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Effect of post-welding heat treatment on mechanical properties of butt FSW joints in high strength aluminium alloys

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The friction stir welding (FSW) is a solid state welding process for joining two dissimilar metals using non consumable tools. This paper deals with experimental investigation on the effect of post welded heat treatment on mechanical properties of butt joint using FSW in aluminium alloys 2024 T6 (soft metal) and 7075 T6 (hard metal). In the post weld treated joint, the increase in hardness homogeneity is analysed in the nugget zone along the profile using micro hardness profile measurement. When the hardness homogeneity is attained, fracture occurs in nugget zone. The butt FSW joint after post welding heat treatment at low temperatures (200°C and 300°C) have tensile properties comparable with the FSW joints and fracture occurs in base metal 7075 T6. In 50% of FSW joints, deformation occurs after heat treatment at low temperature and also failure occurs inside stir zone. This work reveals that the progressive changes in the grain size and morphology in higher temperature post weld heat treated joint owing to abnormal grain growth (AGG) in the stir zone.

Keywords: FSW, Aluminium alloys, Post-welding heat treatment, Mechanical properties

Friction stir welding is one of the solid state joining methods which is particularly more suitable for aluminum alloys. In this type of welding, formation of defects such as hot cracking, porosity or distortion is often difficult. During the process of welding the material is frictionally heated up to the temperature at which the material becomes plastic state. The generation of heat due to friction and plastic flow of material from the rotating tool produce significant changes in micro structure, which lead to local variations in the mechanical properties of the weld[1-6]. FSW is being used by the industries for structurally demanding applications like automotive, aeronautical, navel and defense to provide high performance benefits. The FSW weld zone consists of nugget zone (NZ), heat affected zone (HAZ), thermally heat affected zone (THAZ) and thermo mechanically heat affected zone (TMHAZ). From the micro structural point of view, the grain structure in the weld nugget zone is very fine and equiaxed causing the higher mechanical strength and ductility[7-12]. During FSW process the severe plastic deformation induces the grain refinement.

Recent literature review on FSW joints with heat treatment is analysed the stability of the grain structure at elevated temperature[3]. The Abnormal grain growth is one of the major phenomenon leads to reduction on mechanical properties of the weld.

The data available in literature demonstrated that the mean grain sizes resulting from the FSW process results at least 10 times smaller than those measured in the un-deformed parent material[13,14]. Grain refinement is due to severe plastic deformation that occurs during fsw[15]. recently, the studies have been conducted on friction stir welded joints after a heat treatment to evaluate the stability of the fine grain structure at high temperature. One of the interesting details is the presence of abnormal grain growth (AGG) in the nugget.

The occurrence of this phenomenon may be a problem if it leads to a decay of mechanical properties of the weld[16]. The objective of this work is to analyse the effect of post-welded heat treatments on mechanical properties of butt FSW joints in 2024T6 and 7075T6 aluminium alloys. A post welded heat treatment is done at 500°C temperature on butt FSW joints followed by micro-hardness measurements at different time periods. Microstructure and hardness measurement is done for pre-welding, post-welding and also for post-weld heat treated specimens. Microstructure evolution was characterized by optical

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microscopy and abnormal grain growth (AGG) develops during post-welded heat treatments.

Aydın *et al.*[17], investigated post-weld heat treatment (PWHT) on the mechanical properties of friction stir-welded 2024 aluminum alloys in the T4 temper state. The PWHT procedures caused abnormal coarsening of the grains in the weld zone, which resulted in a drop in micro-hardness at the weld zone compared to the base material of the joints. T6 (190°C – 10 h) ageing treatment after welding was found to be more beneficial than the other heat treatments in enhancing the mechanical properties of the 2024-T4 joints. However, the T6 (190°C – 10 h) heat treatment led to significant ductility deterioration in the joint[17].

Singh *et al.*[18], presented the effect of post weld heat treatment (T_6) on the microstructure and mechanical properties of friction stir welded 7039 aluminium alloy. It was observed that the thermo-mechanically affected zone (TMAZ) showed coarser grains than that of nugget zone but lower than that of heat affected zone (HAZ). The decrease in yield strength of welds is more serious than decrease in ultimate tensile strength. As welded joint has highest joint efficiency (92.1%)[18].

Elangovan *et al.*[19], reports on studies of the influences of various post-weld heat treatment procedures on tensile properties of friction stir-welded AA6061 aluminum alloy joints. Rolled plates of 6-mm thick AA6061 aluminum alloy were used to fabricate the joints. Solution treatment, an artificial aging treatment and a combination of both were given to the welded joints. Tensile properties such as yield strength, tensile strength, elongation and joint efficiency were evaluated. Microstructures of the welded joints were analyzed using optical microscopy and transmission electron microscopy. A simple artificial aging treatment was found to be more beneficial than other treatment methods to enhance the tensile properties of the friction stir-welded AA6061 aluminum alloy joints[19].

Hu *et al.*[20], investigated the way to improve the plasticity of friction stir welded joints for plastic processing applications through post-weld heat treatment (PWHT). Aluminum alloy 2024-O friction stir welding joints was carried out at annealing temperatures from 250°C to 450°C with an interval of 50°C for 2 h, followed by cooling to 200°C in the furnace. The effect of PWHT on the microstructure and plastic deformation behavior of the joints was investigated. It was found that the fine-equiaxed grains are stable and retained in the nugget of the joints even after annealing at 450°C for 2 h. However, the grains in the thermo-mechanically affected zone (TMAZ) of the joints become coarse and equiaxed as annealing temperature increases. The plastic deformation of as-welded joint is very heterogeneous. In contrast, the plastic deformation of PWHT joint is relatively homogeneous by both the nugget and the base material showing large deformation. The decrease in elongation of as-welded joints is completely recovered by PWHT. The high ductility of the joint is mainly attributed to the retention of the fine-equiaxed grains in the nugget during PWHT[20].

Song *et al.*[21], studied the mechanical properties of friction stir welded and post-heat-treated Inconel 625 alloy. Friction stir welding (FSW) was performed at rotation and traveling speeds of 200 rpm and 100 mm/min, respectively; heat treatment was carried out after welding at 700°C for 100 h in vacuum. As a result, the application of FSW on Inconel 625 alloy led to the grain refinement in the stir zone, which resulted in increase in mechanical properties than those of the base material. Especially, applying heat treatment after FSW led to the improvement of mechanical properties of the welds; microhardness and tensile strength increased by more than 30% and 50%, respectively, as compared to FSW alone[21].

Priya *et al.*[22], investigted the effect of post weld heat treatment on the microstructure and mechanical properties of dissimilar friction stir weldments of Al alloys 6061 and 2219 (in peak aged T6 temper). The survey of microhardness profile in the as-welded samples showed fluctuations across the weld zone and a minimum in the hardness occurred in the heat affected zone (HAZ) of alloy 6061. After a post weld ageing treatment at 165°C for 18 h, the hardness was found to increase in weld zone alone and there is no effective improvement in HAZ hardness. On the other hand, a post weld solution treatment at 520°C followed by ageing at 165°C for 18 h resulted in significant improvement in hardness across the whole weldment. This is also reflected in the tensile strength of the joint. These results were correlated with microstructures, observed using optical, scanning and transmission electron microscopes[22].

Ahmad *et al.*[23], studied the effect of a post-weld heat treatment (PWHT) on the mechanical and microstructure properties of an AA6061 sample welded using the gas metal arc welding (GMAW) cold metal transfer (CMT) method. The CMT method was used because the method provides spatter-free welding, outstanding gap bridging properties, low heat input and a high degree of process flexibility. The welded samples were divided into as-welded and PWHT samples. The PWHTs used on the samples were solution heat treatment, water quenching and artificial aging. Both welded samples were cut according to the ASTM E8M-04 standard to obtain the tensile strength and the elongation of the joints. The failure pattern of the tensile tested specimens was analysed using scanning electron microscopy (SEM). A Vickers microhardness testing machine was used to measure the hardness across the joints. From the results, the PWHTs were able to enhance the mechanical properties and microstructure characteristics of the AA6061 joints welded by the GMAW CMT method[23].

The aim of the present work is to investigate the effect of post weld heat treatment on mechanical properties of butt FSW joint in 2024 T6 and 7075 T6 aluminium alloys .The different post welding heat treatment of butt FSW joint have been conducted at different temperatures and time followed by tensile test and micro hardness measurements. The characterization of micro-structure evolution is done by light microscopy and scanning electron microscopy.

Experimental Procedure

Aluminium alloy plates with different compositions and thickness were friction stir butt welded using various weld parameters. The chemical compositions of the 2024 T6 and 7075 T6 materials are given in Table 1. Experimental set up of FSW is shown in Fig. 1. A sample specimen of aluminium alloy 2024 T6 and 7075 T6 with a thickness of 5 mm, length of 150 mm and a width of 75 mm were chosen for the experiment and micro structure test were conducted at room temperature. The rotation speed, transverse speed and axial load are set with 600 rpm, 30 mm/min and 2 kN as process parameters.[1-R(A)] The microstructure of the butt joint is characterized by optical microscopy in the base materials and in the welded zone. The chemical etching was performed by Keller's reagent and anodization by a solution of 5% HBF4 in methanol. Grain structures were observed by polarized optical microscopy (POM).

Vicker's microhardness values were measured on the lateral polished surface and perpendicularly to weld direction for both low and high temperature (200°C and 500°C). The measurements were performed using an indentation load of 500 gf for a dwell time of 15 s. The base metal size selected for friction stir welding is shown in Fig. 2 and the weldments specimen of size 29×20 mm of welded 7075 T6 and 2024 T6 plates samples are shown in Fig. 3. The various zones that are affected during friction stir welding at every particular temperature are shown in Fig. 4.

Results and Discussion

The microstructure of aluminium 7075 T6 and 2024 T6 is shown in Fig. 5(a) and 5(b). From the

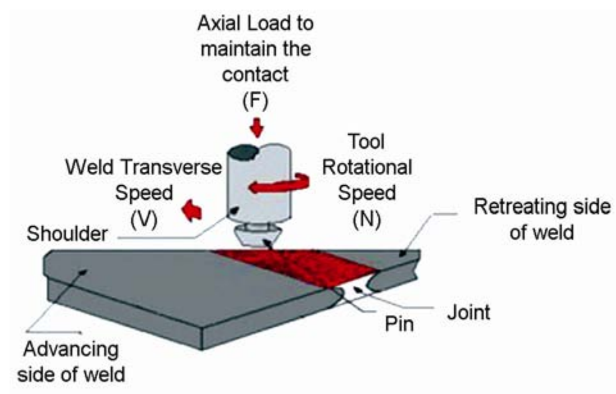

Fig. 1 – Scematic illustration of FSW machine

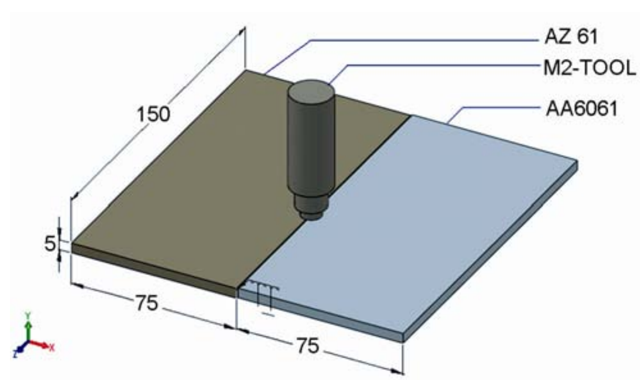

Fig. 2 – Sketch cematic illustration of FSW machine

Table 1 – Chemical composition of the base materials (%)

Material	Si	Fe	Cu	Mn	Mg	Zn	Cr	Al
AA2024	0.103	0.136	4.416	0.535	1.646	0.011	0.1	Remaining
AA7075	0.062	0.186	1.445	0.019	2.55	5.602	0.195	Remaining

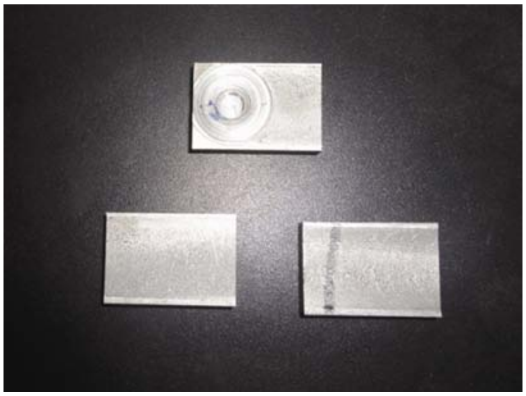

Fig. 3 – The weldments specimen of size 29×20 mm of 7075 T6 and 2024 T6 plates samples

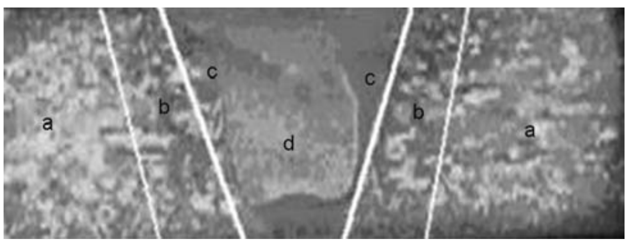

Fig. 4 – Various zones that are affected during friction stir welding: (a) heat affected zone, (b) thermally affected zone, (c) thermo mechanically affected zone and (d) nugget zone

polarized optical microscopy, it has been observed that 7075 T6 has elongated grains in longitudinal direction and 2024 T6 has equiaxed grains. Figure 6(a) shows the nugget zone in the butt joint. The border between TMAZ and nugget zone is clearly visible in Fig. 6(b), because the severe plastic deformation has affected the morphology of the grains. The interpretation of mechanical data depends not only on the grain size but also on particle type. So it becomes a fundamental importance for study on the particle type, their distribution in the different parts of the joint and the evolution during post-welded heat treatments. Particle identification has been performed by X-rays diffractometry in the nugget and in the base material on the plane parallel to the welding direction of butt joint (Fig. 7).

The result shows the presence of Al-Cu-Mg and Al-Fe-Si type particles in the 2024 T3 base material, Al-Fe-Si and Mg-Zn_2 type particles in the 7075 T6 base material Al-Fe-Si, Al-Cu-Mg and Mg-Zn_2 in the nugget region. Even if in the nugget region all the different particle types are present, the peak heights varies when compared to the base materials according to a different particle distribution in the nugget region due to severe plastic deformation. The variation in

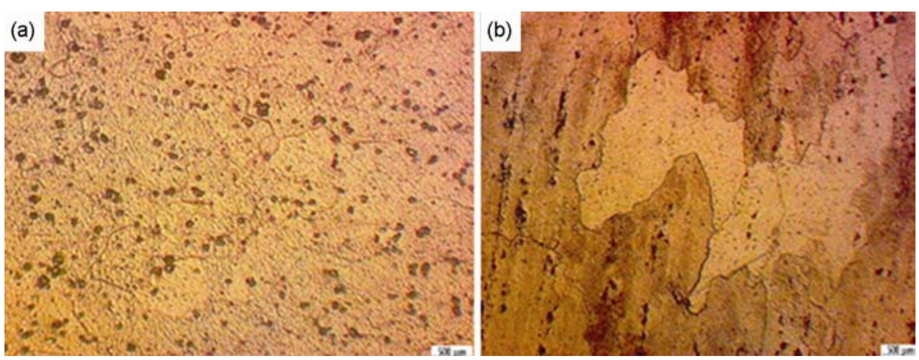

Fig. 5 – Microstructures of aluminium before welding: Polarized optical microscopy of base materials (a) AA 2024-T6 and (b) AA 7075-T6

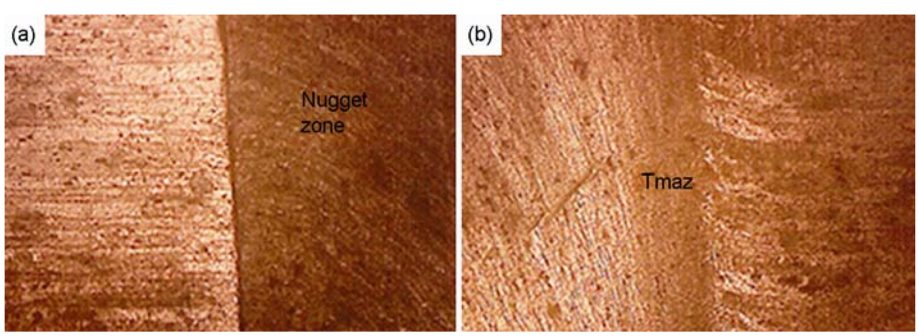

Fig. 6 – Microstructural[2-R(A)] investigation of FSW joint: (a) nugget zone where the dissimilar metals gets welded and (b) TMAZ and HAZ on the retreating side

hardness profiles for the low temperature of 200°C with distance from the weld centre has been measured along ideal lines of the two base metal samples, starting measurements from the base material through the nugget and to the opposite base material the mean hardness value is considered for the base material and the nugget zone which is shown in Table 2.

Post-weld heat treatments

FSW butt joints have been heat treated at 500°C for ½ h,1 h, 2 h, 4 h and 6 h to study the thermal stability of microstructure and mechanical properties evolution.

Microstructure was evaluated by polarized optical microscope while mechanical properties by Vicker's micro-hardness at room temperature. Figure 7 illustrates micro-structure profiles after exposure at 500°C for 6 h.

Microhardness profiles have been measured after exposure at 500°C for 1 h (Table 3). The grain size and shape are quite different in the 2024 T6 and 7075 T6. The microhardness values are comparable. A strong contribution to leveling hardness comes from precipitation and/or dissolution processes occurring at 500°C in these alloys.

Table 2 – Vickers hardness value after low temperature heat treatment for one hour (200°C)

Materials and zone	Hardness value, HV
7075T6	70-105
2024T6	105-150

Table 3 – Hardness value (Vickers) after heat treated with 6 h (for 500°C)

Materials	Hardness value, HV
7075T6	115-132
2024T6	90-98

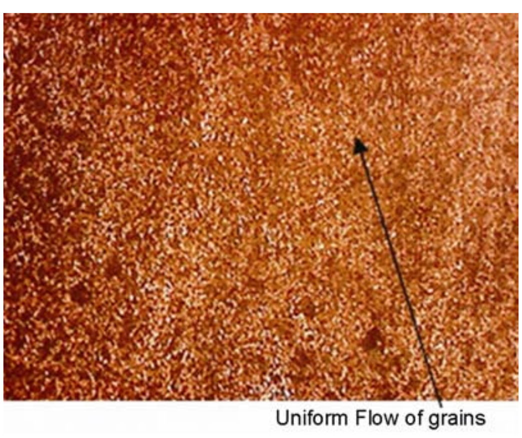

Fig. 7 – Microstructure of FSW butt joint by polarised optical microscope after post weld heat treatment

During post-welding heat treatment at 500°C, the microstructure of the whole joint modifies, especially in the nugget zone. In fact, after half an hour of exposure at 500°C, abnormal grains are visible at the bottom of the nugget zone.

Figure 8 shows the SEM image at the nugget zone for as- FSW weld joint. The maximum grain size of 2.23 μm represents the finer grains which leads to a more yield through grain boundary strengthening. Figure 9 represents the SEM image at the nugget zone for the post weld heat treated specimen at elevated temperture of 500°C. The maximum grain size of 4.64 μm represents the coarser grains leads to a lesser yield point and thereby reducing the elongation.

Grain boundaries disrupt the motion of dislocations through a material, so reducing crystallite size is a common way to improve strength. The grain

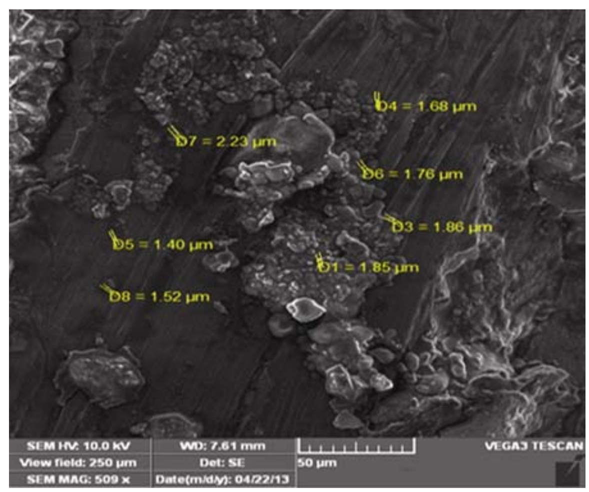

Fig. 8 – SEM image at the nugget zone of as FSW welded joint before heat treatment

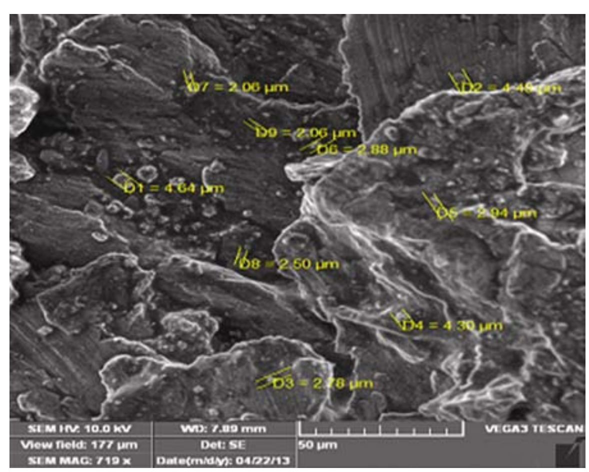

Fig. 9 – SEM image at the nugget zone of FSW welded joint post weld heat treated specimen for 500°C

boundaries act as pinning points impeding further dislocation propagation. Since the lattice structure of adjacent grains differs in orientation, it requires more energy for a dislocation to change directions and move into the adjacent grain. The grain boundary is also much more disordered than inside the grain, which also prevents the dislocations from moving in a continuous slip plane. Impeding this dislocation movement will hinder the onset of plasticity and hence increase the yield strength of the material.

The extension of abnormal grains increases in volume with passing time and after one hour, abnormal grains occupy the whole nugget zone. The variation of microhardness at 500°C in the nugget zone can be due to competing mechanisms such as solid solution strengthening and over-ageing (very few) of particles. For the first half an hour the substantial softening in the nugget can be ascribed to over-ageing (solution temperature is close to 490°C). After 1 h, a light softening due to over-ageing of equilibrium particles is found. For the 7075 T6 nugget, the exposure at 500°C determines, the complete dissolution of small particles and the coalescence of bigger ones giving rise to a light depression in microhardness values after 1 h; afterwards, the solid solution strengthening mechanism increases again hardness value.

It is important to evaluate the effect of post-welded heat treatments on tensile properties of the butt joints. After low temperature heat treatment the range between 200-300°C, the UTS are in the range of 90-100 MPa and the elongations of 4-5%. The fracture mode is also common for these joints because rupture occurs in the 7075 T6 base material. Fracture of the joint was expected to occur in the 7075 T6 base material because, according to HV profiles, the post-welding heat treatment at range between 200-500°C does not substantially modify the initial hardness value profiles of the joints that were extremely inhomogeneous and let the 7075 T6 base material be the softer part of the butt joints.

The tensile behaviour of FSW joints after exposure at higher temperature (500°C) is different. Compared to lower heat treated joints, the stresses increase reaching an UTS of 160 MPa for the sample post-welding heat treated at 500°C for 6 h. The ductility remain rather low at 2-3%. In these samples, failure occurs inside the weld nugget and no more in the 7075 T6 base material. The tensile strength of post-weld heat treated specimens of FSW butt joint of AA7075-AA2024 are given in Table 4.

From micro-hardness profiles it was clear that the nugget zone was slightly softer than other regions of the joint, even for few hardness points.

The graph plotted between nugget distance versus hardness value (HV) is shown in Figs 10-13. Figure 10 shows the micro hardness value (HV)

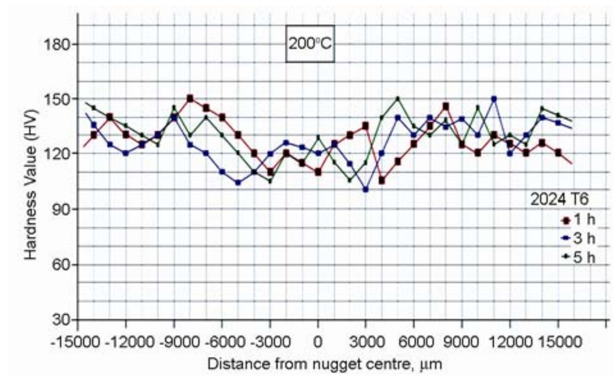

Fig. 10 – Hardness values (HV) versus distance from Nugget centre at low temperature (200°C) for the base metal 2024 T6 on the advancing side and 7075 T6 on retreating side

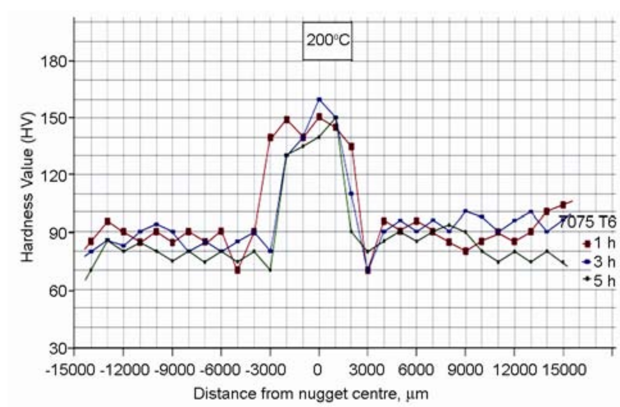

Fig. 11 – Hardness values (HV) versus distance from nugget centre at low temperature (200°C) for the base metal 7075 T6 on the advancing side and 2024 T6 on the retreating side

Table 4 – Tensile properties at nugget zone of AA7075-AA2024

FSW Butt joint	Before post weld treatment		After post weld treament (200°C)		After post weld treament (500°C)	
	Ultimate tensile strength (MPa)	Elongation (%)	Ultimate tensile strength (MPa)	Elongation (%)	Ultimate tensile strength (MPa)	Elongation (%)
AA2024T6-AA 7075T6	90	8	98	4.8	160	2.8

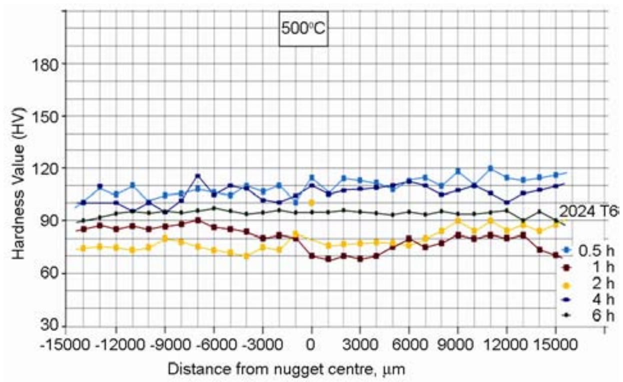

Fig. 12 – Hardness values (HV) versus distance from nugget centre at elevated temperature (500°C) for the base metal 2024 T6 on the advancing side and 7075 T6 on retreating side

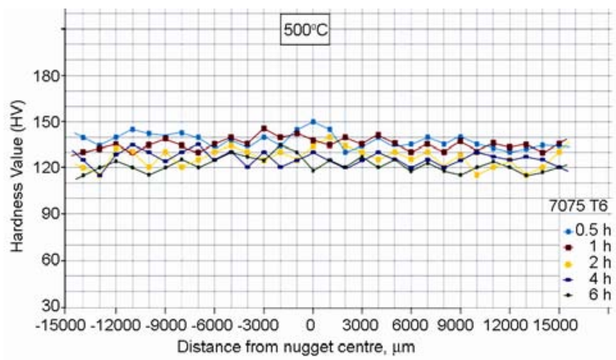

Fig. 13 – Hardness values (HV) versus distance from nugget centre at elevated temperature (500°C) for the base metal 7075 T6 on the advancing side and 2024T6 on retreating side

evaluation of FSW butt joint post weld heat treated for low temperature of 200°C. The 2024 T6 is kept on advancing side (AS) and 7075 T6 on retreating side (RS). The nugget zone (NZ) to heat affected zone (HAZ) the hardness values are scattered uniformly from 120 HV to 150 HV. But while keeping the 7075 T6 on the AS (Fig. 11) the NZ gets maximum HV and remaining zones are close 90 HV.

Both Figs 12 and 13, the elevated temperature heat treated FSW joint shows a constant line or less amount of scatter on HV values.

Conclusions

Butt friction stir welded joints in 2024 T6 and 7075 T6 were subjected to post-welding heat treatments and solution temperature and then to micro-hardness measurements at room temperature. The following conclusions were drawn from the results.

(i) The butt FSW joints after post-welding heat treatment at low temperature (200°C) have tensile properties comparable with the as-FSW joint ones. Also fracture occurs in the same region (7075 T6 base metal).

(ii) Post-welding heat treatments at higher temperature (500°C) induces faster kinetics for particles coarsening and/or solubilization and grain growth. At 500°C, micro-hardness profiles overlap after 1 h, even if microstructure looks very different from base materials to nugget region. Fracture strain is almost 50% of joints deformed after heat treatment at lower temperature and failure occurs inside the stir zone. At this time, abnormal grains occupy the whole nugget.

(iii) The graph plotted for various temperatures versus hardness for both post-weld and post-weld heat treated out of which heat treatment done for 6 h shows improved grain structure resulting in better weldment.

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