Application of the hybrid process ultrasound enhanced friction stir welding on dissimilar aluminum/dual-phase steel and aluminum/magnesium joints

Anwendung des Hybridprozess des ultraschallgestützten Rührreibschweißens auf artfremde Aluminium/Dualphasenstahl- und Aluminium/Magnesium-Verbunde

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Friction stir welding as a solid-state joining method with its comparatively low process temperatures is suitable for joining dissimilar materials like aluminum/magnesium or aluminum/steel. Such hybrid joints are of great interest regarding lightweight efforts in different industrial fields like the transportation area. The present work investigates the influence of additionally transmitted power ultrasound during the friction stir welding on the joint properties of EN AC-48000/AZ91 and EN AW-6061/DP600. Therefore, conventional friction stir welding was continuously compared to ultrasound enhanced friction stir welding. Light microscopic analysis and nondestructive testing of the joints using x-ray and high frequency ultrasound show different morphologies of the nugget for the aluminum/magnesium joints as well as differences in the amount and size of steel particles in the nugget of aluminum/steel joints. Scanning electron microscopy proves differences in the thickness of continuous intermetallic layers for the aluminum/steel joints realized with and without power ultrasound. Regarding the tensile strength of the joints the power ultrasound leads to increased joint strengths for EN AC-48000/AZ91 joints compared to a decrease for EN AW-6061/DP600 joints. Corrosion investigations show an influence of the ultrasound power on the corrosion properties of EN AC-48000/AZ91 joints which is attributed to a changed aluminum content in the nugget region. Because of the great potential difference between the magnesium and the nugget phase the transitional area exhibits strong galvanic corrosion. For EN AW-6061/DP600 joints an increased corrosion caused by galvanic effects is not expected as the potentials of the EN AW-6061 aluminum alloy and DP600 steel are very similar.

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Rührreibschweißen ist als Festphasenfügeverfahren mit seinen vergleichsweise geringen Prozesstemperaturen geeignet, um Werkstoffverbunde artfremder Metalle wie Aluminium/Magnesium und Aluminium/Stahl zu verbinden. Derartige Hybridverbunde sind hinsichtlich Leichtbaubestrebungen in verschiedenen industriellen Gebieten wie beispielsweise der Transportmittelbranche von großem Interesse. Die vorliegende Arbeit untersucht den Einfluss von zusätzlich zum Rührreibschweißen eingeleiteten Leistungsultraschall auf die Verbundeigenschaften von EN AC-48000/AZ91- und EN AW-6061/DP600-Verbunden. Dabei wurde durchgängig das konventionelle Rührreibschweißen mit dem ultraschallunterstützten Rührreibschweißen verglichen. Lichtmikroskopische Analysen und zerstörungsfreie Prüfungen der Verbunde mittels Röntgendurchstrahlung und Hochfrequenz-Ultraschall zeigen verschiedene Morphologien für die Fügezone von Aluminium/Magnesium Verbunden sowie Unterschiede in der Anzahl und Größe von Stahlpartikeln in der Fügezone von Aluminium/Stahl Verbunden. Rasterelektronenmikroskopie weist Unterschiede in den kontinuierlichen intermetallischen Schichten für Aluminium/Stahl Verbunde, welche mit und ohne Leistungsultraschall realisiert wurden, nach. Hinsichtlich der Zugfestigkeiten der Verbunde führt Leistungsultraschall zu einem Anstieg der Verbundfestigkeiten für EN AC-48000/AZ91 Verbunde verglichen mit einem Abfall für EN AW-6061/DP600 Verbunde. Korrosionsuntersuchungen zeigen einen Einfluss der Ultraschallleistung auf die Korrosionseigenschaften von EN AC-48000/AZ91 Verbunden, was auf einen geänderten Aluminiumanteil im Nugget zurückgeführt wird. Aufgrund des großen Potentialunterschiedes zwischen Magnesium und Aluminium unterliegt der Magnesium/Nugget-Übergang starker galvanischer Korrosion. Für Aluminum/Stahl-Verbunde wird eine verstärkte galvanische Korrosion nicht erwartet, da sich die Korrosionspotentiale der Aluminiumlegierung EN AW-6061 und des DP600 Stahls nur wenig unterscheiden.

Schlüsselwörter: Rührreibschweißen / Leistungsultraschallunterstützung / Mikrostruktur / zerstörende und zerstörungsfreie Prüfung / Korrosion

1 Introduction

Regarding the steadily advancing development of new high-performance materials to fulfill different economic and ecologic goals the need of suitable joining methods for realizing innovative dissimilar material welds with these new high-performance materials is also increasing [1]. Conventional fusion welding techniques struggle for the application on joining dissimilar materials like polymer/metals, ceramic/metals or even dissimilar metals. The reasons for this are the extremely different physical properties of the joining partners for these dissimilar material, for example the melting temperature [2]. Regarding the task to join dissimilar metals high process temperatures, which are characteristic for fusion welding techniques, result in the formation of brittle intermetallic phases in the joint zone. These phases reduce the tensile strength as well as the resistance against fatigue of the dissimilar welds [3]. To avoid a strong formation of intermetallic phases the welding temperature needs to be reduced, which can be achieved by using solid-state welding techniques like friction stir welding (FSW). This process is based on the heat generation due to the friction between a rotating cylindrical tool with a pin at its head and the joining partners. The tool rotates with a defined speed and gets applied on the joining partners with an also defined welding force. The resulting frictional heat leads to a plasticization of the material and enables the pin to plunge into the plasticized material. In a next step the tool runs with a defined feed along the joint geometry and stirs the plasticized material together leading to a joint with superior properties [4]. These joint properties are attributed to the low process temperature with a maximum of 0.8 times of the
melting temperature. While using such innovative welding technologies for dissimilar metals like aluminum/magnesium and aluminum/steel suitable non-destructive testing methods need to be considered to ensure high quality of the produced joints and efficiency of the welding process. Furthermore, a consideration of the corrosion behavior of such dissimilar welds needs to be carried out. The combination of dissimilar metals with different electrochemical potentials leads to enhanced corrosion and thereby to weakening of the joints after a certain time.

2 State of the art and aim of the investigations

Friction stir welding of dissimilar metals offers great potential compared to other joining methods like riveting. The possible weight savings due to the loss of the additional rivet and the more homogenous joining zone without the hole for the rivet will lead to a higher lightweight potential as well as it will reduce costs [4]. Thereby the process of friction stir welding is more challenging for hybrid joints due to the different chemical, mechanical, physical and thermal properties of the base materials. Specific adjustments in the process need to be carried out regarding the optimal placement of the different base materials on the advancing and retreating side as well as the optimal offset of the pin with respect to the butt joint [3]. Furthermore, the formation of brittle intermetallic phases is a limiting factor for the joint strength of dissimilar metal joints.

Regarding aluminum/magnesium joints the optimal joint properties were achieved with the aluminum placed on the advancing side and magnesium on the retreating side [5–7]. Furthermore, offsets of the pin into the magnesium varied from 0 mm to 1 mm [5, 8]. A true stirring of the base materials is achieved due to the small offset and the similar melting temperatures of 660°C for aluminum and 650°C for magnesium. The presence of intermetallic phases was detected for several investigations regarding dissimilar aluminum/magnesium joints. Thereby two continuous intermetallic layers consisting of the aluminum-rich β-phase (Al<sub>11</sub>Mg<sub>2</sub>) and the magnesium-rich γ-phase (Mg<sub>2</sub>Al<sub>17</sub>) at the interface nugget/magnesium were found [5, 7].

Aluminum/steel joints show a different behavior due to the strongly differing physical properties, whereas the melting temperature of steel is nearly 2.5 times higher than that of aluminum. For this group of hybrid joints the steel is always placed on the advancing side considering the aluminum as the softer base material which gets stirred onto the steel [9–11]. For the offset of the pin a shifting into the aluminum is common, whereas the pin touches the surface of the steel and thereby activates the interface for an improved bonding between aluminum and steel [9, 12]. This interface is also characterized by the presence of an aluminum-rich continuous intermetallic phase consisting of Fe<sub>2</sub>Al<sub>3</sub> or FeAl<sub>3</sub> [13, 14].

Further investigations proved that a reduction of brittle intermetallic phases at the interface of dissimilar metal joints like aluminum/magnesium and aluminum/steel lead to higher tensile strengths [8, 14]. To achieve such a reduction in the thickness of the intermetallics the process temperature can be reduced, which is limited due to the pressure welding method itself, or alternatively can be influenced by the additional transmission of power ultrasound into the friction stir welding [5, 7, 15]. By using this hybrid joining method of ultrasound enhanced friction stir welding (USE-FSW) compared to conventional friction stir welding for aluminum/magnesium joints the Al<sub>11</sub>Mg<sub>2</sub>-phase could be broken and distributed as fine particles over the nugget, which led to an increase in tensile strength [8, 16, 17]. This power ultrasound transmission influenced the intermetallic phase of aluminum/steel and aluminum/copper joints also by reducing the thickness of the continuous phases, leading to higher tensile strengths as well [18–20].

The present work investigates the influence of power ultrasound on different dissimilar metal joints of EN AC-48000/AZ91 and EN AW-6061/DP600 and continuously compares the friction stir welding with the ultrasound enhanced friction stir welding. Therefore, the ultrasound power as well as the transmission side of the power ultrasound was varied. Beside light and scanning electron microscopic investigations on the resulting microstructure further destructive tensile tests were carried out. As a non-destructive reference method radiography (x-ray) and also high-frequency ultrasound immersion testing were conducted on the same samples. The corrosion properties of the hybrid joints were investigated by scanning Kelvin probe (SKP) measurements in humid air and electrochemical measurements (open circuit potential and potentiodynamic polarization) in sodium chloride solutions. By comparing the measured poten-
Table 1. Chemical composition of the investigated materials.

| Material   | Elements [wt.%]       |
|------------|-----------------------|
| EN AW-6061 | Si 0.64 Fe 0.51 Cu 0.21 Mn 0.14 Mg 0.89 Cr 0.15 Zn 0.04 Ti 0.05 Al Bal. |
| DP600      | C 0.14 Si 1.5 Mg 2 Mn 0.07 P 0.015 S 0.15 Al B N Fe 0.009 |
| EN AC-48000| Si 11.86 Cu 1.02 Mg 1.04 Fe 0.28 Ni 0.99 Cr 0.01 Al 0.08 Mn 0.13 |
| AZ91       | Al 9.39 Zn 0.85 Mn 0.17 Fe 0.003 Si 0.047 Ni 0.002 Cu Be Mg 0.002 Bal. |

3. Materials and experimental details

3.1 Materials

Metal sheets of the two die-casted alloys of EN AC-48000 (AlSi12CuNiMg) and AZ91 (MgAl9Zn1) were used in a sheet geometry of 150 mm × 100 mm × 3 mm, attributed to the die-casting mold. For the aluminum/steel joints the aluminum wrought alloy EN AW-6061 (AlMg1SiCu) and the dual-phase steel DP600 (1.0936) were used. Their geometry was 280 mm × 100 mm × 3 mm. Their chemical composition according to the specifications of the manufacturer can be seen, Table 1.

3.2 Ultrasound enhanced friction stir welding process

A four axis universal machining center DMU80T from DMG Mori was used to realize the friction stir welding. It is additionally equipped with four load cells from Kistler to run the process force-controlled and uses a pneumatic clamping to fix the metal sheets in a butt joint configuration. For the aluminum/magnesium joints the EN AC-48000 was placed on the advancing side and the tool was made of hot-work steel 1.2344 with a shoulder diameter of 16 mm, a pin length of 2.8 mm and a metric thread of M6.4. For the aluminum/steel joints the steel was always placed on the advancing side. The friction stir welding tool had a diameter of 16 mm for the shoulder, a 2.8 mm pin length with a metric thread of M6 and it consisted of a tungsten based alloy with 1% lanthanum oxides, Figure 1b. For aluminum/steel joints a lateral offset of the tool centre axis of 3 mm into the aluminum was applied. The design of experiment method of Taguchi was used to find parameters maximizing the tensile strength of the joints. Therefore, the rotational speed, the welding speed, the tilt angle and the lateral offset of the pin surface to the faying surface were considered. The used parameters for EN AC-48000/AZ91 joints and EN AW-6061/DP600 joints are shown, Table 2. A scheme of the hybrid method of ultrasound enhanced friction stir welding is shown, Figure 1a. An ultrasonic roll seam module of Schunk Sonosystems was installed additionally on the universal machining center. It runs synchronously and parallel to the friction stir welding tool within in the process and transmits the power ultrasound with a resonance frequency of 20 kHz, a generator maximum power of 3000 W and a maximum amplitude of 38 μm. Within the scope of the investigations the
power of the ultrasound was varied for aluminum/magnesium in four steps of 225 W, 450 W, 700 W and 1000 W as well as for the aluminum/steel in two steps of 225 W and 1000 W. The transmission side of the power ultrasound was also varied for the welding of aluminum/magnesium to investigate the influence of the transmitting material.

3.3 Microstructural investigations

The cross sections of the EN AC-48000/AZ91 friction stir welding and ultrasound enhanced friction stir welding hybrid joints were made by using Brillant T250E by ATM and Accutom-50 by Struers cutting machines. The samples were cut into a width of 35 mm across the nugget. The embedded samples were ground using silicon carbide paper with grain sizes from P320 to P4000 by wet grinding. After grinding the samples were polished using grinding sheets from 3 μm to 1 μm and DP lubricant and suspenders. The polished samples were cleaned with acetone and dried. The samples were etched by immersing the cross section surface in Nital etchant (3 % nitric acid and 97 % ethanol by weight) for a few seconds. After etching the microscopic images of different regions of the hybrid joints were obtained using a Leica DMLA light microscope.

The preparation of the EN AW-6061/DP600 joint samples for microscopic analysis of the cross section took place by cutting the dissimilar welds of aluminum/steel and embedding them with cold embedding resin. Afterwards the samples got ground with wet silicon carbide paper (up to P4000), then polished with a DiaPro Nap 1 μm suspension and finally cleaned and dried with ethanol. Light microscopic investigations were carried out on a light microscope Olympus GX51. The amount and size of particles in aluminum/steel joints was determined by the systematic manual point count in accordance with ASTM E562. For the scanning electron microscopy a microscope Leo1455VP from ZEISS was used.

3.4 Destructive and nondestructive testing methods

The tensile tests were performed on a 20 kN Zwick Roell tensile testing machine at room temperature with a strain rate of 2.5·10⁻⁴. The specimen geometry was shape E of DIN 50125 and three specimen of each joint were tested.

Radiographs of the joints were performed using an x-ray system, which is an in-house development of Fraunhofer IZFP, equipped with a 225 kV microfocus x-ray tube, a 4 megapixel detector and a 16 Bit ADC. The radiographic images were achieved by a tube voltage of 100 kV, a tube current of 0.3 mA and an exposure time of 30 s.

To realize high-frequency ultrasound testing, the ultrasound transducer and the samples have to be immersed in water. The presented results were achieved using a point-focused transducer with a frequency of 15 MHz. The investigated area of the sample was scanned in a meandering pattern with a step width of 0.1 mm (scan direction) × 0.2 mm (index direction).

3.5 Corrosion investigations

The surface of the samples was ground with wet silicon carbide paper (up to P1200), rinsed with ethanol and dried prior to all measurements to achieve comparable conditions for all samples.

One method that gives space-resolved information about the corrosion properties of materials is the scanning Kelvin probe (SKP). The Kelvin probe uses a contactless vibrating capacitor technique which allows to measure the changes in the Volta potential or work function of electrons from metals, semiconductors or at phase boundaries of liquids. The method is described in detail in [21–23]. For the investigations of Volta potential differences between the magnesium and aluminum alloy and the formed phases after the friction stir welding and ultrasound

Table 2. Process parameter for aluminum/magnesium and aluminum/steel joints.

| Compound          | Parameter             | Welding speed | Tilt angle | Lateral offset | Welding force |
|-------------------|-----------------------|---------------|------------|----------------|---------------|
| EN AC-48000/AZ91  | Rotational speed [min⁻¹] | 300           | 3          | 0              | 12            |
| EN AW-6061/DP600  | Welding speed [mm/min] | 1250          | 2          | 3              | 2.5           |
|                   | Tilt angle [°]         |               |            |                |               |
|                   | Lateral offset [mm]    |               |            |                |               |
|                   | Welding force [kN]     |               |            |                |               |
enhanced friction stir welding process a scanning Kelvin probe setup with height control (SKP KM, Wicinski-Wicinski GbR) was used. The measuring probe was a chromium-nickel-wire with a diameter of 100 μm. The probe was calibrated at measurement conditions (humid air >90 % RH) with a copper/copper sulfate reference electrode. The measured potential values are given with respect to the normal hydrogen electrode (NHE). The scanned surface area was 25 mm × 5 mm and the step size was 50 μm in x- and y-direction.

Electrochemical measurements have been carried out for the investigation of the corrosion properties of the base materials and joints. A three electrode setup within mini-cells (measurement area 0.071 cm² and 0.019 cm²) was used to enable measurements on different areas of the joints. These areas are the nugget area (stirred zone) and two areas consisting of nugget and magnesium or nugget and aluminum designated as magnesium/nugget transitional area and aluminum/nugget transitional area, respectively. The investigated samples were used as working electrode, a platinum electrode as counter electrode and a standard calomel electrode (+246 mV vs NHE) or silver/silver chloride electrode (+200 mV vs NHE) as reference electrode. The recorded values were converted to values against the normal hydrogen electrode.

The open circuit potential measurements and the potentiodynamic polarization have been done with a Zahner IM 6 measurement unit. The open circuit potential was recorded for 60 min prior to the polarization experiment. The potentiodynamic curves were started −0.05 V relative to the open circuit potential \( E_{oc} \) and recorded up to +0.3 V relative to \( E_{oc} \) with a scan rate of 0.5 mV/s. The electrochemical measurements were carried out in 0.1 molar sodium chloride solution for the aluminum/magnesium joints and in 0.5 molar sodium chloride solution for the base materials of the aluminum/steel joints. Corrosion current densities have been evaluated by Butler-Volmer analysis using the PolCorr module of the Zahner software.

The characterization of the intermetallic phases and corroded areas were carried out with the scanning electron microscope XL 40 from Philips.

4 Results and discussion

4.1 Aluminum/magnesium hybrid joints

4.1.1 Microstructure

Light microscopic investigations

The influence of the ultrasound power and side of introduction of ultrasound on the microstructure of the joints was investigated by light microscopic pictures of cross sections of the joints. The stir zone of the friction stir welding joint exhibits a typical onion like nugget with alternating layers of aluminum and magnesium alloys, Figure 2a. The interface of magnesium/nugget is rather vertical and the dark line separating the magnesium and nugget region consists of intermetallic phases \( \text{Mg}_{17}\text{Al}_{12} \) and \( \text{Al}_{3}\text{Mg}_{2} \) which could be identified by scanning electron microscopy (SEM) and energy dispersive x-ray spectroscopy (EDX) investigations, which are published in [16]. With the increase of ultrasound power the intensity of stirring in the nugget increases. This correlates with investigations stating a better stirring by the introduction of ultrasound [24]. If the ultrasound is introduced from the aluminum side the magnesium/nugget interface is much more inclined compared to the interface of the friction stir welding joint. It seems that the ultrasound oscillations assist in pushing the stirred material further into the magnesium side, as the material is always stirred from the aluminum side (advancing) to the magnesium side (retreating) at the front end of the tool. This also explains the aluminum/nugget interface which is more vertical than the interface in friction stir welding joint, Figure 2a–c. With increasing ultrasound power the nugget structure gets more homogenous. In the case that the ultrasound is introduced from the magnesium side it appears to be the opposing effect, Figure 2d. The stirring material is pushed from the magnesium to the aluminum side and hence a more vertical magnesium/nugget interface and more inclined aluminum/nugget interface is observed. The two interface regions are quite similar to the interface observable in the friction stir welding joint. The pores that are visible at the bottom of the magnesium/nugget region and at the aluminum/nugget transitional region are probably due to tunnel defect which can be eliminated by optimizing the joining parameters [16]. The nugget width at the top side of the joints is
comparatively wider in the joints with ultrasound transmission from the magnesium side than from the aluminum side.

### 4.1.2 Destructive and nondestructive testing

#### Tensile strength

Regarding the mechanical properties of the joints tensile test were performed and evaluated, Figure 3. The diagram shows similar tensile strengths for the base materials of AZ91 and EN AC-48000 with 223 MPa and 204 MPa. Thereby the aluminum shows a smaller statistical scattering, what can be attributed to a lower amount of pores and inner failures while casting. In comparison the friction stir welded joint reaches only 64 MPa, which corresponds to 31% of the weaker base material EN AC-48000. This can be explained mainly by the brittle intermetallic β- and γ-phases which reduce the tensile strength by acting as a discontinuity and could be detected before and are in accordance with the literature [7, 16]. Regarding the fracture area of the specimen the failure always occurred at the interface between magnesium and nugget, where the

![Figure 2. Cross section images of a) FSW zone and USE-FSW zones with ultrasound power of b) 225 W and c) 1000 W introduced from the aluminum side and d) 700 W introduced from the magnesium side.](image)

![Figure 3. Comparison of tensile strength for the EN AC-48000/AZ91 joints with and without additional power ultrasound.](image)
two IM-phases were present. When transmitting additional power ultrasound of 225 W into the aluminum sheet the tensile strength increases to 142 MPa. This value corresponds to 70% of the strength of the aluminum base material and 222% of the friction stir welded joints. This improvement of tensile strength due to the transmission of power ultrasound is also in good accordance with the literature explaining that the power ultrasound interacts mainly with the brittle discontinuities in the form of IM-phases and destroying the Mg$_{17}$Al$_{12}$ phase by the high frequency of its mechanical oscillation [8]. Also here the fracture area occurred at the remained IM-phase of Al$_3$Mg$_2$. The increase of the power for the ultrasound enhancement up to 1000 W for the transmission in aluminum led to a tensile strength of 107 MPa, which corresponds to half the strength of the aluminum base material and 75% of the joints with 225 W, whereas the fracture area of the specimen remained the same like before. So the increase of the power for the ultrasound up to the maximum seems to reduce the strength of the joints. This needs to be investigated in detail with correlated scanning electron microscopic investigations. A possible explanation could be the excessive growth in the thickness of the remained IM-phase when the power ultrasound exceeded a certain limit which was also investigated in the literature [8]. Regarding the transmission of the power ultrasound into the magnesium a power of 700 W led to a value of 118 MPa and fits therewith the before discussed findings for the inverse behavior in reduction of tensile strength of the joints when increasing the ultrasound power. The relatively high scattering of the tensile strength for the ultrasound enhanced friction stir welding could be explained with some irregular appearance of pores or tunnel defects, which were detected by light microscopic investigations before, but could not be seen in the fracture area of the tensile testing specimen. Furthermore, irregularities in the base material such as pores, which are typical for casted alloys, can affect the transmission of the power ultrasound from the introduction area to the faying surface. The ultrasound is known to interact with such irregularities leading to a reflection or deflection and therewith weaken the ultrasound oscillation at the target zone, what possibly result in an inhomogeneous formation of IM-phases at the interface aluminum/steel leading to the detected larger scattering of the tensile strengths.

**Radiography (x-ray)**

The radiographic results from dissimilar friction stir welded and ultrasound enhanced friction stir welded joints with 225 W of the aluminum alloy EN-AC 48000 and the magnesium alloy AZ91 have already been described in [16], Figure 4. As reported no influence of the ultrasound enhancement on the joints can be observed in the radiographic investigations. Several pores at the beginning of the weld seam are present in the joint with power ultrasound, which may be attributed to insufficient heat input at this stage of the process. The radiography of the presented friction stir welded joint did not reveal any defects. In addition to the presented results, several pores were detected in the base mate-

![Figure 4](image-url)

**Figure 4.** Radiographs (x-ray) of EN AC-48000/AZ91 a) FSW joint and b) USE-FSW joint.
rial areas of the joints, which are caused by the casting manufacturing process of the metal sheets.

**High-frequency ultrasound testing**

The results of the high-frequency ultrasound testing measurements on the same samples that were used for the x-ray investigations are presented, Figure 5. In this case, the c-scans are displayed, with the area of the weld being indicated by white dotted lines. Basically, higher intensities of the reflected amplitudes are an indication of inhomogeneities or imperfections within the examined material.

At first glance, various voids seem to be present along the entire weld seam, Figure 5a. Comparing this to the radiographs shown above, however, it is clear that these are not defects. It is reasonable to assume that this is a phenomenon caused by the material flow around the pin of the tool as the indicators pass through the weld in an area that matches the travelling path of the pin. The results of the high-frequency ultrasound testing measurements for ultrasound enhanced friction stir welding are in accordance with the x-ray investigations, Figure 5b. In this case, the link to the material flow described above cannot be detected. Thus, the influence of the ultrasound enhancement on the formation of the joining zone can be assumed here as this coincides with the previously described microstructural finding that the nugget becomes more homogeneous due to the ultrasound enhancement. The pores at the beginning of the weld seam can be identified clearly.

**4.1.3 Corrosion investigations**

The Volta potential plots show not only the Volta potential differences between the different areas of the joints but also their oxidation behavior during the measurement as the duration of one measurement was around 20 hours. The Volta potential difference between the aluminum and magnesium alloy is about 0.8 V to 0.9 V. Because of the oxidation of the surface the Volta potential difference of the alloys and the nugget shifts about 0.2 V to positive values in the first few hours. The Volta potential of the aluminum and magnesium alloy gets stabilized after several hours. However, the nugget phase of the friction stir welding and ultrasound enhanced friction stir welding joint with 225 W of ultrasound power shows a change in Volta potential until the end of the measurement, Figure 6a, b. In the ultrasound enhanced friction stir welding joint with 1000 W of ultrasound power introduced from the aluminum side the Volta potential of the nugget phase reaches a constant value after 4 hours, Figure 6c. This shows that the passivation rate and homogeneity of the nugget phase increases with increasing ultrasound power. The Volta potential difference between the nugget phase and the aluminum alloy is 0.3 V in the case of a friction stir welding and ultrasound enhanced friction stir welding joint with 225 W of ultrasound power, Figure 6a, b. The volta potential difference could be reduced to 0.1 V in an ultrasound enhanced friction stir welding joint with 1000 W of ultrasound power, Figure 6c. This Volta potential shift of the nugget phase to a more positive value is attributed to a higher aluminum content in the nug-

![Figure 5.](image-url) High-frequency ultrasound measurements on EN AC-48000/AZ91 a) FSW joint and b) USE-FSW joint.
The nugget phase of the ultrasound enhanced friction stir welding joints produced with 1000 W ultrasound introduced from the magnesium side exhibits a wider nugget width than that with ultrasound introduction from the aluminum side, Figure 6c, d. This corresponds to the difference in nugget width with the side of ultrasound introduction as observed in the cross sectional pictures, Figure 2.

A comparison of all Volta potential plots clearly indicates that the potential of the nugget shifts to more positive values with increase in ultrasound power. This is attributed to an increasing aluminum content in the nugget. The potential gradient at the magnesium/nugget interface increases with increase in ultrasound power and it is even higher when the ultrasound is introduced from the magnesium side. The potential difference between nugget and aluminum at the aluminum/nugget interface decreases with the increase in ultrasound power. So from the Volta potential plots it can be expected that the electrochemical tests at the magnesium/nugget interface will show higher corrosion tendency in the joints with higher ultrasound power and vice versa at the aluminum/nugget interface.

**Open circuit potential**

Open circuit potential was measured for 60 min prior to all polarization experiments. Measurements have been performed on all hybrid joints processed with the joining parameters described in the experimental section, but only the results for 225 W and 1000 W have been selected for this paper, because of the huge amount of data. A detailed description of all results can be found in [25]. The difference in open circuit potential of AZ91 magnesium alloy and EN AC-48000 aluminum alloy is about 0.85 V in 0.1 molar sodium chloride solution, Figure 7. This difference is in the range of the Volta potential differences observed in the Volta potential plots and is independent of the joining conditions, Figure 6. The other regions within the welding zone exhibit open circuit potential values.

![Volta potential maps of a FSW joint (a) and USE-FSW joints with ultrasound power of b) 225 W and c) 1000 W introduced from the aluminum side and d) 1000 W introduced from the magnesium side.](image)

![Open circuit potentials over time measured on different areas of USE-FSW joints produced with an ultrasound power of 225 W (a) and 1000 W (b) respectively.](image)
between that of the base materials, Figure 7. The open circuit potentials of the magnesium/nugget transitional region exhibit a similar trend over time for all different joining conditions. The values after 60 min are in most of the cases only about 0.1 V more positive than that of the AZ91 base alloy, Figure 7. A distinct influence of the used ultrasound power on the measured open circuit potential was observed for nugget and aluminum/nugget transitional areas of the joints. The evaluation of all measurements on these regions shows a gradual shift to more positive values with the increase in ultrasound power from 225 W to 1000 W, Figure 8. This is attributed to an increasing aluminum content in these regions with increasing ultrasound power. The open circuit potential is comparatively more positive when the ultrasound is introduced from magnesium side. The open circuit potential value at these regions in the friction stir welding joint is more positive when compared to the ultrasound enhanced friction stir welding joint with lower ultrasound power (225 W). This may be explained with a lower magnesium content in the nugget of the friction stir welding joint compared to the ultrasound enhanced friction stir welding joint with lower ultrasound power as the cross sectional pictures show a comparatively darker nugget in case of the friction stir welding joint, Figure 2. Irregularities in the surface area also affect the measured open circuit potential, especially in the aluminum/nugget transitional area. In the presence of even small amounts of magnesium the measured open circuit potential is shifted to more negative values, Figure 7a. This behavior was also observed in other investigations with EN AC-48000/AZ80 hybrid joints obtained by the ultrasound enhanced friction stir welding method [26]. The open circuit potential graph for the measurement on the aluminum/nugget transitional area for the joint produced with 1000 W ultrasound power from the aluminum side exhibits a lot of fluctuations, Figure 7b. Light microscopy investigations of the measurement area after the experiments showed a crevice which is the reason for this behavior.

**Potentiodynamic polarization**

All potentiodynamic polarization measurements were started 60 minutes after immersion at open circuit potential. The base materials aluminum EN AC-48000 and magnesium AZ91 exhibit corrosion potentials of $-0.37 \text{ V}$ and $-1.2 \text{ V}$ vs. standard hydrogen electrode (SHE), respectively. The corrosion current density of the magnesium alloy is about one order of magnitude higher than that of the aluminum alloy, Figure 9. The observed shift in open circuit potential for the nugget and the aluminum/nugget transitional area with increasing ultrasound power from 225 W to 1000 W is also reflected in the potentiodynamic polarization measurements, Figure 9.

![Figure 8. Influence of ultrasound power on measured open circuit potentials for nugget and aluminum/nugget regions.](image)

![Figure 9. Potentiodynamic polarization curves measured on different areas of USE-FSW joints produced with an ultrasound power of 225 W (a) and 1000 W (b) respectively.](image)
sound power corresponds with a shift of the corresponding potentiodynamic polarization curves, Figures 7–9. Corrosion current densities for the different areas have been evaluated by Butler-Volmer analysis. The nugget and the aluminum/nugget transitional area exhibit decreasing corrosion current densities with increasing US power from 225 W to 1000 W, Figure 10. The magnesium/nugget transitional area in all cases shows a very high corrosion current density of several mA cm$^{-2}$, which is 2–3 orders of magnitude higher than that of the base material. This strong galvanic corrosion might destroy the weld within short time if no protection is applied to this area. Irregularities not only affect the open circuit potential but also the corrosion current density. Even small amounts of magnesium in the measurement area at aluminum/nugget transitional regions increase the corrosion current density by about one order of magnitude, Figure 10. This increased corrosion tendency is accompanied by a more negative corrosion potential in accordance with the measured open circuit potential, Figures 7, 9a. A crevice has a great impact on the potentiodynamic polarization curve. The passive range is reduced towards higher potentials (compared to a similar area on a joint without crevice) and an increase of the corrosion current density of about two orders of magnitude at a breakdown potential near to the corrosion potential is observed, Figure 9b. The shift of open circuit potential and corrosion potential of the nugget and aluminum/nugget transitional regions to more positive values with the increase in ultrasound power are attributed to an increased aluminum content in the nugget. This corresponds to the more positive potential observed in the Volta potential plots of the scanning Kelvin probe measurements, Figure 6. This increased aluminum content leads to lower corrosion current densities and therefore better corrosion properties of these regions of the joints.

**Scanning electron microscopy / energy dispersive x-ray spectroscopy**

After the corrosion experiments some samples have been investigated by scanning electron microscopy and energy dispersive x-ray spectroscopy analysis to identify preferred corroded areas. The formation of intermetallic phases in the aluminum alloy EN AC-48000 has great influence on the corrosion phenomena observed after the polarization experiment on an aluminum/nugget region. Especially around the bright intermetallic particles a strong corrosion attack was observed whereas other regions seem to be unaffected, Figure 11. The energy dispersive x-ray spectroscopy measurement in the nearly uncorroded region (1, blue box) showed only aluminum with small amounts of silicon and magnesium, Table 3. This seems to be the α-aluminum phase. The energy dispersive x-ray spectroscopy measurement at the region of the yellow box (position 2), which exhibits a rough surface due to small amount of corrosion, shows nearly 20% of silicon along

![Figure 10](image1.png)

**Figure 10.** Influence of ultrasound power on measured corrosion current densities of nugget, aluminum/nugget transitional and magnesium/nugget transitional regions.

![Figure 11](image2.png)

**Figure 11.** Scanning electron microscopy picture of corroded aluminum area of an EN AC-48000/AZ91 USE-FSW joint produced with 225 W ultrasound from aluminum side after polarization experiment.
Table 3. Elements identified via energy dispersive x-ray spectroscopy surface scan and spot measurements in the corroded aluminum area of the EN AC-48000/AZ91 hybrid joint produced with 225 W ultrasound power from the aluminum side.

| Position | Al [at.%] | Mg [at.%] | Si [at.%] | O [at.%] | Ni [at.%] | Cu [at.%] | Fe [at.%] | Mn [at.%] |
|----------|-----------|-----------|-----------|---------|-----------|-----------|-----------|-----------|
| 1 (blue) | 97.9      | 0.8       | 1.3       |         |           |           |           |           |
| 2 (yellow) | 80.3     | 0.5       | 19.2      |         |           |           |           |           |
| 3 (red)  | 55.3      | 6.4       | 15.3      | 16.4    | 3.3       | 1.2       | 0.4       |           |

with aluminum. This surface part is assigned to the aluminum-silicon eutectic phase. The energy dispersive x-ray spectroscopy spot measurement on the bright intermetallic phase (3, red circle) shows it contains considerable amounts of nickel and copper, Table 3. As the reduction potential of nickel and copper is more positive than aluminum, this phase forms a galvanic site which has resulted in the corrosion of the aluminum matrix around it, Figure 11.

4.2 Aluminum/steel hybrid joints

4.2.1 Microstructure

Light microscopic investigations

For the aluminum/steel joints the different methods of friction stir welding and ultrasound enhanced friction stir welding with varying ultrasound power were investigated in a first step by light microscopic analysis. The cross section of an EN AW-6061/DP600 joint realized by conventional friction stir welding can be seen, Figure 12a. The interface between aluminum and steel is still nearly perpen-
diccular and contains a smaller hook in the middle part (black arrow). This implies that the steel edge was not strongly activated during the joining process, whereas the tool offset was chosen that way that no direct contact between the pin and the steel should occur. This is a major difference between the friction stir welding of aluminum and magnesium where the melting temperatures of the joining partners are nearly equal (aluminum 660 °C, magnesium 650 °C) and the pin is placed centered on the joint, so that a real stirring and mixing can take place. Compared to this the friction stir welding of aluminum/steel joints with the offset of the pin into the aluminum and the stirring of the aluminum against the steel edge leads to no real mixing and the typical interface shown, Figure 12a. The part of the interface below the hook appears nearly straight, what proofs that the thermo-mechanical influence decreases at higher depths of the joint cross section. Regarding the nugget steel particles are visible. This is also in accordance with the literature for aluminum/steel joints [9, 10, 18]. Most of the particles belong to the ASTM 12 (5.6 μm) and ASTM 15 (2 μm) with 18 % each. The largest particles were detected and classified as ASTM 4 (90 μm) with an amount of 3 %. Compared to earlier research on EN AW-6061/DC04 joints the dissimilar welds with the dual-phase steel of DP600 contain smaller steel particles because it is more difficult to remove such particles from the stronger steel [19]. The influence of power ultrasound with 225 W on the microstructure is shown, Figure 12b. The interface that time is more flat with an angle of about 60° against the horizontal and a visibly larger hook in the center of the interface (black arrow). The lower part is nearly straight again and thereby shows the same behavior as the friction stir welded joint in this area with a decreased thermo-mechanical deformation. Having in mind that the pin was not in direct contact with the faying surface of the steel it can be assumed that the power ultrasound has a softening influence on the DP600 due to the additional energy introduction into the steel joining partner by the high frequent mechanical oscillation leading to a higher deformation in the upper part of the cross section. The nugget contains less large steel particles and therewith appears more cleaned up, what corresponds to the literature [19, 20]. The largest particles belong to the class of ASTM 5 (65 μm) with an amount of 1.5 %, which are smaller in size and lower in content compared to the friction stir welded joint. The biggest amount of particles belong again to ASTM 12 and ASTM 15 (21 % and 28 %). Compared to the additional ultrasound transmission in the aluminum/magnesium joints a change in the geometry of the nugget itself cannot be seen for the aluminum/steel joints, which could be expected due to the different stirring and mixing mechanisms. Nevertheless, an influence of the power ultrasound is visible for the steel interface as well by flattening the DP600 interface in the upper part, whereas it behaves generally similar to the nugget of the aluminum/magnesium where the materials appeared to get pushed towards the non-introduction side of the ultrasound. Friction stir welded joints with additional power ultrasound enhancement of 1000 W led to a more pronounced flattening of the interface of about 45° against the horizontal, Figure 12c. Also the hook (black arrow) in the center of the cross section is obviously larger than for an ultrasound enhancement of 225 W, which leads to the assumption that a higher amount of introduced ultrasound energy leads to a more pronounced softening of the DP600. Regarding the size and amount of steel particles in the nugget a similar behavior to 225 W of power ultrasound can be determined with a slightly bigger amount of the smallest ASTM 15 class of 33 %. This led to the assumption that an increase of power ultrasound results in a more activated steel base material and joint interface as well as a reduction of steel particle size in the nugget similar to the breakup of continuous intermetallic layers and their fine dispersed distribution over the whole nugget of aluminum/magnesium joints [7, 16]. This behavior is also in accordance with the more pronounced pushing of the base material in the nugget to the non-introduction side of the power ultrasound of the EN AC-48000/AZ91 joints.

**Scanning electron microscopic investigations**

Knowing that the development at the interface of aluminum/steel joints strongly determines the joint strength further scanning electron microscopic investigations were carried out. The analyzed spot for the friction stir weld is depicted, Figure 13a (white box). The DP600 appears to be a little rugged and is connected to a continuous intermetallic phase (large white arrow Figure 13b). The average thickness is about 422 nm and therewith too small for a
realistic energy-dispersive x-ray spot measurement. Regarding the literature most of the intermetallic phases consist of Fe$_2$Al$_5$ or FeAl$_3$ [13, 14]. So it is assumed that the present intermetallic also consist of an aluminum-rich phase. The determination of the composition will be carried out in further investigations. Using the joining method of ultrasound enhanced friction stir welding with 225 W of power ultrasound the scanning electron microscopic image is shown, Figure 14a, b. The dual-phase steel is more rugged than without ultrasound and a continuous intermetallic phase is visible again at the interface between DP600 and EN AW-6061, which is analogously presumed to consist of a similar aluminum-rich phase like before. Its thickness reaches an average value of 588 nm and therefore is thicker as for conventional friction stir welding. Compared to earlier findings in the field of ultrasound enhanced friction stir welding of EN AW-6061/DC04 joints where the thickness of the intermetallic layers got reduced the dissimilar welds with the dual-phase steel show an opposite behavior for the thickness of intermetallic layers at the interface when additional power ultrasound is used [19]. This investigation may can be explained with the before mentioned softening of the steel due to the power ultrasound introduction, which could also led to an enhanced diffusion between the EN AW-6061 and the DP600. A transmission of power ultrasound with 1000 W resulted in the largest thickness of an intermetallic phase of about 630 nm, Figure 15a, b. The DP600 appears to be rugged stronger and contains some alternating layer structures of steel and intermetallic phases. These findings for scanning electron microscopy leads to the assumption that the transmission of power ultrasound results in a growth of intermetallic phases for joints of dual-phase steel and aluminum. This behavior shows an interesting contrast to the findings for the ultrasound enhanced friction stir welding of aluminum/magnesium joints where two intermetallic phases were detected for the conventional friction stir welding process and by using ultrasound enhanced friction stir welding one of the IM-phases got destroyed and finely dispersed over the nugget [16]. A possible explanation therefore could be the before mentioned pronounced mechanical stimulation of the steel interface due to the power ultrasound.
leading to a softening of the DP600 and an enhanced and temporal delayed formation of IM-phases whereas the formation of the intermetallic phases for aluminum/magnesium may proceeded faster and were more vulnerable against the power ultrasound.

### 4.2.2 Destructive and nondestructive testing

**Tensile strength**

To investigate the linkage of the microstructure and the quasistatic properties tensile tests of the base materials and the varying dissimilar joints were carried out, *Figure 16*. The difference in tensile strength between the two base materials is significantly larger with values of 580 MPa for DP600 compared to the 203 MPa of EN AW-6061. Conventionally friction stir welded joints reached a tensile strength of 148 MPa what corresponds to 73 % of the weaker base material aluminum. The fracture of the specimen occurs at the interface of the aluminum/steel joints where the IM-phase is present. By the addition of power ultrasound with 225 W a reduced value of 135 MPa (66 % of aluminum base material) and for 1000 W of 121 MPa is achieved. The fracture areas remain the same as for the friction stir welding. This decrease can be explained with the thicker intermetallic layers at the interface of the joints, whereas the literature proved a decrease in tensile strength with an increase in the thickness of brittle intermetallics [14]. Regarding the tensile strength of the EN AC-48000/AZ91 joints the scattering of the EN AW-6061/DP600 joints is less pronounced, what confirms more homogenous joints. This can be explained by the lack of irregularities (like pores) in the base material, what enables a more uniform ultrasound oscillation at the faying surfaces leading to a more homogeneous interface between aluminum and steel. Furthermore, the achieved tensile strength for the conventional friction stir welding process reached 2.5 times the value of the aluminum/magnesium. That can be explained with the presence of the two intermetallic phases at the interface aluminum/nugget whereas friction stir welding of aluminum/steel only led to the formation of one comparably thinner IM-phase. The tensile strengths for both hybrid joints of aluminum/magnesium and aluminum/steel...
with an additional ultrasound introduction of 225 W were nearly equal with 142 MPa and 135 MPa showing a positive influence on aluminum/magnesium due to the destruction of one brittle IM-phase and a negative influence for aluminum/steel due to the slight growth of the before present IM-phase. The introduction of 1000 W of power ultrasound in the process of ultrasound enhanced friction stir welding resulted in a stronger pronounced decrease to 107 MPa for aluminum/magnesium and again a slightly decrease for aluminum/steel to 121 MPa. This led to the assumption, that there could be a limitation for the introduction of power ultrasound for aluminum/magnesium joints whereas the aluminum/steel joints showed a steadier behavior.

**Radiography (x-Ray)**

The results of the radiographic measurements on dissimilar friction stir welded and ultrasound enhanced friction stir welded joints of the aluminum alloy EN-AW 6061 and the dual-phase steel DP600 are shown, *Figure 17*. In contrast to the results for aluminum/magnesium joints a significant influence of the ultrasound enhancement on the occurrence and the quantity and size of foreign particles in the welding area can be observed. The conventional friction stir welded joint reveals the presence of numerous foreign particles on the aluminum side of the joining area, *Figure 17a*. These particles are spread almost along the complete length of the weld and seem to be finely distributed. Additionally some pores are present in the center of the weld path. The quantity of foreign particles as well as the area of occurrence are clearly reduced due of the ultrasound enhancement with an ultrasound power of 225 W, *Figure 17b*. The size of the particles also seems to be affected, as the present ones are bigger than those in the conventional friction stir welded joints. A further increase of the ultrasound power up to 1000 W results in an avoidance of foreign particles in the weld seam, *Figure 17c*. The joint appears uniform and exhibits no irregularities. The findings concerning the influence of ultrasound enhancement on the occurrence of foreign particles in the welding area are in accordance with the results on EN AW-6061/C45-joints and EN AW-6061/DC04-joints [19, 27]. In these investigations, the particles could be identified as steel particles deriving from the steel joining partner.

**High-frequency ultrasound testing**

The c-scans of the high-frequency ultrasound testing measurements on the same samples that were...
used for the x-ray investigations are given, Figure 18. All features, foreign particles and voids that were identified in the radiographic images can also be detected by high-frequency ultrasound testing, though a distinction between pores and particles is rather hard to realize in high-frequency ultrasound testing measurements, as both result in an increased signal intensity and are geometrically difficult to differentiate. The area along the weld seam showing high intensities in Figure 18a (displayed in red) could be proven to result from a thin aluminum layer on the steel surface that is transferred by the rotating tool shoulder and could be identified by a visual inspection of the joint.

4.2.3 Corrosion investigations

The investigations of the corrosion properties of EN AW-6061/DP600 hybrid joints are still ongoing. The aluminum alloy EN AW-6061 has already been used for other aluminum/steel combinations like EN AW-6061/DC04 and EN AW-6061/C45 [19, 27]. Therefore, the properties of the dual-phase steel DP600 have been characterized with open circuit potential and potentiodynamic polarization measurements and will be compared with the other steels. The open circuit potential of DP600 steel starts at more negative values compared to DC04 and C45, but the decline with time is less steep than that of the other steels. After 60 min the open circuit potential value stabilizes at −0.5 V vs. NHE, which is nearly the same value as that of C45, Figure 19a. As the potentiodynamic polarization curve shows, DP600 exhibits a corrosion potential of −0.52 V vs. NHE and a corrosion current density of about 3.0 μA cm⁻². This value is higher than that of DC04 and C45 which have corrosion current densities of 2 μA cm⁻², Figure 19b. In the anodic branch, starting around −0.4 V vs. standard hydrogen electrode, DP600 shows a higher increase in current density than DC04 and C45, which have nearly identical graphs in the anodic region, Figure 19b.

Compared to DC04 and C45 steel DP600 exhibits a similar open circuit potential value and slightly higher corrosion current densities. Therefore, for EN AW-6061/DP600 hybrid joints similar results concerning the corrosion properties, compared to the former investigated joints with DC04 and C45, are expected.

5 Summary and conclusions

In the present work hybrid joints of dissimilar aluminum/magnesium and aluminum/steel could be realized successfully by friction stir welding as well
as ultrasound enhanced friction stir welding and got compared continuously with each other. Therewith the transmission of additional power ultrasound in the metal sheets influenced the resulting microstructural, mechanical and corrosion behavior of the joints. For the EN AC-48000/AZ91 joints the ultrasound enhanced friction stir welding lead to an enhanced stirring in the nugget as well as a change in the course of the interface between magnesium/nugget or rather nugget/aluminum depending on the introduction side of the ultrasound, which got more flat due to the power ultrasound. Furthermore, the formation of brittle IM-phases got limited due to the ultrasound enhanced friction stir welding, what resulted in increasing tensile strength for 225 W of power ultrasound. Nondestructive testing of the EN AC-48000/AZ91 joints using radiography and high frequency ultrasound proved itself to be suitable to detect irregularities. The radiography showed no influence of the power ultrasound compared to the conventional welded joints. Also the high-frequency ultrasound testing proved these findings. A comparison of all Volta potential plots of EN AC-48000/AZ91 joints clearly indicates that the potential of the nugget shifts to more positive values with increase in ultrasound power. This is attributed to an increasing aluminum content in the nugget. Open circuit potential measurements show the same potential shift to more positive values with increasing ultrasound power. At the same time current densities of this region are reduced. The magnesium/nugget transitional region exhibits enhanced corrosion because of formation of a strong galvanic element. Therefore, this area has to be protected by a suitable coating (e.g. anodizing layer or polymeric coating) during the use of such joints in an electrolytic environment.

For the EN AW-6061/DP600 joints light microscopic investigations also showed a characteristic interface aluminum/steel and nugget. The nugget contained steel particles, what is typical for a friction stir welding process where the pin does not get in contact with the faying surface of the steel and in contrast to the nugget formation for aluminum/magnesium joints. By transmitting power ultrasound in the steel sheet the interface appeared more flat against the horizontal, whereas this effect got more pronounced with more ultrasound oscillation comparable to the behavior of the nugget of the aluminum/magnesium joints. Furthermore, the nugget contained less large steel particles and appeared more cleaned up due to an increasing introduction of power ultrasound. This generally contrasting behavior of the microstructural development compared to the EN AC-48000/AZ91 joints can be explained by the different stirring and mixing mechanisms for the EN AW-6061/DP600 joints. Further, the formation of a continuous intermetallic layer at the interface aluminum/steel which is assumed to be aluminum-rich got more pronounced with an increased ultrasound introduction. This difference in the formation of brittle IM-phases compared to the aluminum/magnesium joints is attributed to the strongly differing physical properties of the steel. Tensile tests on EN AW-6061/DP600 showed a decrease in the tensile strength of the joints due to the increased power ultrasound, which is related to the increase of the thickness of the brit-
tle intermetallic layers. Regarding the non-destructive testing method of radiography a significant influence of the power ultrasound concerning the amount of foreign particles on the aluminum side of the weld seam could be observed. Numerous steel particles are present in the friction stir welded joint. An increase of the ultrasound power led to a reduction in the amount of such particles. This behavior could also be detected with the method of high-frequency ultrasound testing. For EN AW-6061/DP600 joints increased corrosion caused by galvanic effects is not expected as the potentials of the EN AW-6061 aluminum alloy and DP600 steel are very similar.

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