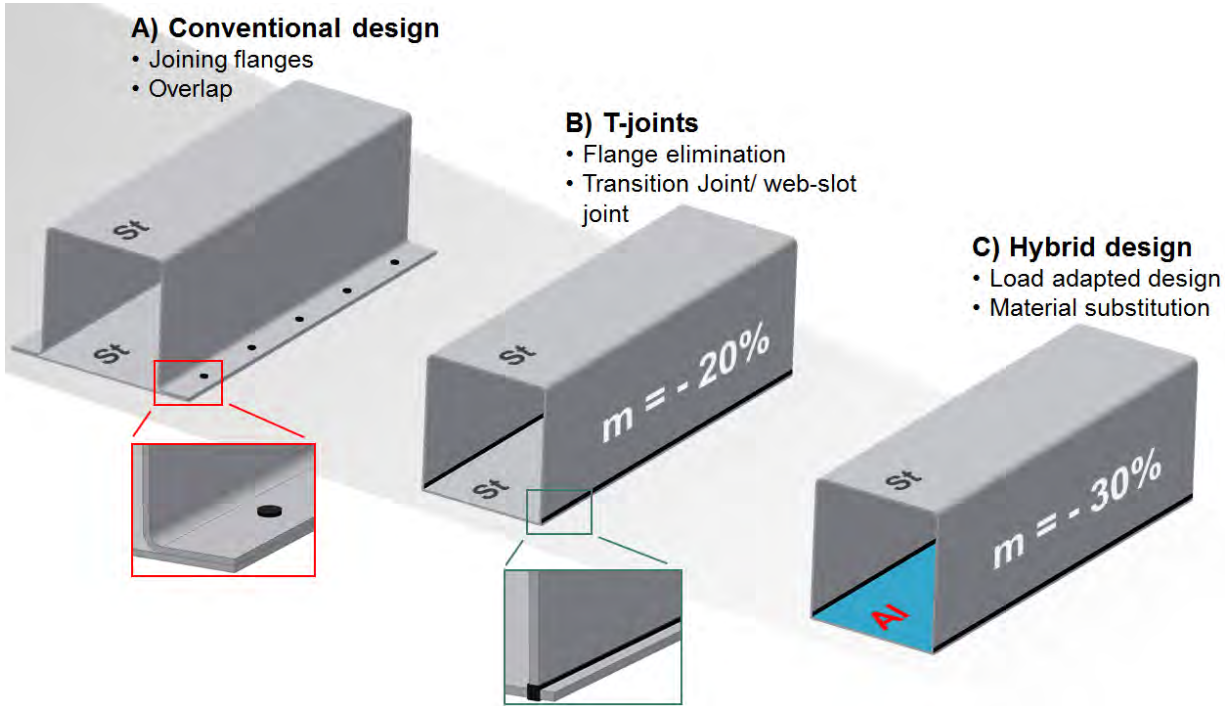


Figure 13: Lightweight design approach for laser welded profile structures

For the research work a high-strength retained austenite steel (HCT690T) and a 5xxx aluminum alloy (Al5083) has been selected. In order to demonstrate the lightweight potential of the new design and for the determination of the crash behavior, two kinds of hybrid parts have been produced and tested in comparison to the conventional spot welded steel component (Figure 14). In order to replace the steel cover plate with an aluminum cover plate, the realization of corner joints is essential. For the web-slot joint the one-sided “laser rivet head” configuration (Figure 4, left) and for the transition element technology the overlap configuration (Figure 7 B) have been selected.

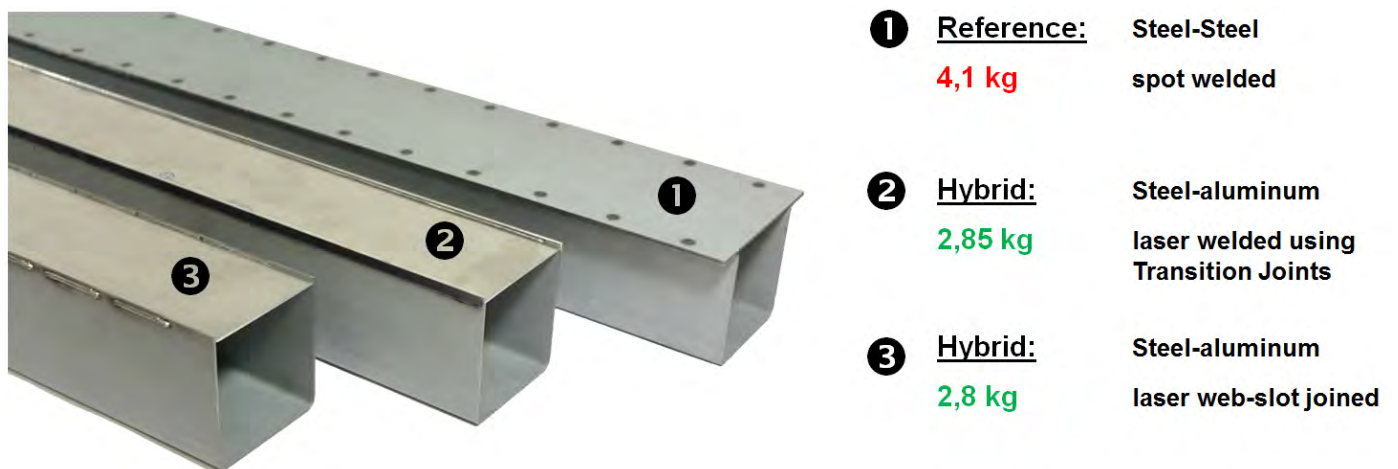


Figure 14: Simplified bumper structures

3.3. Crash performance of laser joined hybrid bumper structures

The numerical simulation of crash structures is an effective tool to estimate the component performance with reduced effort for cost and time consuming crash tests. For the new hybrid joining technologies no conventional numerical joint model can be applied. Hence, novel joining models, especially for the implementation across all solver codes have been researched. Considering the necessary modelling depth for the web-slot design and for the Transition Joint design, basically two different model types, based on solid elements and tied connections, were generated (Figure 15, left). To evaluate the simulation results at TU Freiberg the 3-point bending crash test were performed in reality (Figure 15, right).

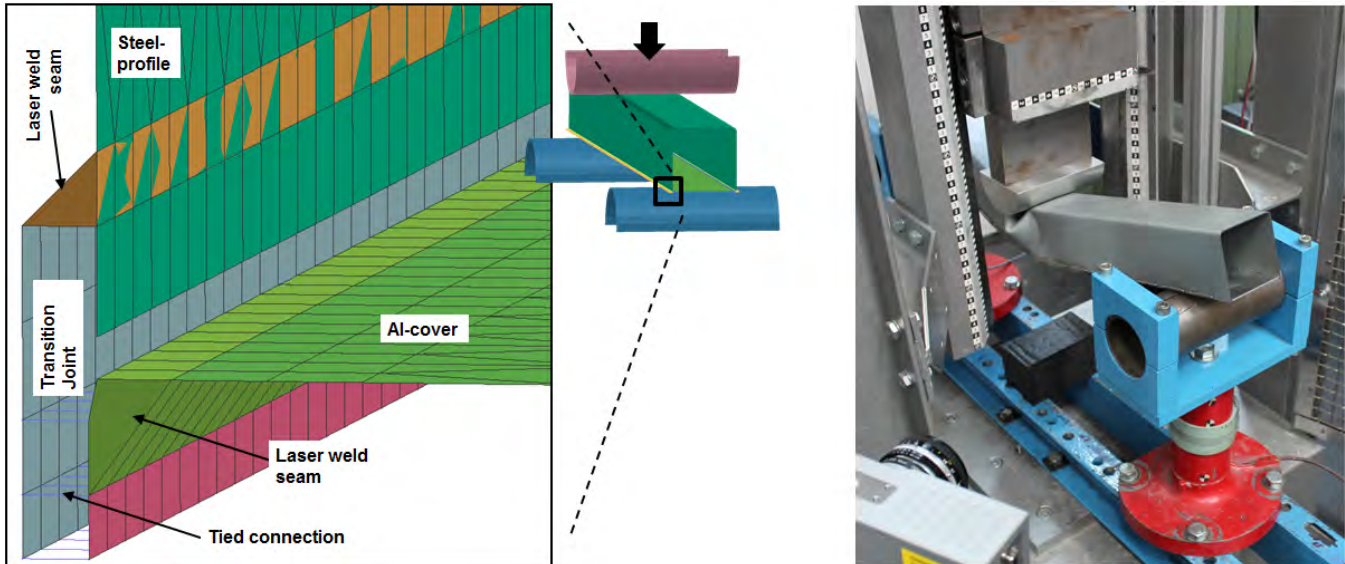


Figure 15: FE-model of the laser welded Transition Joint (left), 3-point bending crash test set up at TU Bergakademie Freiberg (right)

In comparison to the conventional spot welded design the crash test results of the hybrid components show the following results:

- Nearly maintaining the crash performance (Figure 16/ Deformation)
- Mass reduction of 30 % (Figure 16/ Mass)

The loss of bending stiffness, resulting from the welding flange elimination at the hybrid parts can be compensated by a higher structural stiffness of the joints. This is caused by the substitution of punctual connections (spot welding) by linear welds (web-slot / Transition Joint). In addition the simulation work could be evaluated successfully. The variation of deformation between crash test and simulation values was lower than 4 %. Hence, the crash behavior of hybrid components can be successfully estimated by the generated simulation methods.

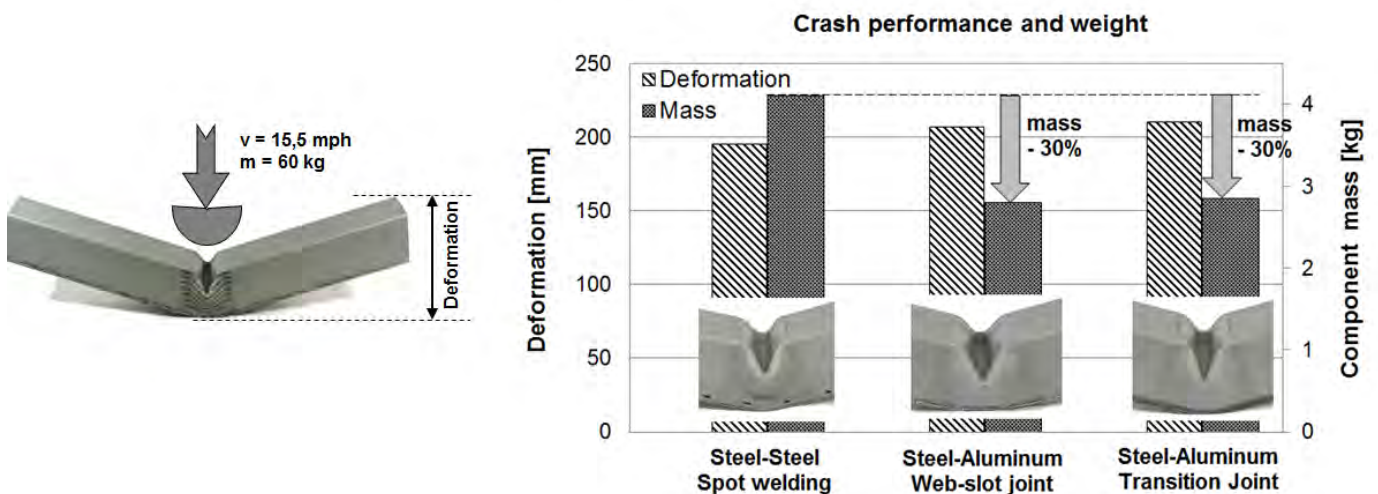


Figure 16: Test results of 3-point bending crash test

4. Summary and Outlook

Modern laser beam welding processes are broadly applied in particular industrial high volume manufacturing environments. The integration of laser beam welding in the manufacturing process of hybrid car body components is the next step to meet the ever-growing demands on lightweight designs.

Due to the research work completely new approaches for steel-aluminum multi-material designs were achieved and are ready for application. The laser induction roll plated (LIRP) bi-metal strips can be used as Transition Joints with high ductility due to avoid inter-metallic phase formations. Hence, the laser beam welding or even spot welding of the similar materials sides produces multi-material components with very good mechanical properties and flexible joint designs. Through welding flange elimination and integral component design significant weight and space reductions can be achieved in addition.

In order to produce steel-aluminum T-joints, the web-slot joining technology can be a good alternative. The combination of joining mechanisms (form fit + material bond) in conjunction with a productive 1-step joining process distinguishes this technology.

In relation to the conventional monolithic spot welded design a significant weight reduction of app. 30% can be achieved while the crash performance of hybrid bumper components can be ensured due to structural stiffness increase. Furthermore new simulation methods in order to create the most effective multi-material component design and to estimate precisely the deformation behavior of hybrid crash components have been successfully developed.

5. Bibliography

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