



INVESTIGATION OF MICRO STRUCTURE AND MECHANICAL PROPERTIES OF FRICTION STIR WELDED AA6061 ALLOY WITH DIFFERENT PARTICULATE REINFORCEMENTS ADDITION

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Abstract

Joining of heat-treated alloys(AA6061-T6) by Welding process often results a deterioration of mechanical properties because of the coarsening and dissolution of the strengthening precipitates(Mg_2Si , Al_3FeSi , $Al_{12}FeSi$) at the weld nugget. However, it scares the applications of AA6061-T6 alloy. In order to enhance mechanical properties of Friction stir welded(FSW) AA6061-T6 alloy and to minimize the loss of T6 condition , four butt joints (FSW-SiC, FSW- B_4C , FSW- Zn and FSW- Al_2O_3)were fabricate with the addition of harder reinforcement materials such as SiC, B_4C , Zn and Al_2O_3 particles. In this study, the microstructure, tensile strength and hardness of reinforced friction stir welded AA6061-T6 alloy joints were investigated, while the base metal and the welded joint prepared without reinforcement material were utilized as reference to control the process. The grains refinement ,which had been the reason for improved mechanical properties was increased with the addition of reinforced particles in the weld region. Due to the high density of homogeneous dispersion of harder reinforcement particles and considerably increased grain refinement in the entire welded joints, all the reinforced welded joints resulted improvements over the unreinforced joint in terms of strength and hardness. The addition of SiC, B_4C , Zn and Al_2O_3 reinforcements particles increases the tensile strength by 24.2% ,1.79%,32.46 and 10.83% respectively, whereas the elongation decreased as compared to unreinforced welded. Due to extremely high hardness value and homogeneous dispersion of B_4C particles in the FSW- B_4C joint .It showed the highest percentage of hardness enhancement that was about 54.9% followed by Al_2O_3 , SiC and Zn with improved hardness percentage as 50.37% 40.9%, and 23.2% respectively.

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**Keywords: Friction Stir welding (FSW) AA 6061-T6 Hardness
Reinforcement particles Microstructure**

I. Introduction

Due to numerous excellent characteristics of 2XXX,6XXX,7XXX series Aluminum alloys, like superior corrosion resistance, high strength-to-weight ratio and easiness in fabrication, many materials are replacing by Al-alloys in numerous application in aircrafts, ships, automobiles, heat exchangers building industries and storage facilities. Sometimes, repairs of AA 6061-T6 fabricated parts are required because of possible damages during service and post-fabrication defects. These parts repairs which regularly involve welding are particularly critical in applications where prime quality and/or precision are required like pressurized tanks in aerospace industry. so as to achieve maximum joint efficiency, the Al-alloys weld joints should have exceptional levels of their mechanical properties while maintaining minimal levels of weld-defect density

The use of conventional fusion welding process in joining Al-alloys, especially heat-treatable ones, is taken into account less efficient because of the high possibility of forming solidification cracking, segregation, oxidation, porosities high power consumption, the occurrence of toxic fume production, need for filler metal, large distortion during the fusion and solidification phases of the process and also it leads to deterioration of mechanical properties and degradation of corrosion resistance within the joint due to phase transition within the weld zone. Friction stir welding (FSW) presents a low processing temperature (0.7 to $0.9 T_m$), thus eliminates the large temperature gradient. Besides that, the residual stress also kept at minimum level. Compared to several of the fusion welding processes that are routinely used for joining structural alloys, FSW is an emerging solid state joining process during which the material that's being welded doesn't melt and recast. Hence it eliminates defects, which generally occurs in conventional fusion welding process, and welds are produced with good surface finish and thus no post weld cleaning is required.

Apart from aluminum alloys, a range of aluminum matrix composites (AMCs) have soundly been friction stir welded since the method invented in 1991 6061/TiC/3 and 7p, 2124/SiC/25p composites plates perfectly fit into this category On the other hand, numerous surface composite layers have been produced using friction stir processing (FSP), which is a derivative of friction stir welding (FSW)

Extensive research has been conducted in the past to offset the strength reduction of friction stir welded aluminum alloys joints through post weld heat treatments. However, since these treatments are generally time consuming and expensive also. it's wise to foreclose the foregoing problem otherwise. In other words, employing reinforcement particles might be inexpensive and effective solution. The results of earlier studies lend support to the eligibility of this approach. The mechanical and microstructure of those welds, at optimized conditions, were

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very near to that of the base metals. However, fulfilling these criteria for heat-treatable aluminium alloys especially, AA 6061-T6 friction stir welds has been difficult. Usually, significant deterioration in the tensile properties and hardness at the weld joints are often observed. This phenomenon has been traced to the dissolution of AA 6061-T6 strengthening precipitates (β'' -Mg₂Si) which occurs at temperature above 200–250°C since the FSW process takes place around 450–500 °C.

During last decades, researchers tried to change the FSW process to improve the properties of the fabricated joint. Like parametric optimization, with the use of various tool shapes and increasing series of weld passes have been made so as to enhance the mechanical properties AA 6061-T6 welds. As an example, improvement of the FSW process parameters including tool pin profile, transverse speed, rotational speed and tool angle, using surface response methodology, for enhanced mechanical properties of AA 6061-T6 has been investigated by Safeen et al. Though ninety two percent of tensile strength, ninety five percent of hardness, and eighty seven percent of impact toughness of the base metal were found because the optimum mechanical properties, tool pin profile was established as the most important parameter influencing these properties. Other processes like applying ultrasonic vibration and also performing the process in presence of cooling have been used for improved properties of the welded joint.

Till date, investigation of the mechanical properties of aluminum alloys (AA7075-T6, AA 6061-T6) friction stir weldments with the addition of reinforcement particles or Association of fine particles into stir zone, has rarely been tried. The wear resistance of these particle reinforced aluminium alloys was found to be influenced by the particle size, shape, type and volume. B₄C, SiC, Al₂O₃, Ti₂O, WC and other hard particles have been utilized as reinforcement particles in enhancing the wear resistance of friction stir welded joints of non-heat treatable aluminium alloys.

The key issue of interest to apply this enhancement strategy to friction stir welded heat treatable AA 6061-T6 alloy joint is to find out at what extent the reinforcement particles addition can sufficiently recompense for or any increase the structural strengthening loss at the welded joint. So far, to the best of knowledge of the author most of the literature focused on improving the some of the mechanical and wear resistance properties of friction stir welds of AA 6061-T6 through some type of particles addition is extremely scanty. Significantly, the role of particle's like SiC, B₄C, Zn and Al₂O₃ addition on the strength and hardness of the FSW joints of AA 6061-T6 haven't been listed. During this work, friction stir welding has been carried out on AA 6061-T6 with reinforcement deposition strategy. And also the study focussed to find out the influence of four different types of reinforcement particles (SiC, B₄C, Zn and Al₂O₃) addition on friction stir welded AA 6061-T6 alloy. The micro structure, strength and hardness properties of the particle strengthened welded (reinforced) joints has been investigated then compared therewith of the joint prepared without reinforcement (unreinforced) material prepared under similar condition

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AI. Material and Experimental Procedures

II.i. Sample Preparation

Welding of heat-treated aluminum alloys usually leads to deterioration of mechanical properties because of the coarsening and dissolution of the strengthening precipitates at the joint. However, its scarce application of AA6061-T6. In order to minimize this problem and to improve the properties of friction stir welded heat treatable aluminum alloys within the joint has been accomplished by the addition of reinforcement particles. In this study rolled 6061 aluminum plates with dimensions 150×75×6(mm) were taken as parent material (BM). Table 1 displays percentage of chemical composition and mechanical properties of aluminum base plates which were used for study. Ceramic micro Powders like SiC, B₄C, Zn and Al₂O₃ of particle size 10µm and with 99% of purity were used as reinforcements. To fill the reinforcement material, a channel of dimensions 130mm × 1.5mm × 1.5 mm were machined at the edges of the each plate, as shown in Fig.1. Then, the channel was filled with slurry of Zn, SiC, B₄C and Al₂O₃ particles premixed with C₂H₅OH. The FSW process was carried out after drying the reinforcements slurry in vertical vacuum oven. The mass (in g) of reinforcement particles added was measured by measuring weight of the temporarily joined plates before particle addition and after reinforced particle addition.

. Reinforcements materials such as Zn, SiC, B₄C and Al₂O₃ was added to in friction stir welding of AA6061-T6 to fabricate FSW-SiC, FSW- B₄C, FSW- Zn and FSW-Al₂O₃ joints respectively. Meanwhile, a joint without reinforcement material (unreinforced joint) sample (FSW-WP) was prepared by putting two plates side by side and with no profile at the adjoining sides of the plates. The welding parameters of rotational speed, travelling speeds as 900 r/min, 50 mm/min for reinforced welded joints and 1120r/min, 50mm/min for unreinforced joint with counter-clockwise tool rotation directions and onward tool tilt angle of 2.5° was employed. The tool used for friction stir welding process was machined out of two materials (Wc pin and H13 steel). The dimensions of the tool used for this work was of shoulder diameter of 20 mm, tapered pin of 5.7 mm height, top edge diameter of 7mm and bottom diameter of 6mm with (Fig. 1.b). While Fig. 2 shows the weld beads with a well forged and defect-free weld joint having a good surface appearance of samples fabricated with different weld conditions. The process conditions employed for the each welding process was presented in Table. 2. To set the process parameters for each welding process, a number of trial experiments were conducted following the previous work done on same Aluminum alloy material. The volume fraction of each reinforcement particle was calculated by dividing the measured mass by its density. The weighing scale used for measured was sensitive enough to trace even small variation in the mass of the reinforcement particles added and atmospheric interference while weighing the samples.

Table 1. Chemical compositions (mass fraction)% and Mechanical properties of the Al 6061 alloy.

Mg	Si	Cu	Zn	Ti	Mn	Cr	Al	YS (MPa)	UTS (MPa)	H (V)
0.85	0.41	0.22	0.07	0.05	0.32	0.06	Bal	300	325	113



Fig.1.a: Grooves prepared at joint interface for particle reinforcement b. (f) tool used

Table-2.Process condition for the Friction Stir Welding							
Sample Name	Reinforce ment Particle	Mass Of Particle added(g)	Volume Of Particle added(mm ³)	Rotational Speed(r/m)	Traverse Speed(mm min-1)	Tilt angle	
FSW-SiC	SiC	1.67	520	900	50	2.5 ⁰	
FSW-Zn	Zn	3.21	454	900	50	2.5 ⁰	
FSW-B ₄ C	B ₄ C	1.308	519	900	50	2.5 ⁰	
FSW-Al ₂ O ₃	Al ₂ O ₃	2.0398	516	900	50	2.5 ⁰	
FSW-WP	-	-	-	1120	50	2.5 ⁰	
Note: density of Zn SiC, B ₄ C and Al ₂ O ₃ are 7.13 g.cm ⁻³ , 3.21 g.cm ⁻³ , 2.52 g.cm ⁻³ and 3.95 g.cm ⁻³ respectively.							

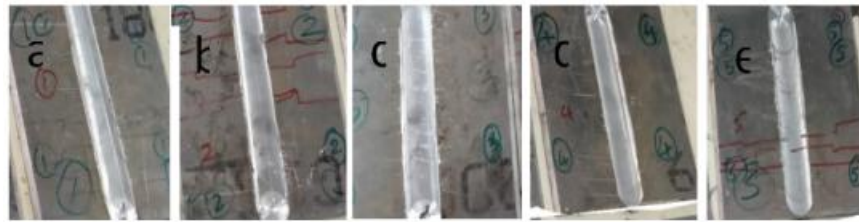


Fig. 2: Pictorial images showing FSW welded joints (a-d) reinforced with SiC,Zn,B₄C and Al₂O₃ (d) unreinforced joint

As the main objective of this study is to investigate the role of reinforcement material on welded joint mechanical performance and make comparison with unreinforced welded joint. After the welding, specimens were cut perpendicularly to the welding direction by an electrical discharge machine for metallographic characterization and mechanical properties examination. Microstructural characterization of the welds was conducted using optical microscope. All metallographic samples were ground and polished according to standard metallographic procedure and etched using Keller's reagent consisting of 2.5% HNO₃, 1.5% HCl, and balance distilled water at ambient temperature. Vickers microhardness was measured over the cross section of welded joints with a spacing of 0.5 mm, and a dwell time of 5 s under a load of 100 gf. Three specimens were prepared for each set of parameters according to standard ASTM E8. Monotonic tensile testing with an initial strain rate of 1 mm/min at ambient temperature was performed.

III. Results and Discussion

III.i. Micro Structure:

For Micro Scopic observation of the weld, welded plate was sectioned according to the dimensions by electro-discharge machining (EDM) perpendicular to the welding direction. To study the weld nugget microstructure and dispersion of harder reinforced materials, Optical microscopy of the samples was carried out across the weld section of all reinforced and unreinforced FSW joints. Microstructure of the weld usually consisting of four different regions. They are: (a) base metal (BM), (b) heat affected zone (HAZ), (c) thermo-mechanically affected zone (TMAZ), and (d) stir zone/Nugget Zone(SZ). Figure 3(a-c) shows base metal micro structure consisting of grains extended parallel to the rolling direction and coarse intermetallic particles. The microstructure of T6 heat-treated 6061 aluminum alloy BM consisting of, artificially formed new precipitates, which leads to higher strength. The grain morphology of weld stir zone ((Figure 3(d-e)) shows a transition from the elongated, rolled grains of the base metal, to an equiaxed grain, which is a typical feature achieved by drastic rise of temperature and severe plastic deformation due to the stirring action of the rotating tool pin. This phenomenon is called as Dynamic recrystallization (DRX). Fig.4(a-d) shows, the stir zone of four reinforced welded joints with uniform distribution of reinforced particles. Among the all reinforcement particle the distribution of B₄C, SiC particles was more uniform in the nugget zone as compared to Al₂O₃, Zn particles, which were attributed to the high density of harder B₄C, SiC particles in the Al-matrix. This results in an intense fragmentation process

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that occurred due to breaking up and symmetric uniform dispersion of small fine particles in the nugget zone centre. It clearly represents the more uniform reinforcement particles distribution in the nugget zone, which was attributed to more intense heat input produced via frictional heating and the pile-up effect exhibited via reinforcement particle particles that helps to prevent the further growth of grains accompanied by dynamic recrystallization throughout FSW process, which lead to more homogenous distribution of particles with reduction in grain size. The spread of nano-SiC particles is more towards the advancing side (AS) in comparison to retreating side (RS). The reason behind this asymmetry may be understood as follows: As tool traverses, there are two sides of the processed zone, namely AS and RS having varied powder distribution and temperature. Although the relative particle velocity at AS is less as compared to RS, the temperature at the AS is higher as compared to RS. Micro structure of reinforced joints has been revealed that the distribution of reinforcement particle was slightly more at advancing side than the retrieving side. The material on the AS is squeezed to the back of the tool along the counterclockwise direction owing to the action produced by the rotating tool. However, the plastic material is extruded to the back of the tool according to the clockwise direction on the RS. Therefore, the deformed material is scattered more towards the AS with the forward tool movement. Fig.4(e-h) reveals, the banded structure consisting of particle-rich and particle-free region in heat affected zone. The heat-affected zone was experienced only the thermal cycle, as a result, sufficient heat was not produced for reinforcement particle to deform plastically. Therefore, few agglomerated reinforcement particles mainly on AS were formed which leads to strengthening precipitates coarsen and enlargement in the without-precipitate area. It is noteworthy to mention that, if the temperature in HAZ is reached above 250 °C then it will exert a pronounced impact on the structure of precipitates. The particle agglomeration of reinforced particle occurred because of the high number of dislocations with coarser precipitates that are formed at the grain boundaries. However, the coarsening of the precipitates in HAZ is governed by the heating cycle or over aging effect occurred in this zone which leads to the decrease in hardness in some regions. Therefore, due to partial fragmentation occurred in the HAZ only a few clusters would break up into small particles and some are agglomerated, later which are distributed uniformly in the nugget zone due to solid-state diffusion occurred via severe plastic deformation during FSW.

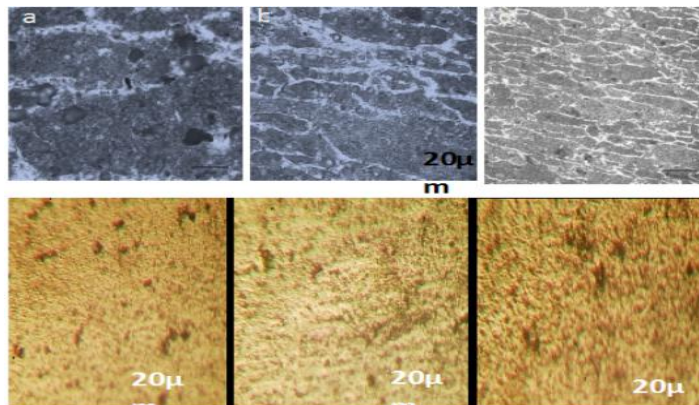


Fig. 3: Optical microscopic images of the (a–c) base metal and (d–g) friction stir welded joint without particles reinforcements at advancing side, retrieving side and at weld zone.

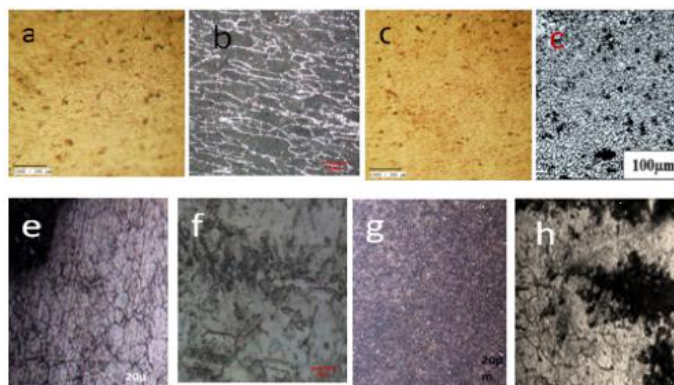


Fig.4: Microscopic images showing nugget zone of the welded joints reinforced with (a) SiC, (b) Zn (c) B₄C (d) Al₂O₃ particles and (e-h) particle agglomeration in reinforced joints

III.ii. Mechanical Properties

III.ii.a.Tensile Properties

The Extracted values of tensile properties (tensile strength, yield strength, and elongation) for SiC, B₄C, Zn and Al₂O₃ particle reinforced and unreinforced friction stir welded samples was shown in Table 3. Fig.5. shows the role of reinforcement particles on the strength properties of friction stir welded. For the sample without particle reinforcement, the tensile strength, yield strength, and % elongation were significantly reduced in comparison to base material which is due to reduction in density of dislocations in the dynamically recrystallized zone, as a result, the fracture of the sample will occur in the nugget zone at low load value as shown in Fig.6.e. It is evident that reinforced joints(FSW-SiC, FSW-Zn, FSW-B₄C, FSW-Al₂O₃) exhibited superior strength and inferior ductility than the unreinforced joint. For the FSW-SiC, FSW-Zn and FSW- Al₂O₃ sample, the tensile properties were increased compared to the unreinforced sample but less than FSW -B₄C sample. The decrease in tensile

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properties was more related to the particles cluster formations in the HAZ, as a result, % elongation was significantly reduced which depends on the behaviour of the deformation SiC, B₄C, Zn and Al₂O₃ particles in respect to tensile load. The higher tensile strength was obtained by refinement of grains and homogeneous diffusion of hard phase reinforcement particles around the surface of rotating tool due to stirring effect of tool and frictional heat generated during the FSW process. For the FSW-B₄C, FSW-SiC samples, the tensile properties, namely, tensile strength, and yield strength was significantly increased as compared to sample without particles and FSW-Zn, FSW-Al₂O₃ samples but whereas % elongation decreased. This was due to the existence of uniformly dispersed higher density of harder SiC, B₄C particles in the welded area in Al-matrix. Also, grain size drop results in an increase of strengthening at the grain boundaries via (a) high dislocation density due to thermal mismatch index, (b) restrictions occurred in the path of grain boundaries which provides more nucleation sites and prevents the grain growth at the grain boundaries as these outcomes are in better concurrence with the findings of Zhang et al. and Li et al. Due to these reasons, the fragmentation process is more intense; as a result, most of the SiC, B₄C particles would break up into small fine particles and uniformly distributed in the nugget zone. Hence, more uniform particles distribution and symmetric flow would occur in the nugget zone centre. Therefore, re-precipitation of strengthening precipitates leads to more coarsening and dissolution of precipitates which helps in retaining the maximum tensile strength and yield strength with an appreciable enhancement in elongation, as a result, the fracture of the sample occurred at high loads. The addition of reinforcements particles SiC, B₄C, Zn and Al₂O₃ increased tensile strength by 24.2% ,1.79%,32.46 and 10.83% respectively, while elongation decreased as compared to Base Metal.

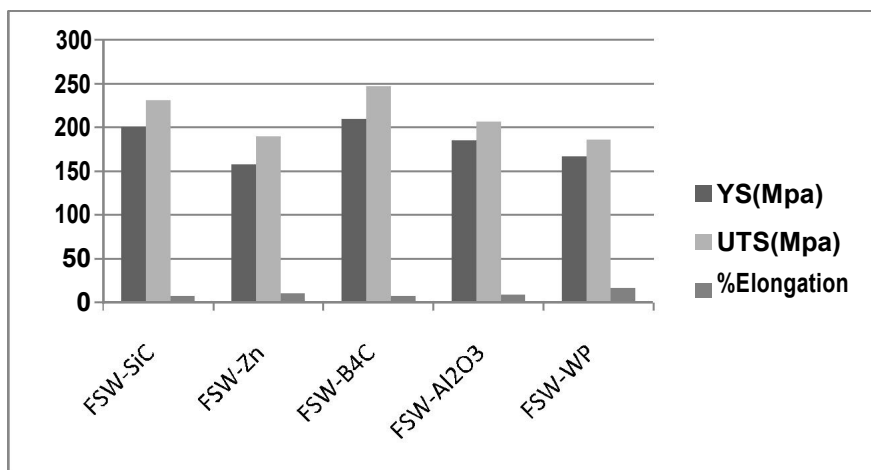


Fig. 5: shows the effect of reinforcement particles on the tensile properties of friction stir welded.

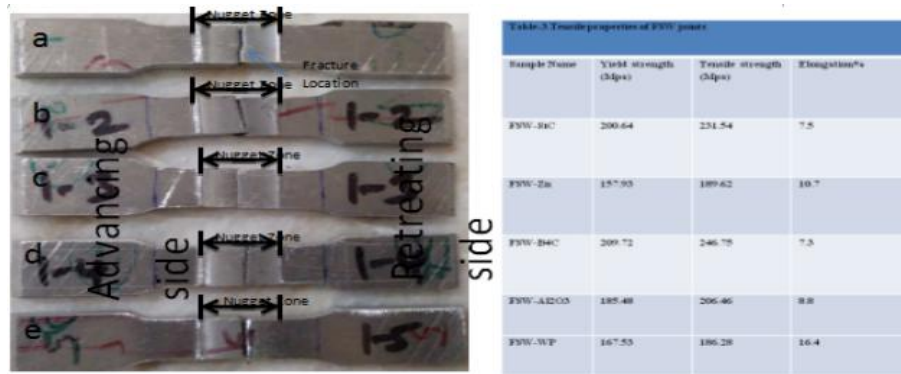


Fig. 6: (a-e) Fracture locations of the FSWed samples after tensile loading

III.ii.b. Micro Hardness

The characteristic microhardness measurements were done for specimens (with and without reinforcement particles) by taking an equal distance from the weld centreline on each side of the nugget zone as shown in Fig. 7. Micro hardness corresponding to different zones of FSW was also evaluated and compared with the as-received base metal. Hardness profile revealed several important points. Hardness in the stir zone was lower than aluminum BM in all the FSW-joints (reinforced and unreinforced). The joint prepared without reinforcement material (FSW-WP) exhibited the less hardness value of about 66.1HV in the SZ and 77.4HV in the TMAZ in comparison to AA6061-T6 Base material. This is because of increasing in localized heating by friction and loss of T6 condition (formation of grain growth and dissolution of strengthening precipitates) during welding process at SZ. In a rolled AA 6061-T6 alloy, the hardness was influenced by artificially formed precipitates and high density of dislocations. However, the nugget zone of the friction-stir welded joint undergoes a severe plastic deformation and drastic rise of temperature due to the stirring action of the rotating tool pin, which causes metallurgical phenomenon (DRX) such as decreasing the dislocation density, dissolving or coarsening of the precipitates Mg_2Si , etc. The hardness was influenced by the extent of grain refinement and inherent properties of the reinforcement particle. On the other hand, the partial dissolution of the strengthening precipitates and not sufficiently refined grains in the TMAZ were responsible for its higher hardness compared with the nugget zone of un reinforced joint.

As seen in Fig. 7, demonstrates hardness variation of the FSW joints fabricated by the reinforced with harder particles. A domed shape hardness curves were observed for all reinforced joints and W shaped curves for un reinforced joint. The addition of all reinforcement particles improved hardness value in the nugget zone and TMAZ of FSW-joints with. The average hardness values observed at nugget zone of the FSW-SiC, FSW-Zn, FSW-B₄C, FSW-Al₂O₃ joints were 93.4HV, 81.6HV, 102.3HV and 99.6HV respectively. The hardness of all the reinforced FSW-joints in the TMAZ region was ranged between 76.4HV and 99.5HV. The reason for enhancement of hardness property could be partly traced to the dislocations and improved fine grain strengthening or pinning effect of hard reinforcements (SiC, Zn, Al₂O₃ and B₄C) particles on grain boundaries. Also, the inherent property of like very high hardness values of the reinforcement particles contributed a important role in the hardness improvement of each reinforced joint.

Consequently, the addition and distribution of these particles in the AA 6061-T6 matrix has compensated for the hardness loss in the unreinforced FSW-joint. Among all the four reinforced FSW-joints, FSW-B₄C joint showed the highest improvement in hardness(54.9%). This was attributed to the extreme hardness (3800 HV) of the reinforcement particle and homogeneous particle distribution (highest among the joints) which enhanced the aluminium matrix grain refinement. Due to the higher hardness value of Al₂O₃ (2248 HV) compared with the SiC, FSW-Al₂O₃ joint produced a better improvement in hardness 50.37%, than the FSW-SiC(40.9%) joint.FSW -Zn joint showed the higher hardness (23.2%)than un reinforced FSW-WP but lesser than other three reinforcements. This observation is consistent with the findings of Sahraeinejad et al. during the friction stir processing of AA 5059 with B₄C, SiC and Al₂O₃ particles addition.

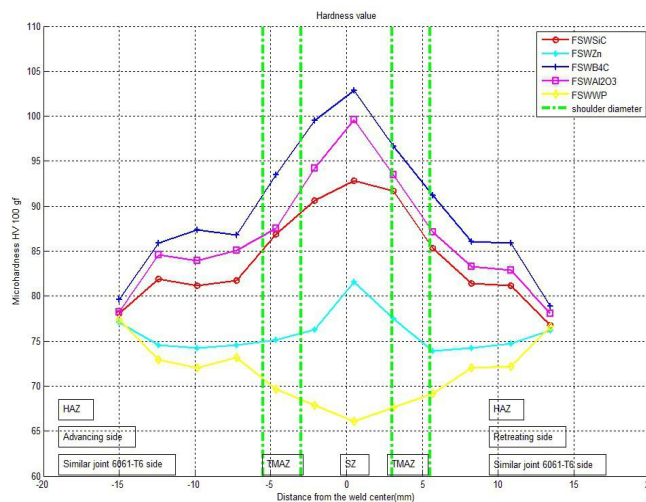


Fig.7: Hardness variation of reinforced and un reinforced joints across the weld nugget.

IV. Conclusion

In this study, AA 6061-T6 alloy joints were fabricated with four different reinforcement materials(FSW-SiC , FSW-Zn, FSW-B₄C, FSW-Al₂O₃)by using friction stir welding process. Results showed that, enhanced grain refinement and uniform distribution of reinforcement particles in the welded region of reinforced FSW joints, which led to improved mechanical properties in weld nugget. Among all reinforcement joints, the joints fabricated with B₄C and SiC particle reinforcement had the most homogenous distribution of particle with no perceptible particle agglomeration and with no surface defect compared to Al₂O₃ and Zn particle reinforced samples due to reduction in relative velocity, temperature and amount of heat (friction) between the tool

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and the non-uniform deformed plasticized material. The friction welded joints prepared with Al_2O_3 and Zn reinforcements included three regions such as particles agglomerations region, moderately particle dispersed region and particle free region in the stir zone. As compared to the hardness of base metal (1~13HV), the hardness of the unreinforced joint (6~6.1HV) was considerably low. However, in reinforced joints because of improved grain refinement and uniform dispersion of hard particle in weld zone resulted a superior strength and hardness properties in the Nugget Zone and TMAZ.

1) The Microstructural observations reveal that B_4C and SiC particle reinforced samples show the fine recrystallized structure of grains in the processed nugget due to concurrent reaction of severe plastic formation and friction heating throughout the FSW process. While Al_2O_3 and Zn particles reinforced samples had average grain size with few particle agglomeration occurred in the HAZ due to the coarsening of precipitates via heating and overaging effect caused during FSW process at high temperature

2) It was observed that the addition of reinforcement particles (FSW- SiC , FSW-Zn, FSW- B_4C and FSW- Al_2O_3) significantly enhanced the tensile properties such as tensile strength by 24.2%, 1.79%, 32.46 and 10.83% respectively but where as elongation was decreased as compared to unreinforced welded joint. This improvement was attributed due to high density of B_4C and SiC particles which provides more nucleation sites that restrict the path of grain boundaries, whereas, Al_2O_3 and Zn particles reinforced sample was resulted a less improvements in tensile properties due to clusters formation which holds back the deformation level of aluminium during tensile loading, as it was led to decrease in ductility.

3) It was observed that in an unreinforced FSW Joint (FSW-WP) the average micro hardness value was 66.1HV, which was much below the Hardness of base metal due to decrease in denseness of dislocated boundaries containing sub-grains, as a result, strengthening precipitates would become coarse and dissolve in the nugget zone. FSW- B_4C samples exhibits higher microhardness of average value 102.3HV in the processed nugget zone, which was because of uniform distribution B_4C particles within Al-matrix and fine grains morphology in the weld zone compared to joints prepared with other reinforcement particles ((FSW- SiC , FSW-Zn and FSW- Al_2O_3). It was observed that the joints fabricated with the addition of the reinforcement particles such as SiC , Zn, B_4C , Al_2O_3 showed improved hardness property about 50.37%, 40.9%, 54.9% and 23.2%, respectively as compared to unreinforced joint.

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