Laser assisted Friction Stir Welding of drawable steel-aluminium tailored hybrids

M. Merklein[1], A. Giera[1]

[1]*Chair of Manufacturing Technology – Egerlandstr. 11, 91052 Erlangen, Germany*
URL: www.lft.uni-erlangen.de e-mail: M.Merklein@lft.uni-erlangen.de; A.Giera@lft.uni-erlangen.de

ABSTRACT: Steel aluminium Tailor Welded Hybrids are still mentioned to be difficult to be joint as intermetallic phases appear during melting welding techniques. These phases are the reason for failure of the joint during loading or forming. As conventional friction stir welding, a solid phase welding technology, is not feasible to join steel and aluminium, laser assistance for preheating the steel sheet is adapted in order to enhance the weldability as well as the welding feed and to reduce the wear at the tool. Tensile tests are performed to achieve mechanical properties of joints, which were welded by systematic variation of process parameters. Finally deep drawing tests are conducted to demonstrate the formability of laser assisted friction stir welded steel aluminium joints.

Key words: Laser Assisted Friction Stir Welding, Steel-Aluminium Tailored Hybrid, Mechanical Characteristics, Microstructure, Cup Deep Drawing

1 INTRODUCTION

As a possible welding process of aluminium alloys, friction stir welding FSW has become a crucial joining method in shipbuilding, railway and airplane industries [1]. But knowledge about FSW of dissimilar metals such as steel and aluminium is still limited. Therefore, the practical realization of steel-aluminium Tailor Welded Hybrid Blanks in present industrial applications is marginal. Joining steel and aluminium with melting welding technologies leads to the challenge, that intermetallic phases appear [2], which influence the product life of the welded assemblies negative [3]. Until now different materials with unequal mechanical, physical and chemical properties are preferred to be joint by mechanical clamping [4] or gluing [5] are realized.
Friction stir welding [6] is an alternative welding technology operating in the solid phase during joining. Nevertheless steel aluminium Tailor Welded Blanks in a sheet thickness of about 1 mm are not feasible within the conventional technology [7].
The objective of this study was to perform butt joints of dissimilar steel and aluminium sheets in a thickness of about 1 mm. The main solution was offered by preheating the steel blank with a laser beam. In the following the experimental setup for laser assisted friction stir welding will be presented as well as results of joining investigations, e.g. regarding the mechanical properties and forming behaviour, which were achieved for steel aluminium blanks in a butt joint configuration.

2 EXPERIMENTAL PROCEDURE

2.1 *Conventional friction stir welding*

The main principle of the friction stir welding is based on frictional heating by the rotational feed of a cylindrical tool and the clamped work piece. In the beginning the rotating tool is slowly plunged into the blank. The first contact between the tool and the sheet is placed at the top of the probe, which extends coaxially from the tool. As soon as the shoulder is in contact with the blank surface, the immersion of the tool is stopped. In these investigations the diameter of the shoulder is 15 mm and that one of the probe 4 mm. Because of the frictional heat, which is generated by the rotating tool between the probe, the shoulder and the sheet as well as the down force of the tool, the material is locally heated. This leads to a loss in strength of the joining parts and because of friction at the surfaces of probe and shoulder the softened material is stirred, whereby three

characteristic zones are developed. The centre of the joint is dominated by the thermomechanically affected zone, which arises from the thermal and mechanic stirring of the abutting faces. Alongside the heat affected zone borders the heat affected zone, which results from the shoulder. The subsequent border area consists of unaffected material. The high process forces in combination with the arising temperatures demand the usage of high temperature resistant tool materials, which exhibit little wear. Nickel based super alloys and tungsten feature these demands.
As mentioned in the introduction conventional friction stir welding does not fit to perform steel-aluminium joints in a thickness of about 1 mm [7]. Therefore the idea was developed to preheat the steel blank in order to diminish the flow strength of the material and to enable a weld.

2.2 Experimental setup for laser assisted friction stir welding

The preheating of the steel sheet is realised by a laser spot, which is generated by the diode laser LDL 160-1500 (company Laserline). This laser is qualified as due to the wavelength of 808 ± 10 nm and 940 ± 10 nm, more than 55 % of the radiation are absorbed in the steel sheet [8].
The diode laser is positioned directly in front of the welding direction of the tool (Fig. 1), so that the laser spot is located 10 mm toward the tool and about 3 mm to the butt joint. The dimension of the laser spot itself is 3 x 3 mm^2. This preheating of the steel plate near the joining zone lowers the yield stress of the steel, which ensures wearless joining using a nickel-base alloy tools.
The tool is driven by an asynchronous motor, which is mounted at the head of a parallel kinematic machine Tricept 605 (company Neos). Latter enables a force control during the initial plunging state of the tool into the work piece, which benefits the reproducibility and the weld seam quality.

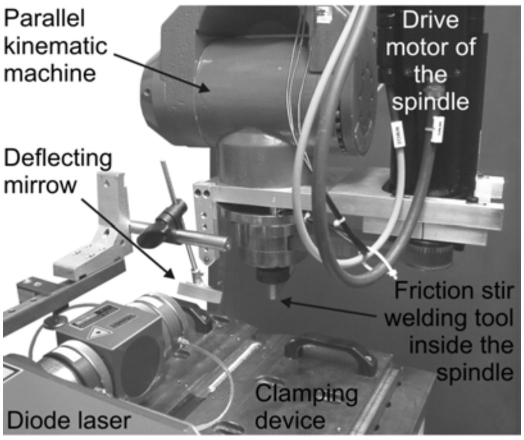

Fig. 1. Setup for laser assisted friction stir welding

Materials used for the presented investigations are the deep drawing steel DC04 and the precipitation hardenable aluminium alloy AA6016 T4 in sheet thicknesses of about 1 mm, which are mainly used for automotive car body components. After welding such hybrid joints, circular blanks are cut by laser beam, readily prepared for forming operations. Cup deep drawing experiments are conducted at a double-acting hydraulic press of the company Lasco (model TSP100S). The diameter of the punch is 50 mm, the inner diameter of the die 52.6 mm, both with a corner radius of 6.3 mm. All specimens were applied on both sides with the deep drawing oil Oemeta IHK 36.

2.3 Investigation and analysis

As no experiences are published for laser assisted friction stir welding of Tailored Hybrids in a thickness of about 1 mm, the main three process parameter, as the welding feed, the rotational speed of the tool and the laser power, have to be varied systematically in order to determine process parameters guarantying best mechanical properties of these welded parts during tensile tests. This is done by statistical means according to the design of experiments [9] and will determine the combination of parameters, with whose the best tensile strength and elongation at fracture of friction stir welded joints are achievable. These blanks will be taken for forming operations in order to receive a high drawing ratio. Results on the formability of steel-aluminium Tailored Hybrids will be shown and discussed.
Exemplarily the microstructures of the steel-aluminium interface were investigated using optical and scanning electron microscopy for explanation of the characteristic zones and the failure behaviour during tensile tests and deep drawing.

3 RESULTS

The process parameters are systematically varied for the experiments according to the DoE in Table 1.

Table 1. Parameter settings of the single trials

No.	Rotational speed [rpm]	Welding feed [mm/min]	Laser power [W]
1	3200	2000	1500
2	3200	2000	1000
3	3200	1500	1500
4	3200	1500	1000
5	2000	2000	1500
6	2000	2000	1000
7	2000	1500	1500
8	2000	1500	1000

Beside the augmentation of knowledge in friction stir welding of steel aluminium butt joints, the main aim for setting up the parameter field was an enhanced welding feed of up to 2000 mm/min in contrary to former investigations on laser assisted friction stir welding of steel and aluminium [10, 11]. Therefore the remaining parameters had to be adapted in order to achieve still a high weld seam quality. During carrying out the tests the first achievement was that the experiments can be executed only by locating DC04 on the advancing side and AA6016 on the retreating side of the joint.

Taking into account this precondition specimens for tensile tests have been cut out of laser assisted friction stir welded blanks. The analysis of tensile tests, which were repeating for each parameter combination by three trails (n=3), shows in trail number 8 in Fig. 2 a maximum tensile strength of Tailored Hybrids of about 200 N/mm². This implicates in comparison to the unaffected base material of AA6016, which exhibits a tensile strength of about 240 N/mm², a loss of strength of about 20 %. In the face of possible initial force transfer, which is essential for deep drawing, it is expected to achieve less drawing ratio than the experiments with the circular blanks of unaffected base material. Never the less this result shows the potential of laser assisted friction stir welding of steel aluminium blanks as this is the first step in this dimension. Additionally it must be taken into account, that due to the process characteristic a thinning of the joint is performed and there is no supplementary brazing solder to transfer the forces.

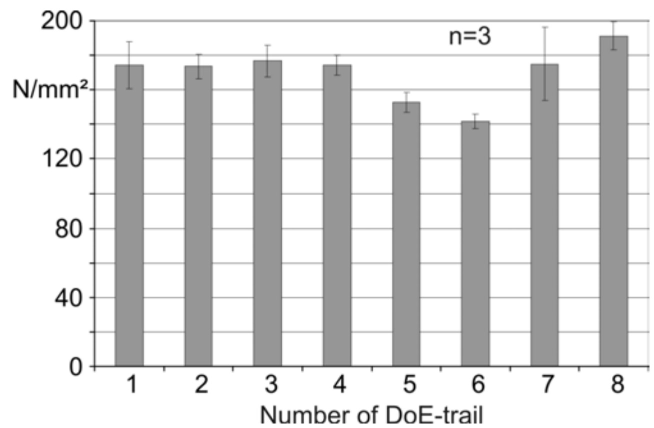

Fig. 2. Tensile strength of the experimental series according to the DoE

Cup deep drawing tests are basic investigations, in order to analyze the formability of homogenous materials and Tailored Hybrids. With the parameter of trail no. 8 steel aluminium blanks were friction stir welded in a butt joint and cut as circular blanks for cup deep drawing. Diameters 80 mm, 90 mm, 105 mm and 120 mm are chosen in order to realize drawing ratios of 1.6, 1.8, 2.1 and 2.4. The maximum drawing ratio is defined as the ratio between the maximum drawing diameter of the circular blank and the diameter of the drawing punch, which is formable without failure.

Fig. 3 shows the good formability of steel aluminium Tailored Hybrids up to a drawing ratio of 1.6 for the combination of DC04 and AA6016. For the result there is no difference between laying the rough top surface of the weld seam on the face of the punch or the fine bottom side. As the mechanical properties indicated a drawing ratio of 1.8 is not feasible (Fig. 3) as failure appears in the weld seam at the contact zone between steel and aluminium. This fact is confirmed by comparing the transferable force of 17.4 kN during cup deep drawing of a circular blank with a drawing ratio of 1.6 and 21.8 kN for a drawing ratio of 1.8, which is almost comparable. The blank holder force was kept constant at about 5 kN.

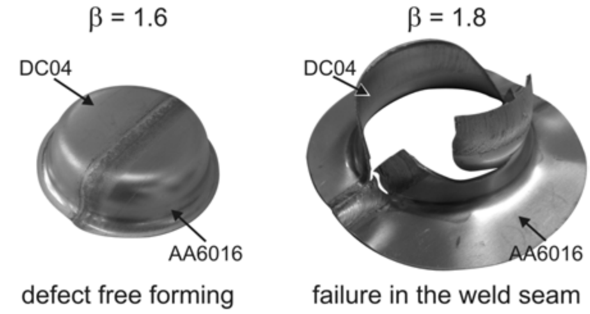

Fig. 3. Results on deep drawing of laser assisted friction stir welded steel aluminium circular blanks

As the failure during deep drawing appears at the contact zone between steel and aluminium, metallographic investigations were conducted in order to analyze the structure of the material. Because of the process temperature of about 450 °C intermetallic phases are anticipated.

Analysis proved neither with light microscopy nor with scanning electron microscopy the existence of intermetallic phases. This coincides with former results on friction stir welding of steel and aluminium in a lap joint [7].

In Fig. 4 the typical appearance of a weld seam in a cross section as well as in a top view are shown. Cross section I already indicates some darker regions in the stirring area of AA6016. The magnification (cross section II) exhibits characteristic zinc cords at the top side of AA6016, which are transferred because of the frictional forces during stirring from the top surface of the steel blank into the aluminium sheet. Cross section III of Fig. 4 marks the grain deformation and its refinement of DC04 at the contact area of steel and aluminium, which is caused by the effect of thermomechanical stirring during the welding process.

As there is obviously almost no diffusion between the two materials of the Tailored Hybrids, the question is open regarding the reason for the joining mechanism between steel and aluminium. By investigating the top view of the weld seam (Fig. 4) a hooked configuration at the contact area is visible. This structure arises from the process itself, similar to the arced top surface of the weld seam. One possibility is based in an insufficient stiffness of the working machine, which leads to a cyclic loading. Other reasons are the complex interactions between the various simultaneously occurring physical processes, which cyclically affect the structure and properties of the welded joints because of heating and cooling rates [12]. This means that the tool has to heat cooled areas, which will locally reduce the welding feed as the forces increase. Subsequently the plastified material will be amounted and due to the higher temperature transferred by frictional forces around the probe to the back of the tool. The tool will temporary increase the feed as the forces are reduced until it hits cooler areas again.

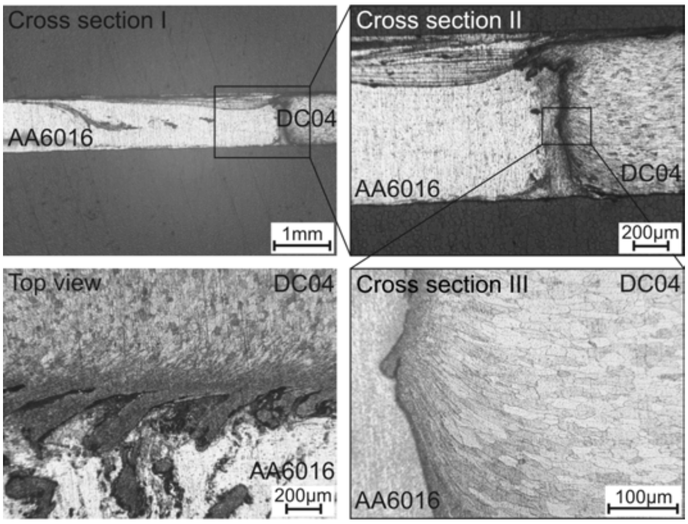

Fig. 4. Appearance of the weld seam in a cross section (I-III) and a top view

4 CONCLUSIONS

The documented investigations show the high potential of laser assisted friction stir welded steel aluminium Tailored Hybrids in a sheet thickness of about 1 mm, which were joint in a butt joint configuration. Even of this thickness they feature good possibilities to be assembled in automotive industry. Friction stir welding of these blanks was basically enabled by preheating the steel sheet by a diode laser spot. Simultaneously the welding feed had been significantly increased up to 2000 mm/min. By the means of statistical investigations a parameter field has been established in order to varying systematically the main process parameter welding feed, rotational speed and laser power. Tensile tests of these welded blanks confirm high tensile strength of up to 200 MPa, which corresponds about 80 % of the tensile strength of unaffected aluminium base material. This enables a primary formability in deep drawing tests by an achieved drawing ratio of about 1.6. Further investigation will concern the improvement of mechanical properties of steel aluminium Tailored Hybrids by narrowing the process window. This procedure is regarded as a very promising step as no intermetallic phases between steel and aluminium have been detected even by preheating the steel sheet with a diode laser spot.

ACKNOWLEDGEMENTS

The authors are grateful to the Deutsche Forschungsgesellschaft DFG for supporting the investigations in the framework of the dislocated research group “High performance welding technology for hybrid assemblies” (ME2047/7-2).

REFERENCES

1. Nicholas D., Friction Stir Welding: Benefits, Second EuroStir Workshop, Cambridge, (2002).
2. Achar D.R.G., Ruge J., Sundaresan S., Verbindung von Aluminium mit Stahl besonders durch Schweißen, Aluminium, Ausgabe 56, (1980) Heft 2: 147-149, Heft 3: 220-223, Heft 4: 291-293.
3. Radscheit R.R., Laserstrahlfügen von Aluminium mit Stahl, Dissertation, Universität Bremen (1996).
4. Abea Y., Katob, T., Mori K., Joinability of aluminium alloy and mild steel sheets by self piercing rivet, Journal of Materials Processing Technology, Vol. 177, Issues 1-3 (2006) 417-421.
5. N.N.: Aluminium/ steel construction on the BMW 5 series, www.i-caar.com [03.12.2007].
6. Thomas M.W., Nicholas J., Needham J.C., Murch M.G., Temple-Smith P., Dawes C.J., Friction Stir Butt Welding, GB Patent Application No.9125978.8, Dec 1991. US Patent No.5460317, Oct. 1995.
7. Merklein M., Giera A., Friction stir welding of thin steel aluminium hybrid blanks, The 9th International Conference on Material Forming, ESAFORM 2006, Glasgow, United Kingdom, April 26-28 (2006) 859-862.
8. N.N.: user’s guide: manual diode laser, lasertyp: LDL 160-1500. Laserline GmbH, Koblenz (2000).
9. Anderson V.L., McLean R.A., Design of experiments, Statistics/5, Dekker, New York (1974)
10. Giera A., Merklein M., Baumeister P., Laser-assisted Friction Stir Welding of Dissimilar Steel and Aluminum Alloys, 2nd International Conference on New Forming Technology ICNFT, Bremen (2007) 421-430.
11. Giera A., Merklein M., Geiger M., Joining of DC04 and AA5182 in a butt joint configuration by laser assisted friction stir welding, 5th Laser Assisted Net Shape Engineering LANE, Erlangen (2007) 1239-1247.
12. Nandana R., Roya G.G., Lienert T.J., Debroya T., Three-dimensional heat and material flow during friction stir welding of mild steel, Acta Materialia, Volume 55, Issue 3 (2007) 883-895