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Keyhole Closure using Friction Spot Welding in Aluminum Alloy 6061 – T6

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Abstract

A new approach to refill keyholes using the friction spot welding (FSpW) technology was developed. Keyholes with a diameter of 7.5 mm in aluminum alloy 6061-T6 rolled sheets were filled with a cylindrical plug of the same material. Afterwards, the FSpW process joins the plug to the surrounding workpiece resulting in a sealed keyhole.

Microstructural analysis and mechanical testing of keyhole closures have been performed. The mechanical properties have been determined in terms of microhardness, tensile strength, yield strength and elongation at fracture. Design of experiments and analysis of variance techniques were employed to evaluate the influence of the gas shielding, post-weld heat treatments and the plug itself on the properties of the welds.

The experimental results demonstrate that the proposed method is suitable to refill keyholes in AA 6061-T6 and produce flawless joints with a superior surface appearance. The welds show high strength and hardness, especially when heat treatments are applied. The high strength of the welds were achieved at the expense of elongation at fracture, which is caused by a strengthened zone in the center of the welds.
Keywords
aluminum alloy 6061; friction spot welding; keyhole closure; design of experiments; solution treatment and aging; metallurgical features

1 Introduction
During production or repair of workpieces made of aluminum alloys, problems can occur such as damage on through holes, broken tools, or keyholes left at the end of friction stir welding (FSW) joints. This is particularly problematic in the case of parts with high quality standards such as aluminum housings or pressurized tanks for aerospace applications. Until now there has been no suitable method to fulfill the requirements for high quality repair welds. It is, of course, possible to refill keyholes with conventional fusion welding processes. However, the application of such processes to aluminum alloys is generally associated with hot cracks and low mechanical properties due to high heat input. Furthermore, not all aluminum alloys are weldable. (Schilling and dos Santos, 2004)

Friction-based welding processes are excellent methods to process aluminum workpieces as summarized by Mishra and Ma (2005) for FSW or as demonstrated by Wang and Lee (2007) for friction stir spot welding (FSSW). In recent years, a series of friction-based keyhole closure techniques were reported that attempted to transfer the advantages of friction-based welding processes to keyhole closure methods.

A method called friction taper plug welding (FTPW) was invented by TWI (Dunkerton et al., 1991). The FTPW is also referred to as friction plug welding (FPW) as shown by Du et al. (2016). In this method, a tapered keyhole is sealed by a plug with a taper similar to the hole by co-axially forcing the rotating plug into the keyhole. The conical surface of the tapered plug is therewith welded to the surface of the hole. However, the geometry of the plug has to be adapted to the tapered hole dimensions; machining is necessary on both sides of the workpiece to remove the unconsumed parts of the plug from the top as well as the material that is extruded out of the plate from the bottom.

A similar method, filling friction stir welding (FFSW), was introduced by Huang et al. (2011) and has been analyzed by Han et al. (2013) and Behmand et al. (2015) to seal keyholes created via tool extraction at the end of the FSW process. The FFSW is derived from the FTPW and adds a shoulder part to the tapered plug and avoids concentrating stress at the interface between the plug and hole. Zhang et al. (2014) modified the FFSW method by separating the shoulder and plug. They used a pin free tool and a T shaped filler bit to avoid the setup time of replacing the tool between filling operations. However, the FFSW process has only been proven to seal keyholes left by a conical FSW tool on which the geometry of the filler bit has to be adapted.

Zhou et al. (2012) proposed the self-refilling friction stir welding (SRFSW) with a series of non-consumable tools with gradual changes in pin geometry and size based on FSW. Sealing keyholes using the SRFSW –
tools step-by-step is a multi-stage process - a wide and shallow exit hole remains at the surface due to the lack of material that can fill the termination hole. In addition, this method cannot be applied to seal through holes.

In this study, the friction spot welding (FSpW) is introduced as a method to refill through holes. Friction spot welding, also known as refill friction stir spot welding (RFSSW), is a solid-state welding process developed and patented by Helmholtz-Zentrum Geesthacht GmbH (Schilling and dos Santos, 2004). The process was developed as an alternative to riveting or resistance spot welding to produce similar and dissimilar overlap joints. It has been used successfully to produce joints of different materials such as aluminum alloy joints as shown by Rosendo et al. (2011) for similar joints and by Amancio-Filho et al. (2011) for dissimilar joints and dissimilar joints of aluminum to magnesium by Suhuddin et al. (2014) as well as dissimilar joints of aluminum to copper by (Shen et al., 2014).

The advantages of this solid-state welding technology are the absence of defects associated with conventional fusion welding techniques like pores and hot cracks. In addition, the FSpW process is not limited by the presence of the oxide layer on the surface of an aluminum workpiece. Therefore, all aluminum alloys are weldable. Furthermore, the process produces a superior surface appearance (absence of keyholes or larger weld seams), which results in improved mechanical behavior and eliminates the need for additional surface treatment.

FSpW uses a non-consumable tool consisting of three independent movable parts including a stationary clamping ring and two rotating parts - the sleeve and the probe. The principles of keyhole closure using FSpW are presented in Figure 1. First a plug of the same material than the surrounding workpiece is inserted into the hole. The FSpW process starts with the clamping ring moving downwards to fix the workpiece for the rest of the process. The sleeve and probe start to rotate in the same direction under a pre-set speed. Next, the sleeve plunges downwards into the workpiece while the probe is simultaneous retracted. The rotating sleeve generates frictional heat plasticizing the workpiece material. The downward movement of the sleeve forces the softened material into the cavity left by the probe. When a pre-determined plunge depth is reached, the rotating probe and the sleeve move back to their initial position. This pushes the material back into the joint to refill the keyhole left by the retracting sleeve. Metallic bonding is created at the interface between the refilling plasticized material and the surrounding workpiece. Finally, the tool is retracted from the surface to leave a spot weld without a keyhole.
The aim of this work was to investigate the mechanical properties of the keyhole closure friction spot welds in AA 6061 – T6. In addition, the influence of gas shielding, different heat treatments and the plug itself on the strength of the welds were investigated. A 2^k Full Factorial Design DoE approach was selected for this purpose, and the average values measured during tensile tests were taken as the main response. Analysis of variance was performed to evaluate the statistical confidence of the designed models. Examples of the microstructural changes, the hardness distribution across the spot weld, the tensile and yield strength and the elongation at fracture as well as the failure mechanisms of the welds were discussed to identify the main characteristics of the welds.

2 Materials and Methods

2.1 Experimental Procedure
The welds were produced with a commercially available RPS 100 FSpW machine (Harms & Wende, Germany). Threaded FSpW tools made of molybdenum-vanadium alloyed hot work tool steel with a 14.5 mm diameter clamping ring, 9 mm sleeve and 6 mm probe were used (Figure 2).
A clamping force of 16 kN, rotation speed of 2290 rpm and plunging speed of 1.93 mm/s were selected from a preliminary work (Lietz, 2012) and held constant. Dwell time was not used in this work.

A two level full factorial design of experiments approach with three factors (artificially aged, gas shielding and welding mode) was selected and randomized with three replicates. The artificial aging process was carried out at 180 °C for 18 h. Argon was the shielding gas for weld zone gas shielding. The two levels for the factor “welding mode” were plug refilled keyhole and bead on plate welds to identify the influence of the plug – workpiece interface on the mechanical properties. Table 1 summarizes the $2^3$-full factorial design used in this work.

### Table 1 Full factorial design of experiments used to evaluate mechanical properties of FSpW keyhole closure-method.

<table>
<thead>
<tr>
<th>Artificial aged</th>
<th>Welding mode</th>
<th>Gas shielding</th>
</tr>
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<tbody>
<tr>
<td>without</td>
<td>plug</td>
<td>without</td>
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<tr>
<td>with</td>
<td>plug</td>
<td>without</td>
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<tr>
<td>without</td>
<td>bead on plate</td>
<td>without</td>
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<tr>
<td>with</td>
<td>bead on plate</td>
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<td>without</td>
<td>plug</td>
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<td>with</td>
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<td>without</td>
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<tr>
<td>with</td>
<td>bead on plate</td>
<td>with</td>
</tr>
</tbody>
</table>

To understand the effect of heat treatments on the mechanical properties of the spot weld, some samples were solution heat treated and artificially aged for 1 h at 530 °C and 18 h at 180 °C (with an interruption of 9 h at RT after 10 h of treatment) after the welding process.
2.2 Aluminum Alloy 6061-T6
The 4.8 mm thick rolled sheets with 7.5 mm diameter trough holes and 7.5 mm diameter plugs of AA6061-T6 were used in this study. AA 6061 –T6 is a precipitation hardened AlMgSi alloy that is widely used; its mechanical properties have been investigated and summarized by Totten and MacKenzie (2003). This alloy has been shown to be weldable by a friction-based welding process by Venukumar et al. (2014). Figure 3 presents the microstructure of the used AA 6061 – T6 alloy base material parallel to the rolling direction. The rolled material shows pancake-shaped grains with a diameter of 40-400 µm and a height of 30-100 µm. The mechanical properties of the base metal at room temperature are presented in Table 2.

![Microstructural aspects of the as received AA 6061 –T6 alloy base material.](image)

Table 2 Mechanical properties of base material.

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield strength (MPa)</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Elongation (%)</th>
<th>Vickers hardness (HV0.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Metal:AA 6061-T6</td>
<td>255</td>
<td>311</td>
<td>22.3</td>
<td>112</td>
</tr>
</tbody>
</table>

2.3 Metallographic Characterization and Mechanical Testing
For microstructural analysis, samples were sectioned across the weld center and prepared through standard metallographic specimen preparation procedures. Polished specimens were etched with Keller’s reagent (190 ml H₂O, 5 ml nitric acid, 3 ml hydrochloric acid and 2 ml hydrofluoric acid, 65 seconds) for macrostructural characterization and with Weck’s reagent (100 ml H₂O, 4 g potassium permanganate and 1 g sodium hydroxide, 15 seconds) for microstructural analysis.

Tensile tests were carried out in a universal testing machine in accordance with ISO 6892-1:2009 in the rolling direction, Figure 4. Prior to testing, the specimens were machined to remove 0.3 mm from the top
and 1.6 mm from the bottom. A hardness testing system LECO, type M-400-H, performed the microhardness measurements in accordance with ISO 6507-1:2005.

![Geometry of the samples used for the tensile test](image)

Figure 4 Geometry of the samples used for the tensile test, F=tensile force (scale in mm).

3 Results & Discussion

3.1 Microstructural Features
The typical microstructure of an AA 6061 – T6 alloy spot weld (without heat treatment, with plug and without gas shielding) is presented in Figure 5 (A). The interface between the plug and surrounding workpiece is not visible due to stirring during the FSpW process. No defects can be observed in the weld, neither on the surface of the weld, nor at the area of the maximum plunging depth of the tool.

Three characteristic zones of the FSpW process can be observed, Figure 5 (A). The stirred zone (SZ) is located in the center of the weld showing typical fine dynamic recrystallized grains with an average diameter of 9.7 µm that are generated by high shear rates and high process temperatures, Figure 5 (B). The SZ shows a wider diameter than the sleeve meaning that some material on the outside of the sleeve experienced high shear rates and underwent dynamic recrystallization.

Figure 5 (C) shows the thermo-mechanically affected zone (TMAZ). The TMAZ experiences moderate temperatures and strain rates leading to deformed grains. A deformation of the grains in the direction of the tool-axis is clearly visible, Figure 5 (D). In the circumferential direction, no principal deformation is obtainable. Sub-grain boundary-like structures are seen in the TMAZ, see Figure 5 (C).

The Heat Affected Zone (HAZ) is only affected by the thermal cycle and experiences no plastic deformation. Therefore the grain size corresponds to that of the unaffected base material (BM), see Section 2.2.
The outer sleeve path shows even finer grains than the rest of the SZ, see Figure 5 (E). This might be caused by the threaded sleeve and direct contact from sample material to the rotating sleeve. This results in even higher local shear rates. In addition, a finer grain structure is the reason for the drop-shaped areas just below the maximum plunging depth of the sleeve, see Figure 5 (A and D). This most likely originates from a swirl-like movement of the plasticized material during the FSpW process. A similar effect is obtained at the FSSW process where a vortex swirl zone is formed typically beneath the rotating tool as observed by Gerlich et al. (2008).

Figure 5 (F) shows the absence of refilling defects. The sharp interface where the plasticized material refills the cavity left by the retracting sleeve and connects with the surrounding material has a thread-like structure. This interface is not flat and leads to an increased surface for boundary effects. The thread-like structure and size of the boundary surface is controlled by the retracting and rotational speed of the sleeve.

Figure 5 Low magnification Keller-etched overview and Weck-etched detailed images. (A) Macrograph of the weld cross-section; (B) Detail of the SZ; (C) Detail of the TMAZ; (D) Region showing the transition between SZ, TMAZ and HAZ; (E) Magnification showing the fine grain structure at the outer sleeve path; (F) Micrograph showing the thread-like structure at the interface where the plasticized material refills the cavity left by the retracting sleeve.
The different macrostructural appearance between a bead on plate weld and a weld on a plug-refilled keyhole can be seen in Figure 6. The stirred interface of the plug and surrounding workpiece leads to dark structures in the SZ after etching with Keller’s solution. This might originate from the surface oxide layer that was then stirred into the volume of the weld spot. This phenomenon is currently under investigation.

![Figure 6 Overview of spot welds without (A) and with plug (B).](image)

3.2 Microhardness

Figure 7 shows a typical hardness distribution after 28 days of natural aging. The SZ shows a relatively constant hardness of 87 HV$_{0.1}$ on average. In the TMAZ, the hardness decreases continuously to a minimum of 66 HV$_{0.1}$ in the HAZ. In the outer limits of the HAZ, the hardness increases to the average BM hardness value of about 112 HV$_{0.1}$ 17 mm from the weld center.
AA 6061 is a precipitation hardening alloy, and the changes in mechanical properties are mainly determined by changes of precipitate features during and after welding. Before welding, the main precipitation phase is the coherent β''- phase, which is also referred to as GP(II) – zones due to the –T6 heat treatment (solution heat treated, quenched and artificially aged) of the BM (Ostermann, 2007). This corresponds to a hardness distribution—different weld zones can be characterized with respect to the local changes in precipitate morphology.

The SZ experiences a maximal temperature above 500°C during the FSpW process as shown by Lietz (2012). Elangovan and Balasubramanian (2008) observed a partial dissolution of the precipitates at similar temperatures. After 28 days of post-weld natural aging the reported hardness values are observed.

The HAZ is exposed to temperatures from 270-460°C (Lietz, 2012), therefore softening by coarsening and dissolution of the strengthening precipitations might prevail in this region similar to the findings by Hirose et al. (1999). Maisonnnette et al. (2011) could not find β'-precipitations after heating AA6061-T6 to 300°C in contrary to heating to 400°C. This suggests that the outer limits of the HAZ (regions that are associated with lower temperatures during FSpW) are primarily softened due to coarsening. The area of lowest hardness adjacent to the TMAZ is associated with maximum temperatures of about 380-400°C (Lietz, 2012). This is similar to the findings of Maisonnette et al. (2011)—the precipitates are assumed to evolve into β'-phases, which cause low hardness in this area.

The TMAZ is a transition zone that reaches a maximum temperature of about 460-500°C during the FSpW process (Lietz, 2012). The reduced hardness might therefore be connected to overaging effects in combination with partial dissolution and reprecipitation during post-weld natural aging. A degree of
deformation and associated work hardening effects cannot be ruled out; indications are the deformed grains in this zone.

Solution treated and artificial aged

Solution heat treatment and artificial aging of the samples after FSpW increased the hardness distribution homogenously, Figure 7. The average hardness was 122 HV$_{0.1}$. Therefore the solution heat treatment seems to have evenly dissolved all precipitates. The artificial aging process produced a good distribution of strengthening precipitations to produce an even higher hardness than the BM. The changed grain morphology in SZ and TMAZ has a unique inhomogeneity.
3.3 Analysis of Tensile Characteristics

Figure 8 shows a tested welded sample in comparison to a BM sample. The plastic deformation is noticeable along the entire length of the samples and the lateral contraction is equally distributed. Especially near the fracture surface the orange peel effect appears which is associated with the coarse grains of the BM.

The typical fracture mode of the naturally aged samples can be observed in Figure 8. The main area of lateral contraction and fracture is located 8-10 mm from the center of the spot weld. This corresponds to the area of lowest hardness in the HAZ as explained above.

![Figure 8 Typical fracture mode in samples: (a) BM and (b) welded samples](image)

The fracture surface in the welded sample and BM shows normal ductile behavior. In both cases, a ductile fracture with many microvoids and dimples is obtained, Figure 8. Additionally trans- and inter-crystalline fracture portions are visible.

As a result of the microstructure changes discussed in section 4.1 and 4.2, the average naturally aged samples have 68.5% tensile strength, 54.5% yield strength and 59.2% elongation at fracture versus BM, Table 3.

Table 3 Tensile test: average results.

<table>
<thead>
<tr>
<th>Tensile strength [MPa]</th>
<th>Yield strength [MPa]</th>
<th>Elongation at fracture [%]</th>
</tr>
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</table>

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### 3.4 Effect of Artificial Aging

The analysis of variance generates a model that only includes the factor “artificial aging” when the tensile strength or the yield strength are chosen as the main system response for an interval of confidence of 95% ($\alpha=0.05$). The influence of the factors “welding mode” and “gas shielding” is thus non-existent and can be neglected. With correlation coefficients of $R^2 = 95.6\%$ (tensile strength) and $R^2 = 99.6\%$ (yield strength) the models are adjusted properly and describe nearly all of the total variability.

The artificial aging increases the tensile strength of the samples about 51 MPa and the yield strength about 94 MPa, Figure 9. This is probably caused by the restored strengthening effect of precipitates in the weld including the weakest area of the HAZ.

The measured elongations are better explained by a model that contains the factors “artificial aged”, “welding mode” and the interaction between them for an interval of confidence of 95% ($\alpha=0.05$). The model is adjusted properly with a correlation coefficient of $R^2 = 92.3\%$. At p-values lower than 0.05, the factors “artificial aged” ($p=0$) and the interaction between “artificial aged” and “welding mode” ($p=0.026$) seem to be significant.

The main effects and first order interactions for the mean elongation at fracture are shown in Figure 10. Artificial aging decreases the elongation from 13.2% to 7.5%. The main effect of the welding mode on the

<table>
<thead>
<tr>
<th>Base material</th>
<th>311</th>
<th>255</th>
<th>22.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSpW – natural aged</td>
<td>213 ± 7.4</td>
<td>139 ± 2.3</td>
<td>13.2</td>
</tr>
<tr>
<td>FSpW – artificial aged</td>
<td>264 ± 3.4</td>
<td>233 ± 3.8</td>
<td>7.5</td>
</tr>
<tr>
<td>FSpW – solution treated and artificial aged</td>
<td>331 ± 7.3</td>
<td>282 ± 2.5</td>
<td>15.5</td>
</tr>
</tbody>
</table>
elongation is not significant. However, if the samples are not artificially aged, then the welds without a plug-filled keyhole show higher elongation, Figure 10. This decreased elongation is the only negative impact of the plug in comparison to bead on plate welds.

![Figure 10 (a) Main effect plots and (b) effects of the interaction between artificial aging and welding mode on the elongation at fracture](image)

The relatively low values of elongation at fracture are caused by the overaged low strength local area in the HAZ. This results in strain concentration around this area. The surrounding areas do not contribute to the plastic deformation process. This reduces the elongation at fracture in comparison to the BM.
4 Conclusions

The following conclusions were derived from the current analysis of FSpW as keyhole closure method in AA 6061-T6:

1) It is feasible to use FSpW as a keyhole closure method. Defect-free spot welds have been achieved without strength reduction compared to spot welds in the bead-on-plate samples.

2) The microstructure of the friction spot welds displayed typical metallurgical features. The welded area is mainly composed of very fine dynamically recrystallized grains in the SZ as a result of high shear rates and process temperatures. The surrounding zones show typically deformed grains (TMAZ) and a heat-affected zone (HAZ).

3) For samples without artificial treatment, a joint efficiency of 59% and 68% was achieved when choosing the hardness or tensile strength as main response, respectively.

4) Suitable heat treatments significantly increase the strength of the tested samples. Nevertheless the elongation at fracture is limited due to the concentration of plastic deformation in the low strength area in the HAZ. The effect of the plug-filled keyhole in comparison to bead-on-plate spot welds is a slight decrease in elongation at fracture in the naturally aged specimens.

Acknowledgments

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