Hybrid Al/steel-joints manufactured by ultrasound enhanced friction stir welding (USE-FSW): Process comparison, nondestructive testing and microscopic analysis

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Abstract. The process of friction stir welding (FSW) is an innovative joining technique, which proved its potential in joining dissimilar metals that are poorly fusion weldable. This ability opens a wide range for applications in industrial fields, where weight reduction by partial substitution of conventional materials through lightweight materials is a current central aim. As a consequence of this, the realization of aluminum / steel-joints is of great interest. For this material compound, several friction stir welds were carried out by different researchers for varying Al/steel-joints, whereas the definition of optimal process parameters as well as the increase of mechanical properties was in the focus of the studies. To achieve further improved properties for this dissimilar joint a newly developed hybrid process named “ultrasound enhanced friction stir welding (USE-FSW)” was applied. In this paper the resulting properties of Al/steel-joints using FSW and USE-FSW will be presented and compared. Furthermore, first results by using the nondestructive testing method “computer laminography” to analyze the developed joining area will be shown supplemented by detailed light-microscopic investigations, scanning electron microscopic analysis, and EDX.

1. Introduction
Recent developments in many industrial sectors regarding lightweight constructions to save energy in different ways lead to the necessary realization of components out of dissimilar materials like aluminum or aluminum alloys and steel. But in this case, established fusion welding methods struggle with the development of brittle intermetallic (IM) phases in the welding area, which results in a significant reduction of the strength of the joint [1, 2]. In comparison to fusion welding friction stir welding (FSW) as a low temperature joining process is a more appropriate method, because of the reduced development of intermetallic phases. FSW is characterized by a rotating cylindrical tool, which gets plunged in a butt or overlap joint of two materials and then runs along contact area with a defined feed rate [3]. Several research work has been performed on the field of Al/steel-joints concerning the realization of high-strength welds [4–7]. Watanabe et al. reached a maximum tensile strength for their FSW-joints of 86 % of their aluminum base material [4]. But in the most cases in literature the presence of intermetallic phases in the nugget and at the interface of the joints after the
friction stir welding process is described [4, 6–8]. This verified that IM-phases also cannot be completely reduced by using FSW. Furthermore, the intermetallics appear as brittle separating layers between the base materials. This weakens the joint strength additionally. To reduce these detrimental effects, different approaches were investigated for FSW of Al/steel-joints. Liu et al. and Ferrando worked with an electrically assisted friction stir welding system, which enables a local electrical current density field to run synchronous to the FSW tool. The occurring electro-plastic effect results in a material softening due to the elevated process temperatures and also in the formation of a thin layer of IM-phase, which was believed to increase the joint strength by micro-interlocking [8, 9]. This additional heating approach for the contact area was also applied by Merklein et al. who used laser assistance for their friction stir welding process. They further observed a reduced tool wear and a higher drawing ratio for their joints [10]. Another method for extra heating was the gas tungsten arc welding (GTAW) supported version of FSW introduced by Bang et al., where a GTAW torch runs in front of the friction stir welding tool and also leads to joints with higher tensile strength. This is attributed to an improved material plastic flow and partial annealing effects [11]. A further concept was realized by Klag et al. and Straß et al., who investigated Al/Mg-joints by using additional power ultrasound during the friction stir welding process [12, 13]. This hybrid joining method named “ultrasound enhanced friction stir welding (USE-FSW)” improves the joint strength by the mechanical breakup and fine dispersion of the continuous brittle intermetallic layers. With this method an increase of the tensile strength of 25 % for USE-FSW compared to conventional FSW can be achieved directly.

Based on this positive effects in the recent work the potential of the USE-FSW for dissimilar joints of aluminum with steel will be presented. Therefore, FSW- as well as USE-FSW-joints were realized and analyzed by light-microscopic and scanning electron microscopic methods. Additional nondestructive computer laminography examinations were carried out to find possible weld defects in the bonding area.

2. Experimental Procedure

For the investigations the commercially available aluminum wrought alloy EN AW-6061 T6 (AlMg1SiCu) and the deep-drawing steel DC04 (1.0338) are used in a sheet geometry of 280 mm length, 100 mm width and 3 mm thickness. The chemical composition of the materials according to the manufacturer specifications can be seen in table 1.

| Table 1. Chemical composition of the investigated materials. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Material        | Elements (wt%)  |
| EN AW-6061 T6   | Si   | Fe   | Cu   | Mn   | Mg   | Cr   | Zn   | Ti   | Al   |
|                 | 0.64 | 0.51 | 0.21 | 0.14 | 0.89 | 0.15 | 0.04 | 0.05 | bal. |
| DC04            | C    | Si   | Mn   | P    | S    | Al   | Ti   | Nb   | Fe   |
|                 | 0.041| 0.015| 0.3  | 0.01 | 0.0077| 0.49 | 0.0007 | 0.0037 | Bal |

For the friction stir welding process a universal four axis machining center DMU80T from DMG MORI was used extended with a pneumatic clamping for the metal sheets as well as four load cells from Kistler to realize a force controlled process (figure 1).
For the investigations a butt-joint configuration was chosen, whereby the steel plate was placed on the advancing side and the aluminum plate on the retreating side. The welding direction was perpendicular to the rolling direction of EN AW-6061 and parallel to the rolling direction of DC04. For the FSW tool a hot-work steel 1.2344 (X40CrMoV51) with a shoulder diameter of 16 mm, a probe length of 2.8 mm and a metric thread of M4.5 was used. An axial force of 4 kN, a tool rotation speed of 1500 rpm, a travel of 20 mm/min, a tilt angle of 2°, and a lateral offset of the probe surface to the faying surface of the steel of 0.3 mm were chosen for conventional friction stir welding. For USE-FSW the machining center was additionally equipped with a Lab VIEW-controlled ultrasonic roll seam module of Schunk Sonosystems, which moves synchronously and parallel to the tool (figure 2).
The roll seam module works with a resonant frequency of 20 kHz, a generator maximum of 3000 W, and a constant amplitude of 18 µm. The transmission of the ultrasound takes place in the steel sheet located on the advancing side.

3. Results and Discussion

The analysis on the microstructure of the developing joining area was carried out by light microscopic investigations first. The comparison of the two cross-sections clearly show the influence of additional ultrasound power on the joining area (figure 3).

![Figure 3. Cross section images of Al/steel-joints: (a) FSW and (b) USE-FSW.](image)

For conventional friction stir welding larger steel particles can be detected in the nugget area (white circles in figure 3 (a)). Furthermore, an extensive steel hook from the base material DC04 is apparent. In comparison to this for USE-FSW Al/steel-joints the interface between EN AW-6061 and DC04 is nearly perpendicular and the nugget clearly defined (white dashed line figure 3 (b)). It is recognizable that simultaneous transmitted power ultrasound improves the development of the bonding zone during the FSW process.
Furthermore, a detailed analysis of the microstructure of the stirred zone for FSW and USE-FSW was carried out by scanning electron microscopy (SEM). Thereby different types of particles could be found in the welding area of FSW-joints. In figure 4 (a) larger particle within the nugget of an FSW Al/steel-joint is depicted and analyzed.

The particle consists of a partially present shell and a fine stripped layer structure inside. For the shell two different intermetallics were identified by energy dispersive X-ray spectroscopy (EDX) spot measurements (figure 4 (b) 1 and 2). The particle facing layer (1) was determined as a Fe$_2$Al$_5$-phase and the nugget facing IM-phase (2) contents out of the aluminum-rich FeAl$_3$. Due to the small width of the intermetallic layers in the inner structure of the particle (figure 4 (c)) only an average EDX analysis could be performed. With that, a quantity proportion of 83 % iron and 17 % aluminum was detected. The structure and morphology of this particle leads to the assumption that it was formed at the contact area of the base materials due to the FSW process and afterwards, as a result of the stirring, transferred into the nugget. Similar observation are also described by different authors in the literature [4, 6, 7, 11].

The same procedure can be assumed for another type of particles consisting of nearly pure steel and found in the nugget, too. But, in this case it can be presumed that the steel particles are from the DC04 joining partner or from the FSW-tool.

In comparison to the FSW-joints, for USE-FSW-joints in the nugget only steel particles were found by SEM-investigations (figure 5 (a)).
Unlike the fine stripped intermetallic layer particle for FSW-joints the particles of USE-FSW-joints are nearly completely surrounded by an IM-phase shell. Again, EDX-spot measurements were performed for the shell and the inner structure (figure 5 (b)). It revealed that the intermetallic layer (1) consists of the aluminum-rich FeAl$_3$ whereas the particle itself (2) contains of 98 % iron. The formation can be explained by the transfer of steel particles from the DC04 through ablation caused by the material flow on the surface of the contact area between the base materials. Moreover, the process temperature is high enough to enable the development of the FeAl$_3$-phase on the surface of the particle.

Furthermore nondestructive computer laminography (CL) investigations were carried out for both process variants (figure 6).

The CL-investigations confirm the flawlessness for both joints. Also no fundamental differences between FSW (Figure 6 (a)) and USE-FSW (Figure 6 (b)) can be found in the welds. But both joints contain some irregularities, probably larger steel particles and the USE-FSW joint shows a smaller amount of these irregularities. This can be a consequence of the power ultrasound and the related reduction of larger intermetallic phases in the welding area. These approaches will be checked in further investigations.
4. Summary
It could be shown, that it is possible, to realize Al/steel-joints by FSW as well as by USE-FSW. Therefore central parameters like axial force, tool rotation speed, travel speed, tilt angle and lateral offset were optimized.

For both FSW variants, the microstructure of the welding zone were investigated. For conventional FSW two types of particles, particles out of intermetallic phases and steel particles were detected in the nugget. Particles characterized by a fine stripped layer structure consisting of 83 % iron and 17 % aluminum and a two layer partial shell consisting of the two intermetallic phases FeAl
3 and Fe2Al5, whereas USE-FSW-joints only contained steel particles with an nearly closed FeAl3 shell. This is a clear indicator that the additionally introduced power ultrasound reduces the amount of particles and intermetallic phases in the nugget for EN AW-6061/DC04-joints.

By computer laminography it could be shown that the realized joints for both variants of FSW are sound free. Small irregularities were detected for FSW- and USE-FSW-joints, whereas the amount of them were lower for ultrasound enhanced friction stir welding.

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