Recent Developments for Ultrasonic-Assisted Friction Stir Welding: Joining, Testing, Corrosion – an Overview

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Abstract. Due to the steadily increasing demand on innovative manufacturing processes, modern lightweight construction concepts become more and more important. Especially joints of dissimilar metals offer a variety of advantages due to their high potential for lightweight construction. The focus of the investigations was Al/Mg-joints. Friction Stir Welding (FSW) is an efficient process to realize high strength joints between these materials in ductile condition. Furthermore, for a simultaneous transmission of power ultrasound during the FSW-process (US-FSW) a positive effect on the achievable tensile strength of the Al/Mg-joints was proven. In the present work the industrial used die cast alloys EN AC-48000 (AlSi12CuNiMg) and AZ80 (MgAl8Zn) were joined by a machining center modified especially for Ultrasound Supported Friction Stir Welding. The appearing welding zone and the formation of intermetallic phases under the influence of power ultrasound were examined in particular. In order to identify optimal process parameters extensive preliminary process analyzes have been carried out. Following this, an ultrasound-induced more intensive stirring of the joining zone and as a result of this a considerably modified intermetallic zone was detected. At the same time an increase of the tensile strength of about 25% for US-FSW-joints and for fatigue an up to three times higher number of cycles to failure in comparison to a conventional welding process was observed. Moreover, detailed corrosion analyzes have shown that especially the welding zone was influenced by the corrosive attack. To expand and deepen the knowledge of the US-FSW-process further material combinations such as Ti/Steel and Al/Steel will be considered in future.

1. Motivation
Aluminum and magnesium die cast alloys possess a high potential for industrial applications due to their low density and high specific tensile strength in combination with low manufacturing costs [1]. The fabrication of tailored components made of these two light metals is of central interest in many industrial sectors like the automotive sector and the aerospace industry. The main aim actually is to find alternative welding methods for these materials, because it is not possible to join aluminum and magnesium by fusion welding due to the strong formation of brittle intermetallics in the whole bonding zone. However Friction Stir Welding (FSW) as a low temperature pressure welding method is a suitable alternative to manufacture hybrid joints while largely avoiding intermetallic phases (IM-phases) [2], because these precipitates have a limiting influence on the mechanical properties of the realized Al/Mg-joints. But also for FSW the formation of IM-phases cannot be avoided completely. In
the contact area between the dissimilar base materials two continuous IM-layers occur. To reduce their influence on the mechanical properties Ultrasonic Supported Friction Stir Welding (US-FSW) was developed with regard to disperse the IM-phases in the welding zone [3]. The present work will give an overview about the possibilities of US-FSW, the resulting microstructure as well as the monotonic and cyclic properties of Al/Mg-joints. Furthermore the corrosion behavior and suitable non-destructive testing methods will be discussed.

2. Experimental Procedure
The commercially available cast-alloys EN AC-48000 (AlSi12CuNiMg) and AZ80 (MgAl8Zn) were used for the investigations. For US-FSW the materials were butt-welded in die-casted condition using sheet geometry of 280 mm x 100 mm x 3.3 mm. For the welds a machining center DMU80T from Deckel Maho was used modified for FSW (Figure 1 a) [4].

![Figure 1. a) Machining center DMU80T modified for FSW, b) 3D-model of a welding tool [4]](image)

The Al/Mg-hybrid-joints were produced with a welding tool made of hot-work steel 1.2344 (X40CrMoV51) (Fig. 1 b). It has a tool-shoulder of 16 mm diameter, a pin with a length of 3.1 mm and a metric thread (M4.5). For the input of the ultrasound a specially designed ultrasonic seam module type RM 20 from Schunk Sonosystems was used (Figure 2).

![Figure 2. Ultrasonic assisted Friction Stir Welding, schematically [5]](image)

The seam module works with a resonant frequency of 20 kHz, a maximal generator power of 3000 W and an amplitude of up to 35 µm. The optimized work distance between sonotrode and welding zone was 95 mm. The input of the ultrasound is controlled via LabVIEW and takes place in the aluminum sheet, which is also located as the Advancing Side.
3. Results and Discussion
Based on light-microscopic cross-section images a comparison between EN AC-48000/AZ80-FSW-joints and EN AC-48000/AZ80-US-FSW-joints was carried out regarding the influence of the ultrasound (Figure 3).

![Microscopic cross-section images of a) Al/Mg-FSW and b) Al/Mg-US-FSW](image)

It is obvious that the ultrasound has an influence on the nugget shape and also on the microstructure of the welded joints. While the conventional FSW-nugget shows a vertical edge on the Mg-side (Fig. 3 a), the US-FSW-nugget is much flatter (Figure 3 b). In addition, the use of ultrasound strongly intensified the mixing of the joining-materials within the nugget – an observation that was already made by other researchers [6]. As a further part of the microstructural investigations Scanning Electron Microscopy (SEM) was carried out to gain a deeper understanding of the nugget-zone. Thereby two continuous intermetallic layers could be found at the interface of Mg and nugget. This effect for Al/Mg-FSW-joints had also been detected by Klag et al. [2]. The layers could be identified by EDX-Spot-Measurement as the intermetallic phases Mg$_{17}$Al$_{12}$ and Al$_3$Mg$_2$. These brittle precipitations impair the mechanical properties of the EN AC-48000/AZ80-FSW-joints. In comparison to this, the use of ultrasound-supported Friction Stir Welding leads to just one intermetallic Mg$_{17}$Al$_{12}$ layer (Figure 4).

![Interface Mg/nugget schematically of a) FSW and b) US-FSW](image)

The aluminum rich Al$_3$Mg$_2$ is cracked by the ultrasound and then dispersed over the nugget-zone [4]. A better understanding of this process could be achieved by EBSD-mappings of the nugget (Figure 5).
Figure 5. EBSD-analysis of Al<sub>3</sub>Mg<sub>2</sub> in the nugget-zone: a) FSW and b) US-FSW [4]

The pictures show the described morphology of Al<sub>3</sub>Mg<sub>2</sub> in the welding zone of EN AC-48000/AZ80-FSW-joints (Fig. 5 a) and in EN AC-48000/AZ80-US-FSW-joints (Figure 5 b). This advantageous impact of US-FSW was also discovered by Park [7].

Further investigations of the mechanical properties by static and dynamic testing were carried out in this work. Figure 6 represents a comparison of the tensile strengths of the two base materials, Al/Mg-FSW-joints and Al/Mg-US-FSW-joints.

Figure 6. Comparison of the achieved tensile strengths of the base materials, the FSW-joints and the US-FSW-joints [4]

The conventionally welded joints achieve an average tensile strength of 98 MPa, which corresponds to 50 % of the strength of the weaker joining partner AZ80. The ultrasound-supported EN AC-48000/AZ80-joints show higher values of about 122 MPa, a tensile strength increase of 25 % in average.

The cyclic fatigue behavior of the welded materials was characterized by an S/N-curve (Figure 7). It can be seen that Al/Mg-US-FSW-joints attain significantly higher lifetimes for the same stress.
Figure 7. Comparison of S/N-curves for the EN AC-48000/AZ80-FSW-joints and the EN AC-48000/AZ80-US-FSW-joints [4]

Beside destructive testing non-destructive test methods, electro-magnetic-induced ultrasound (EMUS) and X-ray radiography were carried out on the Al/Mg-joints to verify their capability of detecting welding defects. Figure 8 shows the results of the EMUS-testing.

Figure 8. Non-destructive testing via EMUS at a sound FSW-weld (a) and at a flawed weld (b) [4]

A sound welding joint shows a weld echo and an edge echo by elevated intensities. The flawed weld exhibits only higher intensities only for the weld echo due to the present defects. Also by using X-ray radiography differing images for conventional welded joints and ultrasound-supported welded joints could be observed (Figure 9).
Both images show a high weld quality and only one irregularity over the weld length, which could be attributed to the mold of the sheets. Additionally several pores in the aluminum base material could be detected. For US-FSW the more intensive stirring of the material in the joining area is clearly recognizable.

To attain more detailed results about corrosive processes, especially in the nugget area, spatially dissolved corrosion tests were carried out by means of Scanning Kelvin Probe microscopy. Figure 10 shows a comparison for the electrochemical potential difference for FSW- and US-FSW-joints.

Generally clear differences in corrosion behavior for the welding zone and the two base materials could be detected. In comparison to conventional FSW-joints an increase of the potential difference in ultrasound-supported joints can be observed, especially for the EN AC-48000-alloy and the nugget.
Furthermore a considerably higher gradation for US-FSW-joints can be observed in the welding zone and at its transition to the magnesium alloy.

4. Summary
The investigations have shown that ultrasound support during Friction Stir Welding positively influences the resulting microstructure and the achievable mechanical properties. The tensile strength increases up to 25% and for fatigue the number of cycles to failure is three times higher for the same stress amplitude. Furthermore non-destructive testing methods have proven to be suitable to characterize joints. The important role of corrosion for joints made of dissimilar metals was presented by Scanning Kelvin Probe measurements, which have shown that the corrosive behavior of welded EN AC-48000/AZ80 sheets is determined by the microstructure of the developing nugget.

Acknowledgement
We would like to thank the “German Research Foundation (DFG)” for the support of the present work as a part of the Priority Program 1640 “Joining by Plastic Deformation”.

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