The effect of solution annealing and ageing during the RSW of 6082 aluminium alloy

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Abstract. In the automotive industry there is a growing tendency for the application of high strength aluminium alloys. In spite of their significant role in weight reduction there are still obstacles for their wider use due to their limited formability and weldability. Hot forming and in-die quenching (HFQ) process was recently developed for the forming of car body sheets. During the HFQ technology the sheet metal forming should be performed in a solution annealed condition. In the solution annealed condition the aluminium alloys have lower strength and better formability properties. The forming process is followed by a precipitation hardening which is generally connected with the painting of body parts (bake hardening). Besides the formability the implementation of HFQ has an effect on the weldability properties, too. HFQ must have an effect on the resistance spot welding (RSW) of aluminium sheets since the weld nuggets are produced after the HFQ, in the assembly part of the production chain, when the aluminium alloy is in a solution annealed and formed condition. The final properties of the welded joints are determined by the precipitation hardening which is the final step of the whole production process. The present research work aims to investigate the effect of the HFQ process on the weldability of AA6082-T6 aluminium alloy. The properties of the RSW joints are examined in different conditions (T6 delivery condition, solution annealed, precipitation aged). The materials tests include conventional macro testing, hardness tests and tensile-shear tests extended with EDS (Energy Dispersive Spectroscopy) and EBSD (Electron Backscatter Diffraction) tests in order to characterize the distribution of alloying elements and to analyze the grain structure.

Keywords: Resistance Spot Welding (RSW), AA6082, aluminium alloy, hot forming and in-die quenching (HFQ), EDS-mapping, EBSD test

1 Introduction

In the past decade there is an increasing demand for the application of aluminium alloys in the automotive industry, where they considered among the best engineering materials nowadays [1]. Their relatively low density and good resistance to corrosion are among the main reasons for their spreading utilization. By the increasing strength properties aluminium alloys have been recently the relevant competitors of steel nowadays. The most commonly used types in the order of strength level are the 5xxx, 6xxx and 7xxx groups, for example: AA5754, AA6082 and AA7075 respectively [2]. The investigated AA6082 alloy is applied in the structural elements of modern premium cars such as BMW 6, Ferrari 548 Italia, Jaguar XJ, Range Rover etc. [3].

Besides the favorable properties of high strength aluminium sheets there are still limitations for their wider application in the lower car categories. Replacing steel with lighter materials such as aluminum, magnesium, etc. can be costly and is not simply straightforward [4]. Within the obstacles not only the expensive base material but challenges of the production technology (e.g. metal forming, joining method) are also considered. Aluminum sheet has much lower formability at room temperature than typical sheet steels [4], therefore the formability properties should be improved. Regarding the joining methods of aluminium alloys the engineers face also difficulties which can be originated from the special properties of aluminium. The characteristics of aluminium which influences their weldability can be summarized as follows [3, 5]:

- oxide layer,
- gas porosity, shrinkage cavity,
- hot cracking sensitivity,
- reduced mechanical properties (softening) in the weld and the heat-affected zone,
- low electrical resistance,
- good heat and electrical conductivity.

The most common welding method in the automotive industry is the resistance spot welding (RSW), however friction stir welding (FSW) can have a prosperous future [2, 6]. One of the major advantages of RSW is the easy automation (high speed and adaptability) in high-volume production. However this statement presently valid primarily for the joining of steel components, since the RSW of aluminium sheets is still complicated due to the abovementioned characteristics. In order to compensate the low electrical resistance and the good heat conductivity of aluminium alloys hard or extra hard program should be applied during RSW, which means high welding current and short welding time. The presence of oxide layer generally affects the properties of the RSW joints, therefore surface pre-treatment methods are recommended to be applied. However, in industrial practice the removal of the oxide layer is often neglected due to technical difficulties and financial reasons. The formation of shrinkage cavity and the avoidance of hot cracking can be treated by the application of higher post-pressing force, which requires supplementary equipment in the welding machine. The compensation of the reduced mechanical properties in the weld metal and in the heat-affected zone are in the main focus of researchers in the field of joining technologies. New welding processes and complex technologies with limited welding heat input are successfully developed and tested [2, 7, 8], however the further optimization of RSW cannot be neglected due to its high productivity in sheet metal joining [9].

The present research work aims to analyze the possible positive effects during the implementation of advanced forming technology of aluminium sheets (HFQ) on the properties of the RSW joints.

2 The HFQ process

One of the major obstacles to use sheet aluminium alloys in car-body is their limited formability at room temperature, which is especially the case for the higher strength alloys. In addition to work being done to develop alloys of improved formability, advanced forming technologies are also being investigated to form complex shaped parts from these alloys [10]. Solution heat treatment, forming, and in-die quenching (HFQ) is one such technology [11]. In this process, the blank is first heated up to its solution heat treatment (SHT) temperature. At this elevated temperature, the solid solubility is increased and the alloying elements, or precipitates, fully dissolve into the aluminium matrix. Consequently the yield strength and the residual stresses are reduced and the material becomes more ductile due to the fewer obstacles to dislocation movement, enabling more complex shapes to be formed [12]. The blank is then transferred to a cold die, formed at a high speed and held in the cold tool to achieve a rapid cooling rate to room temperature. The fast pace of the process allows a supersaturated solid solution to be obtained [13].

After the successful pressing process the car-body elements should be joined to each other, usually with RSW. Finally the assembled car-body is moved to the paint shop, where the aluminium can reach its increased mechanical properties during the ageing, however the time of painting process is much shorter than the conventional ageing. It means that the aluminium sheets are joined in a solution annealed (softened) and furthermore formed condition. Although it might be considered that the sheets are primarily joined at the less shaped parts of the car-body elements. Since the artificial ageing is connected to the painting of the car-body, therefore the joint connections (RSW, FSW, clinching, adhesive bonding etc.) should be prepared before. It means that joints are heat treated as well, which might influence the mechanical properties of the weld metal and the heat-affected zone [14]. The whole process can be seen in **Fig. 1**.

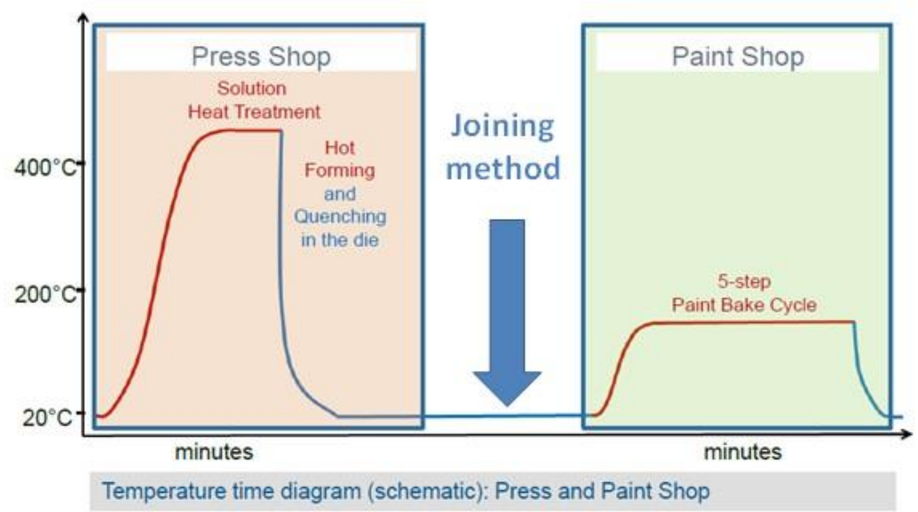

Fig. 1. The whole cycle of the HFQ process according [15].

3 Experimental procedure and methodology

The RSW experiments aim to investigate the possible benefits of the implementation of HFQ technology to the production chain. Therefore three experimental variants have been determined. In the first experiment the aluminium sheets were welded in the T6 delivery condition. During the second case the aluminium sheets were solution annealed before joining in order to simulate that the welding should follow the HFQ process. However, it is important to note that only the heat treating effect of HFQ was analysed, the forming consequence was neglected in present case. In this case the sheets were welded in a softened condition. The third experiment was used to examine the effect of post weld ageing on the joint properties. In this case similarly to the second experiment the sheets were solution annealed before joining that was followed by an aging heat cycle due to the conventional base metal production technology. Although it should be noted that among the ongoing research goals the reduction of ageing time is also is the focus areas related to the development of HFQ process [13].

3.1 Investigated material

From the commonly used aluminium alloys the AA6082-T6 sheet with thickness of 1 mm was chosen for our investigations. This base material includes mainly magnesium and silicon as alloying elements, and its strength can be increased with annealing hardening. The relatively high strength is derived mainly from the finely dispersed Mg_2Si precipitates both within grains and along grain boundaries. The base material chemical composition can be seen in **Table 1**, and the mechanical properties are found in **Table 2**. The T6 condition means, that this aluminium base material has a homogenizing solution annealing at 535 °C for 30 min, then quenching, and finally aging at 190 °C for 8 hours.

Table 1. Chemical composition of AA6082-T6 aluminium alloy (wt%).

Cu	Fe	Mn	Cr	Mg	Ti	Si	Zn	Al
0.090	0.460	0.460	0.020	0.700	0.030	0.900	0.080	rest

Table 2. Mechanical properties of AA6082-T6 aluminium alloy.

R_m, MPa	$R_{p0.2}$, MPa	A_{50}, %
348	303	15

3.2 Experimental circumstances

The aluminium sheets were cut into 100 x 30 mm specimens for the welding process (**Fig. 2**). Welding was performed by overlapping the plates linearly to fabricate the specimens for tensile shear tests.

Specimens were welded using a TECNA 8007 welding equipment with a TE 550 control unit, with a capability of a 26 kA effective weld current. The welding machine was equipped with a second valve and a pressure controller in order to realize a post pressing force for the avoidance of shrinkage cavity and hot cracking. A Cu-Al_2O_3 composite electrode with a half orb 7.5 mm radius was used for the experiments.

For joining, a 7-cycle weld time was set with two level of electrode forces (3-4 s and 2.7 kN; 2-3 s and 4.4 kN), and with constant electrode holding time (7 cycles). The welding experiment were performed at room temperature and one cycle corresponds to 0.02 s. Other welding parameters such as the weld current and the actual cycle times were changed before present experiments in order to determine the optimal welding lobe. Water cooling of electrodes at a rate of 5 l/min was set during the experiments.

For the solution annealing and post weld aging heat treatments a standard electrical furnace was used.

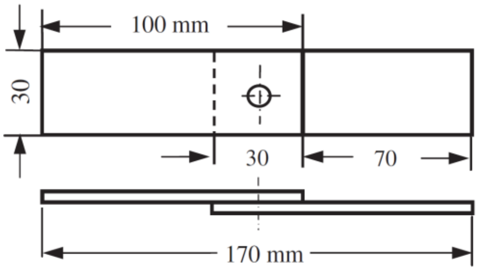

Fig. 2. Specimen configuration for the RSW experiments.

Based on the preliminary determined welding lobe and previous experiments [16] the highest possible welding current (of our machine) was chosen for the actual experiments (~ 26 kA), with two exact level of electrode forces (F_e = 3 s x 2.7 kN and F_{ny} = 2 s x 4.4 kN). The pre-force time (t) and the after-force time (t) were set to 1 cycle, the total welding time (t_h) was 5 cycles. The whole welding cycle can be seen in **Fig. 3**.

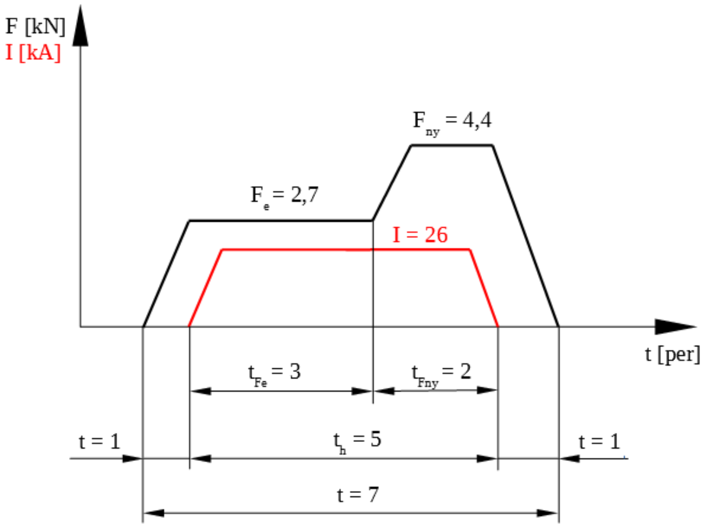

Fig. 3. The applied welding cycle diagram for the RSW of AA6082 alloy.

4 Results and discussion

4.1 Tensile-shear tests

Specimens for the tensile shear test were constructed as shown in **Fig. 2**. Its dimensions differ from standard sizes with respect to material savings. Bracket sizes are valid in 0.5-1.5 mm range, according to standard EN ISO 14273. The tests were performed with static loading. Due to the different plain of the sheets a bending force is also present. According to that, the possible failure modes during the tensile-shear tests are pull out, partial pull out, interfacial mode. During pull out failure the weld nugget tears out from one of the base materials completely, while in interfacial mode the weld nugget shear completely in half [17].

In order to gain reliable results 11 test pieces were used in every cases for the statistical evaluation. The maximal tensile-shear forces (F_{TS}, kN) and the diameters of the nuggets (d, mm) were measured in every cases. The average tensile-shear force (F_{TS}', kN) (1), the standard deviation (SD, kN) (2), the standard deviation coefficient (SD_c, %) (3), the design tensile-shear force (F_d, kN) (4) were calculated.

$$F_{TS}' = \frac{\sum_{i=1}^{n} F_{TS}}{n} \tag{1}$$

$$SD = \sqrt{\frac{\sum_{i=1}^{n} (F_{TS} - F_{TS}')^2}{n-1}} \tag{2}$$

$$SD_c = \frac{SD}{n} \cdot 100 \tag{3}$$

$$F_d = F_{TS}' - 2.23 \cdot \frac{SD}{\sqrt{n}} \tag{4}$$

The gained results can be seen in **Table 3** with the three types of heat treating condition. From the tensile shear force values it can been clearly seen that the post weld ageing can significantly improve the load bearing capacity of the RSW joint. We can state, that the strength of the welded joints could be further increased with the higher welding current, but this is possible only with a larger capacity equipment.

Table 3. Tensile-shear force results of AA6082 aluminium alloy.

Specimen	F_{TS}, kN		
	T6 condition	Solution annealed	Post weld aged
1	2.55	1.85	3.40
2	2.55	2.05	3.25
3	2.55	1.95	3.25
4	2.45	2.15	3.15
5	2.25	2.05	3.15
6	2.35	2.00	3.25
7	2.35	2.00	3.25

8	2.45	2.00	3.40
9	2.40	1.85	3.10
10	2.35	2.15	3.30
11	2.55	2.00	3.20
F_{TS}', kN	**2.44**	**2.01**	**3.25**
SD, kN	**0.11**	**0.10**	**0.10**
SD_c, %	**4.31**	**4.92**	**2.96**
F_d, kN	**2.36**	**1.94**	**3.18**

4.2 Macroscopic tests

For these test the cutting of the joints was done by mechanical method, sawing, and by grinding the remaining material layer until the exact centre line of the joint. After grinding the surfaces were etched for the 16× magnification macroscopic images. Besides analysing the joint properties, joint defects and deformations, the images were also needed to determine the nugget diameter, which is the basis of comparability. Macroscopic images were made using a digital camera using a Zeiss Stemi 2000 C stereomicroscope (**Fig. 4**).

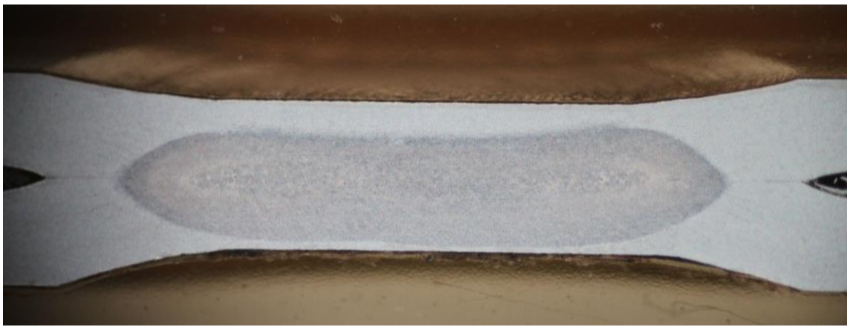

Fig. 4. Macroscopic image of AA6082 alloy (magnification 16x, t = 1 mm).

The weld nuggets shape was regular in every cases, only a small asymmetry can be observed, which can be explained with the different electrode conditions. Cracks and other dissimilarities could not be found in the welded joints and in the heat-affected zones.

4.3 Hardness tests

Vickers microhardness tests were performed with a Mitutoyo equipment, where the loading force was 200 g and the step of the measuring sequence elements was 0.2 mm. The measuring sequence was started in one of the base materials and was gone through the weld nugget diagonally due to the electrode pit, then was ended in the base material again similarly to the applied methods in the literature [10]. Such measuring line can be seen in **Fig. 5**.

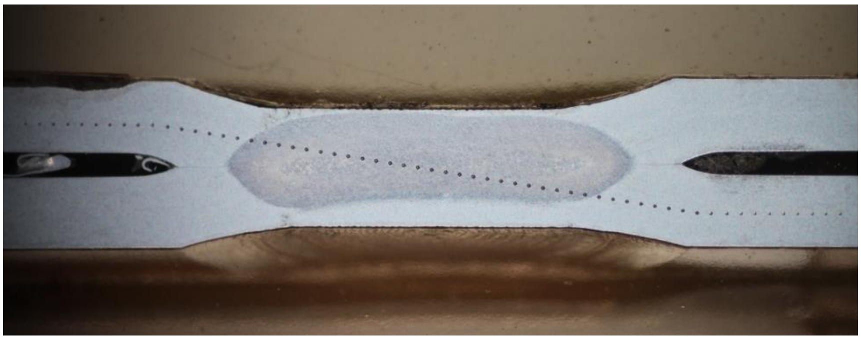

Fig. 5. Hardness identifications through the weld nugget and the HAZ on AA6082 alloy (t = 1 mm).

The measured hardness results can be seen in **Fig. 6**. The average of the measured values in the base material were 100-105 HV0.2. The diagram shows that in the weld nugget and in the heat-affected zone a significant softening can occur due to the welding heat input. The highest hardness values were measured in the heat-affected zone, and they were around 124 HV0.2, while the minimum hardness's were measured in the middle of the nugget, 49 HV0.2 and 52 HV0.2 respectively.

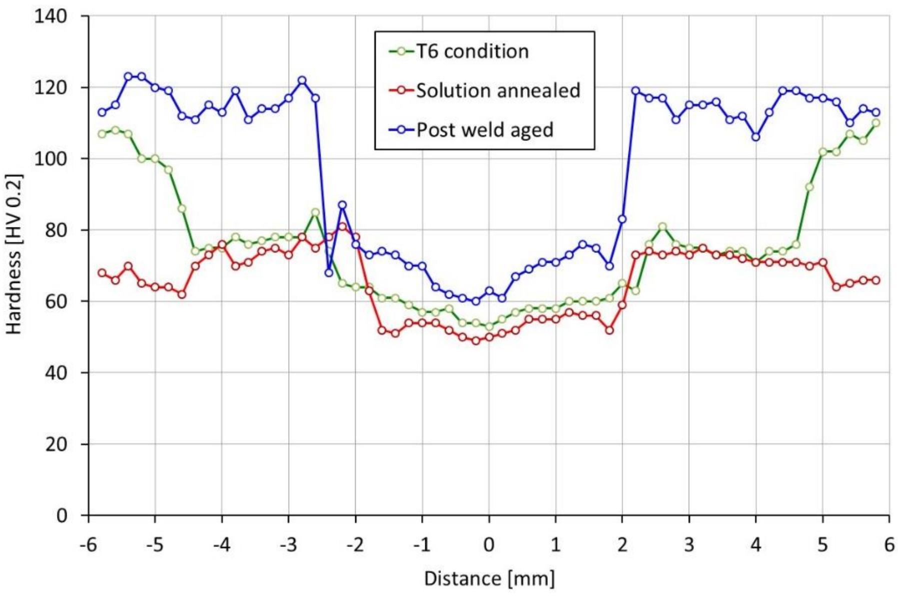

Fig. 6. Hardness distribution through the weld cross section on AA6082 alloy.

If the AA6082 alloy is welded in T6 delivery condition a significant softening can be noticed in the weld nugget and the heat-affected zone (marked by green colour). If the same material is welded in a solution annealed condition the base material softens as it is expected. Regarding the hardness of weld nugget and HAZ there is no significant difference compared to the previous experiments. If these specimens are precipitation hardened in a furnace for an eight our ageing tempering the base material and the HAZ harden to the level of the T6 as delivery condition, and a slight hardening can be noticed in the weld nugget as well. The slighter hardening of the weld nugget might be correlated with the microstructure and the segregation of alloying elements participating in the precipitation hardening. A higher hardening of the weld nugget may be achieved by the change of the microstructure and the solution of the precipitated alloying elements. The application of pulsed RSW may further improve the properties of the weld nugget. It should be important to mention that the conventional heat treating circumstances of the AA6082-T6 alloy were applied during these experiments; however one of the main targets to shorten the time of the solution annealing and the artificial ageing.

4.4 EBSD tests

EBSD (Electron Backscatter Diffraction) tests were performed at the University of Oulu for the investigation of microstructure and grain orientation. In the presented results the grain boundaries are defined using the ≥15° boundaries. However, especially in nugget areas also low angle boundaries (<15°) were detected. This can be seen in the images as change of colour within the big grains (**Fig. 7**, **Fig. 8** and **Fig. 9**). Different colours mean the different orientations of grains.

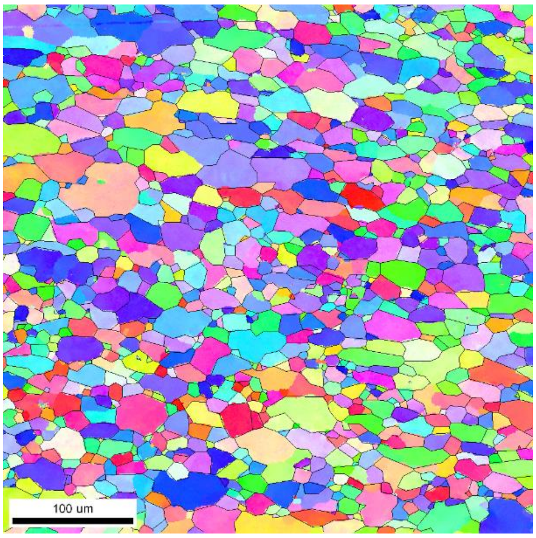

Fig. 7. Base metal (average grain size: 12 μm, cumulative 90% grain size: 30 μm)

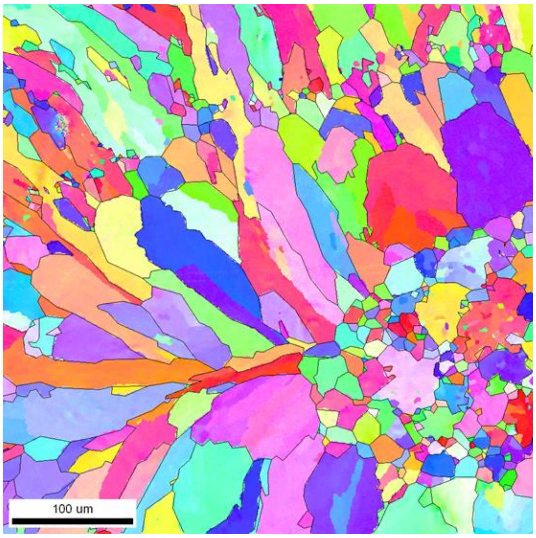

Fig. 8. Columnar dendritic ring and a fine grained core in the weld nugget (average grain size: 15 µm, cumulative 90% grain size: 70 µm)

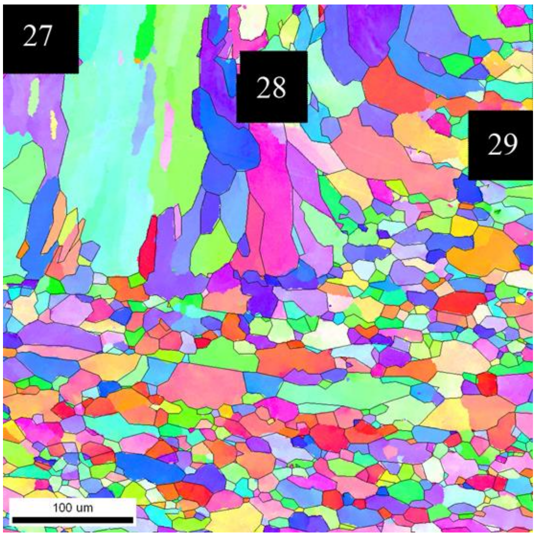

Fig. 9. Edge of weld nugget and a part of HAZ (average grain size: 14 µm, cumulative 90% grain size: 44 µm)

Average grain size is calculated from all the grains in the image. The count shows the number of grains and the 95% confidence interval is the scatter of the average and is needed to compare the results statistically reliably. Cumulative 90% grain size means that 90% of the total sum of grains is smaller than the given size. This method makes difference in case of homogeneous or heterogenous microstructure and emphasizes the effect of single big grains. The change of the fine-grained microstructure to a coarse, dendritic structure could been clearly seen during the EBSD tests. By the application of pulsed technology more favorable microstructure might be achieved similarly to DP steels [16].

4.5 EDS studies

EDS (Energy Dispersive Spectroscopy) mapping was performed at the University of Oulu in the different areas of the RSW joints. The testing method can be used to characterize the chemical composition and the distribution of segregated alloying elements. The EDS results are presented in **Fig. 10**, **Fig. 11** and **Fig. 12**.

In the base metal coarse particles can be identified which seem to consist of Si, Fe and Mn, while Mg is homogeneously distributed in the matrix.

Regarding the weld nugget especially Si and in some extend also Mg are segregated on grain boundaries, which can be connected to the melting of base material. It means that the level of silicon and magnesium reduced in the inner part of the grains and therefore disperse precipitations cannot be formed. The results show that there is also Fe in the grain boundaries.

During the examination of HAZ the distribution of Mg and Si seemed similar as in the base metal. Mg is homogeneously in the matrix and Si is both in the matrix but also in the coarse particles together with Fe and Mn.

The formation or precipitates can be mostly expected in the base material and in the heat-affected zone during post weld ageing, since the segregation of the important alloying elements at the grain boundaries limits the possibility of precipitation hardening in the weld nugget.

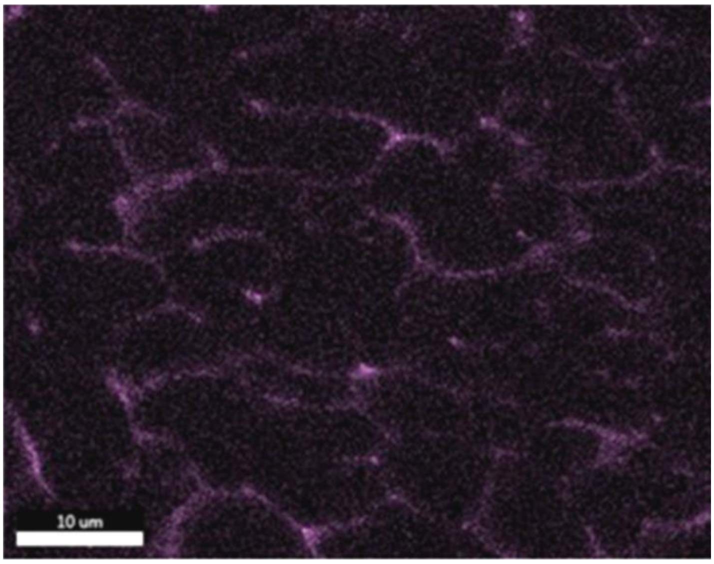

Fig. 10. Silicon segregation to the grain boundaries in the weld nugget

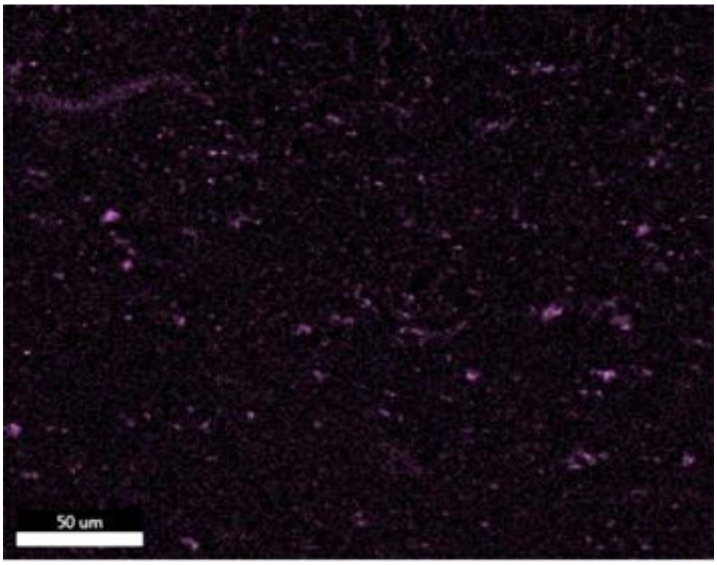

Fig. 11. Silicon distribution in HAZ

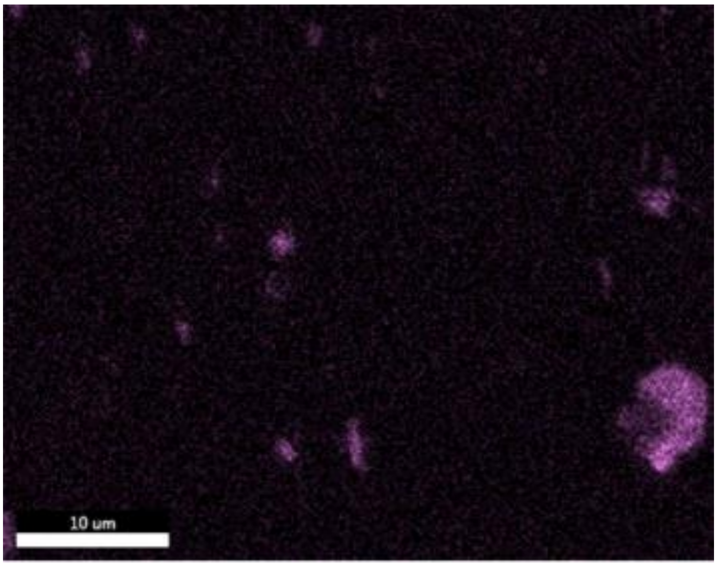

Fig. 12. Silicon distribution in the base metal

5 Conclusions

Based on the preliminary determined welding lobe the AA6082-T6 aluminium sheets with 1 mm thickness were successfully welded by resistance spot welding (RSW). The

application of post pressing force was significantly favorable to the strength of the welded joints.
According to the performed materials tests the implementation of hot forming and in-die quenching (HFQ) process can have a significant positive effect on the hardness and the strength of the resistance spot welded joints due to the possibility of post weld ageing in the production chain. By artificial ageing the hardness of heat-affected zone significantly increases and a slight hardening can be also noticed in the weld nugget. However, a similar precipitation hardening in the weld nugget as in the heat-affected zone cannot be expected due to the segregation of the main alloying elements, especially silicon. According to our opinion the properties of the weld nugget may be re-examined in a later phase due to the natural ageing, and the strength of the weld nugget should be further developed by the application of pulsed RSW.

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