EXPERIMENTAL INVESTIGATION OF THE WELDABILITY OF HIGH STRENGTH ALUMINIUM USING FRICTION SPOT WELDING

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Abstract: Friction spot welding is a technique for joining lightweight aluminium and magnesium alloys in the overlap configuration by means of frictional heat and mechanical work and has a high potential for industrial applications. As this is a very recent technique, little information is available regarding the evaluation and optimisation of process parameters for specific material combinations. The process has been used to investigate the weldability of the high strength aluminium alloy EN AW-7475-T761, aiming to produce high quality joints in terms of mechanical performance and microstructure. More specific, the influence of the plunge depth, rotation speed and welding time was investigated. The paper first shortly describes the process and continues with the results of the microhardness, static tensile and optical microscopy tests.

Keywords: EN AW-7475-T761; friction spot welding; parameter study

1 INTRODUCTION

The increasing need for strong and lightweight materials in automotive and aerospace industries aiming for fuel savings, performance and safety have led to the development of new joining techniques for aluminium and magnesium alloys. Up to date, most spot joints are made with mechanical fastening or resistance spot welding. Mechanical fastening methods as riveting, self-piercing riveting and bolting add considerable weight, when significant amounts are required, and are more difficult to automate. The pierced surface resulting from these methods also give rise to sealant and corrosion prevention challenges. Traditional fusion welding of some high strength aluminium alloys, is difficult due to hot cracking and hydrogen void generation. The higher thermal and electrical conductivity of aluminium also lead to a higher energy consumption in resistance spot welding or laser spot welding and thus to higher operating costs.

The new joining technique known as friction spot welding (FSpW), or refill friction stir spot welding, is one of the alternatives overcoming these disadvantages and even offers additional advantages. These include: no filler material is required, environmentally friendly (no generation of fumes, IR, UV and electromagnetic radiation), limited or no waste products, fast processing speeds, no pre-cleaning needed and the good surface quality requires no post-processing. The goal of this research is the investigation of the influence of the most important process parameters (plunge depth, rotation speed and welding time) on the microstructural and mechanical properties of friction spot welds in the alloy 7475-T761, aiming at strong connections with a high reproducibility.

2 FRICTION SPOT WELDING

2.1 Process description

Friction spot welding (FSpW), also known as refill friction stir spot welding is a technique for joining sheets in the overlap configuration invented and patented by GKSS Research Centre GmbH [1]. The workpiece does not reach temperatures above the melting temperature, making this a solid-state joining technique. This process is suitable for spot welding lightweight materials with low melting point such as aluminium and magnesium alloys. The mechanical nature of this welding process makes it possible to weld any alloy which presents some degree of plasticity [2]. Friction spot welding evolved from friction stir welding (FSW), removing the traverse part of FSW and adding a refill stage. This is done by using a three piece non-consumable tool, consisting of a concentric clamping ring, centre pin and sleeve. The welding tool during the different process steps is schematically depicted in figure 2.1, courtesy of Rosendo et al. [3].

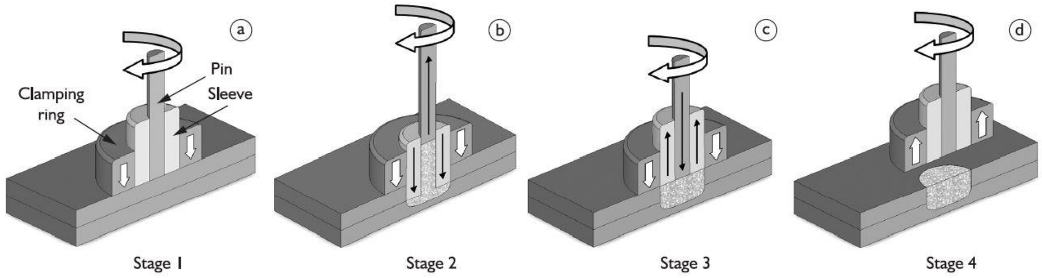

Figure 2.1. Schematical representation of FSpW process [3]

The process can be described in four stages. In the first stage the tool is lowered to the zero level, which is equal to the top surface of the upper sheet. Here the clamping ring, located at the outside of the tool, fixates the two plates between the weld head and the backing anvil by applying pressure. At the same time, the pin and sleeve start to rotate at identical rotational speeds, touching the upper sheet. The friction causes the lightweight alloy to heat up and plasticise. In the following stage, the sleeve is pushed into the workpiece whilst it is still rotating until it reaches the pre-set plunge depth. Simultaneously, the pin retracts, creating a cavity of the same volume, where the material displaced by the sleeve is accumulated. In stage three, the sleeve is retracted and the pin pushes the plasticised material back down, filling the weld and creating a weld nugget. As a last stage the entire weld head is withdrawn from the workpiece, revealing a circular mark on the top sheet, but without keyhole or significant material loss. This particular sequence is called sleeve-plunge. The pin-plunge variant also exists, where the pin first plunges into the workpiece, but this would lead to a smaller effective weld area and as stated by Suhudinn et al. [4], this will result in a lower joint strength. The fact that there is no keyhole leads to less stress concentrations and corrosion problems.

The process parameters consist of the rotation speed, the plunge depth and the joining time. The joining time can be divided into three different parts, the plunge time, the dwell time and the retraction time. These time parameters are visualised in the figure below.

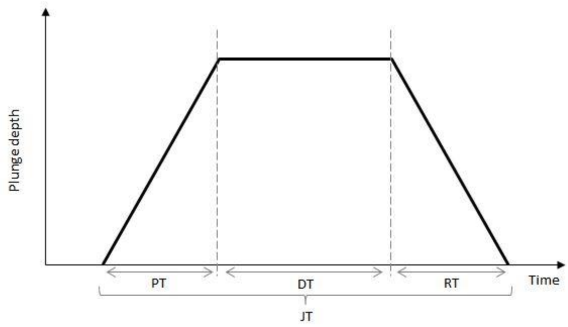

Figure 2.2. Plunge depth as a function of the joining time with the plunge, dwell and retraction time indicated

2.2 Weld properties

A typical cross-section of a FSpW weld nugget is depicted in figure 2.2 and consists of 4 distinct zones, each with different microstructures and axi-symmetrical to the tool axis [5]. The approximate locations of these zones can also be seen in Figure 2.3. The zones, named from the middle of the weld outwards, are: the stir zone (SZ), the thermo-mechanically affected zone (TMAZ), the heat affected zone (HAZ) and the base material (BM).

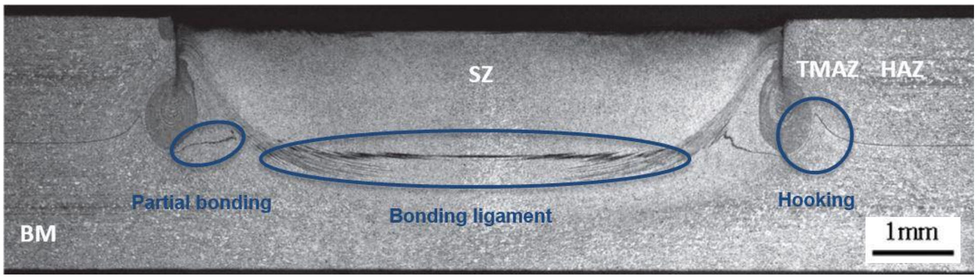

Figure 2.3. Typical cross-section by Rosendo et al. [3]

The SZ has approximately the same width as the pin diameter and is characterised by a fine equiaxed grain structure. The result of the dynamic recrystallisation caused by high strain and the intense thermal cycle during welding, causing solubilisation of the precipitates and the ageing afterwards [3]. The TMAZ is concentrated below the periphery of the sleeve and consists of elongated grain structures due to moderate deformation and frictional heating as concluded by Shen et al. [5]. The HAZ undergoes, as the name implies, only a thermal cycle caused by the frictional heating. This results in a non-deformed microstructure. However, the exact extension of the TMAZ and therefore, the boundary between the TMAZ and the HAZ is difficult to localise with an optical microscope. Rosendo et al. [3] defined the boundary between the TMAZ and the HAZ as the location with the minimum hardness between the stir zone and the base material.

Microhardness profile measurements performed at mid thickness of the upper sheet, result in various profiles, mostly depending on the kind and temper of the aluminium alloy used. Heat-treatable alloys exhibit a distinct W-shaped microhardness profile, with the minimum hardness located in the HAZ. In between, an elevated hardness is observed in the stir zone [6]. Shen et al. [5] noticed that the intense stirring in the region below the space between the pin and the sleeve causes even finer grains than in the bulk of the SZ. The hardness in the TMAZ is seen as a slope connecting the SZ and the HAZ.

The cross-sections of the weld nugget also reveal some geometric patterns associated to the plasticised material flow and common to most welds as examined by Rosendo et al. [3]. These consist of hooking, partial bonding and the bonding ligament. These features can also be seen in Figure 2.3. Hooking is caused by plastic deformation of the lower sheet and the lack of mixing of the sheets at that location. It has an upside down V-shaped appearance. According to [3], it is formed during the penetration and the retraction of the sleeve in the bottom sheet. The tip of the hook acts as a crack initiation location and for that reason sharp and large hook is avoided in literature as it decreases the joints strength. Partial bonding is a region where the bonding of the two sheets is not that strong, located between the bonding ligament and the hooking [3]. It resembles a short jagged line underneath the sleeve and together with hooking, it plays an important role in crack initiation as cracks can easily propagate in the weakly bonded region to create a circumferential tear [3]. The authors define the bonding ligament (BL), found centrally below the stir zone, as a banded structure where the two sheets have a strong metallurgical bond. Depending on the alloy used, the evidence of the presence of the bonding ligament may be different. Investigations by Tier et al. [7] and Suhuddin et al. [4] describe a linear relationship between the BL length and the lap shear strength of the welds.

In the weld nugget, imperfections may also be present. Defects like lack of mixing and incomplete refill were found by metallographic inspection by Rosendo et al. [3] and they attributed these defects to insufficient heat input. Both are found at the path of the sleeve plunging into the workpiece. Shen et al. [5] also noticed voids inside the weld nugget, stating that void formation is mainly due to poor material flow caused by inappropriate welding parameter combinations. Shen et al. [5] also stated that the voids become smaller with increasing welding time and larger with increasing rotation speed. They pointed out that voids are very unfavourable for the integrity and strength of the weld, so they should be avoided or minimised.

The overall tensile strength of the weld is mostly dependent on the welding parameters and the presence of imperfections. Zhang et al. [8] investigated the impact of hooking defects on the lap shear strength in friction stir spot (FSSW) welded joints. They reported that the tensile shear loads of joints without any hooking defects almost doubled compared to joints with defects. Direct comparisons were made between the strength of FSSW and refill FSSW in [9]. In this work Uematsu et al. concluded that the refilling process increased the cross sectional area of the nugget, hence increasing the tensile strength. They noticed a 30% improved tensile strength by the refilling process so better results for defect free FSpW welds are also expected. Tier et al. [7] made a statistical analysis to link the lap shear load to the weld parameters in case of 1,5 mm thick EN AW-5042-O sheets. They reported that the plunge depth plays a dominant effect on the lap shear strength. The rotational speed of the tool is an important parameter for the final weld strength. Shen et al. [5] concluded in their investigation regarding refill friction spot welded 2mm thick EN AW-7075-T6 aluminium sheets that the best results were achieved at a lower rotational speed and a shorter joining time. They noticed a maximum when plotting the lap shear strength versus the joining time.

3 EXPERIMENTAL DATA

3.1 Material

In the present research, sheets of aluminium alloy EN AW-7475-T761 were welded in the overlap configuration. The sheets had a thickness of 1,6 mm and were used in the bare condition, meaning without any coating. The chemical composition of the alloy is shown in table 3.1. The main mechanical properties following from its temper condition are shown in table 3.2. This alloy has a poor weldability when considering traditional fusion welding processes.

Table 3.1. Composition of the alloy used. [10]. *= max value

Chemistry	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	V	Zr	Other
7475 [wt%]	0,10*	0,12*	1,2-1,9	0,06*	1,9-2,6	0,18-0,25	5,2-6,2	0,06*	/	/	0,15*

Table 3.2. Typical mechanical properties of the alloy used [10].

	Ultimate strength [MPa]	Yield strength [MPa]	Elongation [%]
7475-T761	524	448	12

3.2 Equipment

The welds were performed using a commercial RPS 100 friction spot welding machine manufactured by Harms & Wende Germany. The three piece welding tool, consisting of the clamping ring, the sleeve and the pin is shown in figure 3.1. They have the following dimensions: the outer diameter of the clamping ring and sleeve is 14,5 and 9 mm respectively while the pin has an outer diameter of 6 mm.

The machine is capable of applying axial forces and rotational speeds up to 15 kN and 3300 rpm respectively. The thread at the end of the pin and sleeve acts as a barrier, limiting the amount of plasticised material that is pressed between the tool parts, but it also improves the material flow as concluded by Zhao et al. [11].

Figure 3.1. From left to right: clamping ring, sleeve and pin

3.3 Experiments

The three most important process parameters were varied: the rotation speed was varied between a low and a high value (1500 - 2500 rpm), the dwell time had three possible values (2,5 - 3,5 - 4,5 s) and the plunge depth had two settings (1,6 - 2,1 mm). This resulted in the twelve welding conditions found in table 3.3. As can be seen, only the dwell time is varied, meaning that the plunge and retraction time are kept constant at 2 and 1,5 seconds respectively. After welding, a longitudinal section through the centre of the weld nugget was ground, polished and etched using Keller's reagent, to reveal the weld microstructure. Lap shear strength tests were performed on the welds using an Instron model 1342 with 10mm/min displacement speed. Microhardness maps (HV0,3) were also made using a Leco AMH43 system of welds with low and high heat input parameter combinations.

Table 3.3. Welding conditions

Weld condition	Rotation speed [rpm]	Plunge depth [mm]	Dwell time [s]
1	1500	1,6	3,5
2	2500	1,6	3,5
3	1500	1,6	2,5
4	2500	1,6	2,5
5	1500	1,6	4,5
6	2500	1,6	4,5
7	1500	2,1	3,5
8	2500	2,1	3,5
9	1500	2,1	2,5
10	2500	2,1	2,5
11	1500	2,1	4,5
12	2500	2,1	4,5

4 RESULTS

4.1 Metallographic examination

The weld microstructures for the EN AW-7475 alloy resembles those mentioned in literature. One of the best results obtained, in terms of microstructure and defects is shown in figure 4.1. This weld was made with condition 7. Condition 11 closely resembles this cross section. The stir zone is characterised by fine equi-axed grains, with a band of coarser grains down the middle. For the welding conditions with the lower rotational speed this band is rather thin, whereas for higher rotational speeds, this band was much broader. An increase of the dwell time results in a narrower coarse central band for either one of the rotational speeds. A slight form of incomplete refill is noticed as seen in figure 4.2. This is due to the insufficient plunge depth of the pin in the refill stage of the process, as all of the twelve parameter combinations exhibit this kind of incomplete refill and a slightly elevated pin surface area is noticed. Most of the cross-sections didn't show voids, lack of mixing or other defects.

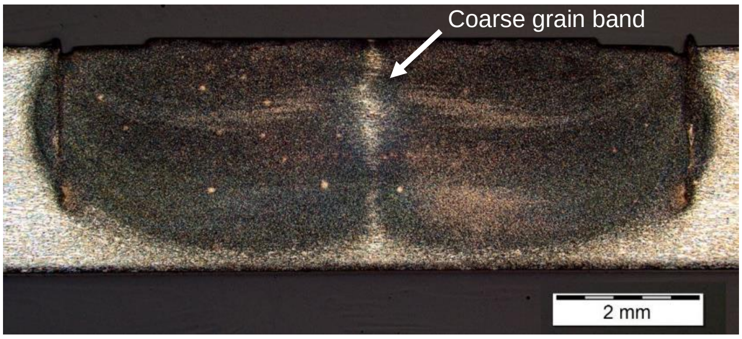

Figure 4.1. Cross-section of weld (condition 7)

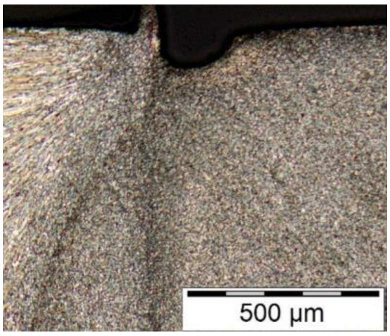

Figure 4.2. Incomplete refill (condition 7)

The presence of the bonding ligament is not easily distinguished. Two types of behaviour are noticed at the expected bonding ligament location. The first being a very fine banded structure centrally below the stir zone, seen in all the welds made with a rotational speed of 1500 rpm. The banded structure consists of alternating coarser and finer grains. This type of bonding ligament is limited in width and can be seen in figure 4.3. It is a region of good adhesion between upper and lower sheets, with a strong resistance. The opposite is true for the second behaviour noticed which is attributed to all welds made with a rotational speed of 2500 rpm. Within these welds, there is a zone where the two sheets are not bonded. At the ends of this un-bonded zone, the normal bonding ligament is observed which continues to the outside of the weld nugget. The debonding never extends underneath the sleeve area, which suggests that the bonding under the sleeve area is stronger than the bonding centrally under the pin. The un-bonded zone can be seen clearly when looking at the un-etched samples, like the one in figure 4.4. No clear correlation can be found between the plunge depth and the extent of the debonding. For a plunge depth of 1,6 mm, the worst debonding is seen for a dwell time of 4,5 seconds (i.e. condition 6). The least amount of debonding is observed for the 3,5 seconds dwell time (i.e. condition 2). This is the opposite for samples with a plunge depth of 2,1 mm, where a dwell time of 3,5 seconds (i.e. condition 8) is the worst case and a dwell time of 4,5 seconds the better one (i.e. condition 12). The shortest dwell time of 2,5 seconds resulted in a mediocre amount of debonding for both plunge depths.

Figure 4.3. Fine banded structure (condition 9)

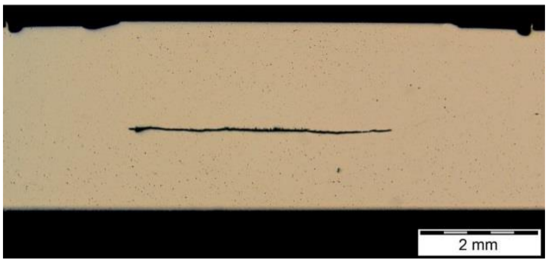

Figure 4.4. Un-bonded zone (condition 6)

A dark line, like the one in figure 4.5, is observed in the middle of the weld nugget for the welding conditions 8 and 12. It connects the outer areas of the nuggets surface and has a W-shaped appearance. This line represents an axi-symmetrical plane of very fine grains around the nuggets centre.

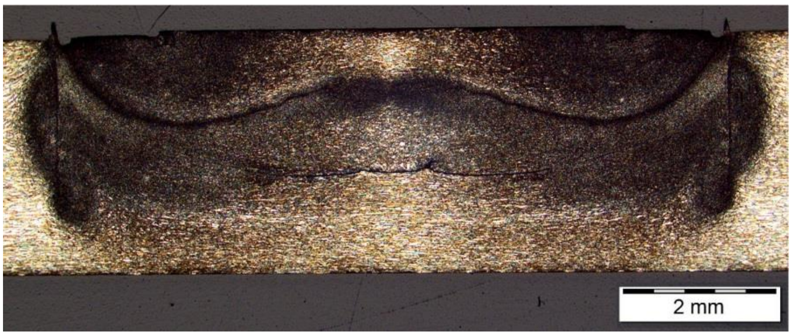

Figure 4.5. W-shaped fine grain structure (condition 8)

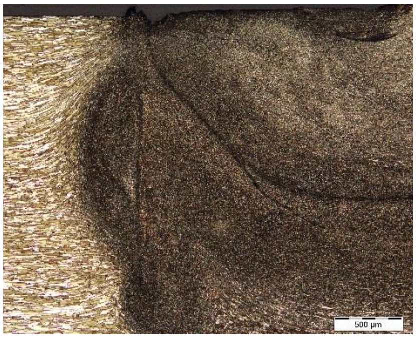

Figure 4.6. W-shape and BL fusion

Hooking was the most pronounced for the lower plunge depth of 1,6 mm. Hooking had the sharpest appearance for conditions 1, 3, 5 and 6. Conditions 2 and 4 showed a broader two pointed M-shaped hook tip. No sharp hooking was observed for the samples with the deeper plunge depth of 2,1 mm. Hooking was either absent or in the cases of conditions 10 and 8, very blunt and weak. The height of the hook, from the sheets interface to the tip of the hook, was measured for conditions 1 through 6, as these allowed accurate measurements. This revealed that the hook height increases with increasing rotation speed and dwell time. This could be attributed to the fact that higher levels of these parameters cause more plasticisation of the material, which increases the vertical material flow during the process. When comparing the hook height to the weak ones in the 2,1 mm plunge depth welds, an even higher hook is present. This might indicate that the hook height also increases with the plunge depth due to the larger vertical displacement and thus a more vertical material flow. The most extreme condition in this regard (condition 12) even revealed that the bonding ligament line fused with the fine W- shaped fine structure mentioned above. This can be seen in figure 4.6.

Weld defects were only noticed in some weld samples. Lack of mixing was observed at the sleeve plunge path for conditions 1 and 3 and voids were also present at the edge of the hook for condition 1. It thus seems that these defects can be attributed to an insufficient heat input and poor material flow. In all samples, partial bonding was not visible.

4.2 Lap shear strength

The lap shear strength of all weld conditions was determined, with three times repetition, in order to study the influence of the process parameters on the mechanical performance of the welds. The individual results ranged from 2 to 6 kN. The worst results were obtained for weld condition 3 and the best for weld condition 11. From this it can be concluded that absence of defects results in stronger joints. The lap shear strength increased with the plunge depth. This can be attributed to the fact that the increase in plunge depth causes the absence or very weak presence of hooking. As hooking is one of the most important crack initiation sites, a reduction in sharp hook thus results in an increase in lap shear strength. The strength of the joint also increases with increasing dwell time. This can be due to the fact that an increase in dwell time causes a more homogeneous nugget microstructure. Both effects can be seen in figures 4.7 and 4.8, which also show the large scatter of the tests performed. A slightly lower strength was observed for the higher rotational speed. This could be due to the formation of the large un-bonded regions, which compromised the joints integrity.

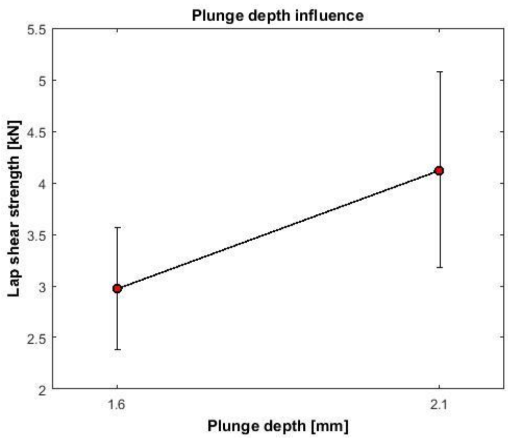

Figure 4.7. Influence of plunge depth on strength

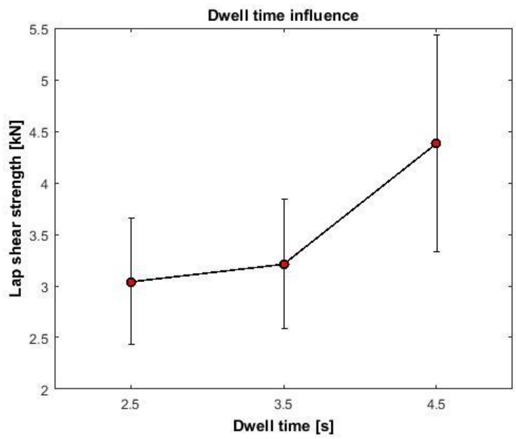

Figure 4.8. Influence of dwell time on strength

4.3 Microhardness

The microhardness maps from the low and high heat input parameter combinations at a 2,1 mm plunge depth (i.e. conditions 9 and 12) are depicted in figure 4.9. The origin of the maps is located in the middle of the nugget's surface and the edge of the sleeve plunge path is marked with a black dotted line.

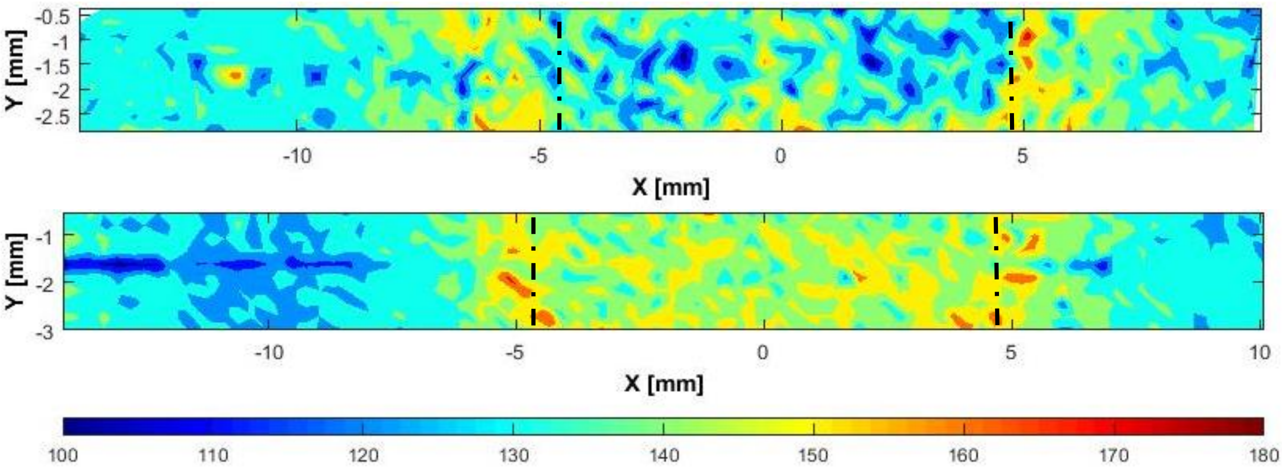

Figure 4.9. Microhardness maps of condition 12 (top) and condition 9 (bottom)

It is clear that the overall hardness inside the weld nugget of condition 9 is higher than the base material and the distribution is fairly homogeneous, whereas condition 12 show large areas with a lower hardness. For both conditions, the highest hardness values are reached in the vicinity of the sleeve plunge path. The absence of sharp outlined zones may be the consequence of the 7475 alloys ability to naturally age, as the hardness maps were made several months later.

5 CONCLUSIONS

The friction spot welding process has been used for joining the high strength aluminium alloy EN AW-7475. Different welding parameter settings were used, aiming to produce high quality connections in terms of microstructure and mechanical performance. More specific, the influence of the plunge depth, rotational speed and welding time on the microstructure and shear strength was investigated. The main conclusions are:

- The strongest welds are made with the parameters: rotation speed 1500 rpm, plunge depth 2,1 mm and dwell time 4,5 s. This resulted in a lap shear strength of 5,38 ± 0,56 kN.
- A rotation speed of 2500 rpm resulted in an un-bonded zone centrally under the stir zone which resulted in a lower lap shear strength.
- The lap shear strength increased with dwell time and plunge depth.
- A higher hardness is noticed along the sleeve plunge path.
- A higher heat input results in a lower hardness inside the weld nugget.

6 ACKNOWLEDGEMENTS

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