Original Article

Investigation of the microstructure, mechanical and wear properties of AA6061-T6 friction stir weldments with different particulate reinforcements addition

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\textbf{A B S T R A C T}

Welding of heat-treated AA6061-T6 often results in mechanical and wear properties deterioration because of the dissolution of the strengthening precipitates at the joint. Enhancement of these properties has been accomplished for non-heat treatable aluminium alloys through the addition of reinforcement particles in the joint. However, its application to AA6061-T6 is scarce. In this work, the microstructure, hardness and wear resistance of AA6061-T6 friction stir welded joints reinforced with SiC, B\textsubscript{4}C and Al\textsubscript{2}O\textsubscript{3} particles were investigated while the base metal and the unreinforced welded joint were utilised as the control. Aluminium matrix grains refinement which improved with increased particle distribution homogeneity occurred in the entire welded joints. All the reinforced welded joints showed improvements on the unreinforced joint in terms of hardness and wear resistance because of the particles high hardness and substantially increased grain refinement that occurred in the reinforced welded joints. Due to B\textsubscript{4}C extremely high hardness and homogeneous distribution in the joint, B\textsubscript{4}C reinforced joint exhibited the highest improvements in hardness (42\%) and wear rate (67\%) at low-load condition. However, at high-load condition, SiC followed by the Al\textsubscript{2}O\textsubscript{3} reinforced joints showed the least wear rate even lower than the base metal. The matrix hardness significantly influenced the wear performance at low-load but the overall effects of the reinforcement particles were predominant at high-load condition. The reinforcements’ additions reduced the wear rate of the welded joint by up to a factor of 1.7 and 1.9 at low and high load conditions respectively.

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1. Introduction

AA 6061-T6 is a precipitation hardened aluminium alloy 6061. It is widely used in manufacturing industries due to its combination of favourable properties such as high strength to weight ratio, excellent corrosion resistance, good ductility and low cost [1,2]. The alloy is specifically used for the fabrication of aircraft wings and fuselages, yacht construction and automotive wheel spacers [2]. Sometimes, repairs of AA 6061-T6 fabricated parts are required due to possible damages during service and post-fabrication defects. These parts repairs which often involve welding are particularly critical in applications where high quality and/or precision are required such as pressurised tanks in aerospace industry [3]. Achieving high quality welds of aluminium alloys via fusion welding is always challenging because of high tendency for solidification cracks and vapourisation of alloying elements (causing loss of weld strength) resulting from high heat energy input.

Due to these shortcomings, friction stir welding (FSW) is now being utilised. FSW is a solid state joining process invented almost three decades ago in UK by “The Welding Institute” [4]. It offers some unique advantages over fusion welding due to its characteristic low heat energy input [5]. These include extremely low tendency for distortion, solidification cracking and formation of secondary compounds which often characterises dissimilar metals fusion welding [6,7]. High quality welds of aluminium alloys [8,9], dissimilar aluminium alloys [10], aluminium alloys with copper [11,12], aluminium alloys with steels [13] and aluminium alloys with magnesium [14] have been obtained via FSW technique. The mechanical and wear properties of these welds, at optimised conditions, were very close 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, hardness and wear resistance at the weld joints are often observed [15]. 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.

So far, several efforts such as parametric optimisation, use of different tool shapes and increasing number of weld passes have been made in order to improve the mechanical properties AA 6061-T6 welds. For example, optimisation of the FSW process parameters including tool pin profile, rotational speed, welding speed and tool tilt angle, using surface response methodology, for improved mechanical properties of AA 6061-T6 has been investigated by Safeen et al. [16]. Though 95% hardness, 92% tensile strength and 87% impact toughness of the base metal were found as the optimum mechanical properties, tool pin profile was established as the most significant parameter influencing these properties. Also, the mechanical properties of AA 6061-T6 weldments had been studied under varying tool tilt angles for taper and taper threaded tools [17]. Due to the fact that higher material volume is accommodated under the tool shoulder as the tilt angle increased from 0° to 3°, the torque and forces associated with FSW increased as the tilt angle increased. Also, the welding force fluctuation was minimal around 2 °C tilt angle for the taper tool while for the tapered threaded tool the welding force fluctuation was observed to reduce at higher tilt angle. Eventually the appropriate tilt angles at which enhanced mechanical properties of AA 6061-T6 can be achieved for both threaded and unthreaded taper tools were established.

Till date, investigation of the mechanical properties of AA 6061-T6 friction stir weldments with the addition of reinforcement particles has rarely been tried. However, the strategy has been widely applied to non-heat-treatable aluminium alloys including AA 5052 [18], AA 5086-H34 [19], AA 5083 [20] and AA 5182 [21] because the reinforcement particles provide additional strength to the weldments. Besides the mechanical properties, the wear resistance which is also an important weld quality performance index was also improved. 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, TiO2, WC and other hard particles have been utilised as reinforcement particles in enhancing the wear resistance of friction stir welded joints of non-heat treatable aluminium alloys [20–22].

The main issue of concern with the application of this improvement strategy to heat-treatable AA 6061-T6 friction stir welded joint is whether the reinforcement particles addition will sufficiently compensate for or further increase the structural strengthening loss at the welded joint. So far, existing literature focusing on enhancing the mechanical and wear performance of the friction stir welds of AA 6061-T6 have not been investigated. In this work, friction stir welding of AA 6061-T6 was performed with the addition of different reinforcement particles. The microstructure, hardness and wear resistance properties of the particle reinforced welded joints were investigated and then compared with that of the unreinforced welded joint fabricated under similar condition.

2. Materials and methods

2.1. Materials

Rolled AA 6061-T6 (i.e. base metal) was machined into plates of dimension 100 × 50 × 6 mm. The chemical composition of the base metal, as obtained from XRF analysis, is given in Table 1. SiC, Al2O3 (alumina) and B4C with size range of 3–15 μm were used as the reinforcement particles. Fig. 1 shows the scanning electron microscopy images of the three reinforcement particles. Prior the welding process, the adjoining side of each plate was machined into a profile of dimension 94 × 1.5 × 4.5 mm, as shown in Fig. 2a. Thereafter, a groove of dimension 94 × 3 × 4.5 mm was created in the centre by temporarily joining two plates together, as shown in Fig. 2b. The groove was filled with SiC particle and then closed by passing a pinless tool over it so as to prevent the scattering of the reinforcement particles during the friction stir welding (FSW) process. The amount (mass in g) of the SiC added was determined by weighing the temporarily joined plates before and after the particle addition. This process was repeated for B4C and Al2O3 particles additions so as to have three friction stir
welded joint samples that are reinforced with SiC (FSW-SiC), B₄C (FSW-B₄C) and Al₂O₃ (FSW-Al₂O₃) particles respectively. Meanwhile, an unreinforced joint sample (FSW-WP) was prepared by temporarily putting two plates with no profile at the adjoining sides together.

2.2. Friction stir welding

The entire temporarily joined plates (reinforced and unreinforced) were welded at the centre (i.e. joint) via friction stir welding technique by using high speed steel (HSS) tool, as shown in Fig. 3a. The tool shoulder is of diameter 20 mm while the tool pin is of diameter 4 mm and length 4.5 mm. Fig. 3b shows the pin and pinless tools used in this work while Fig. 3c shows some selected friction stir welded samples. Table 2 presents the process conditions utilised for the entire welding process. The utilised parameter setting was selected after trial experiments were conducted following the previous work done by the authors [5]. The volume of each reinforcement particle was calculated by dividing the measured mass by its density. The slight difference in the volume of the reinforcement particles added can be traced to the sensitivity of the weighing scale and atmospheric interference while weighing the samples.

2.3. Microstructural investigation

Samples of dimension 20 × 10 × 6 mm were transversely cut at the friction stir welded joints (FSWed-joints). An additional sample from the base metal (BM) was cut so as to serve as a reference. Prior the microstructural investigation, the surface of all the five samples were ground and polished to 0.5 μm surface finish. The samples were later etched using modified Poulton’s reagent (50 ml Poulton’s reagent + 25 ml HNO₃ + 1 ml HF + 1 ml H₂O₃) for about 5–7 s. Thereafter, the etched cross-sectioned surface of each sample was investigated for grain structure and grain size measurement using Xptron optical microscope (X-80 series) equipped with digital microscope image analyser. The reinforcement particle distribution and size after FSW were examined with the aid of scanning electron microscopy (SEM).

2.4. Hardness and wear tests

Vickers hardness tester (Future Tech) was used to make indentions along and across the entire FSWed-joints (cross-sectioned surface perpendicular to the FSW direction) with a minimum spacing of about 1 mm in-between successive indentations. The micro-hardness of the entire samples was measured using 300 g load and dwell time of 10 s. Pin-on-disk wear test was performed on the friction stir welded surfaces and the BM surface following ASTM G99 standard. The test was performed at a room temperature using parameters specified in Table 3. The disk (i.e. counter) surface is made of hardened EN-31 carbon steel of hardness 62 HRC. The weight in gram of the samples before and after the wear test was measured and recorded. The volume loss in mm³ (Vₐ) and wear rate (Wₐ) in mm³ m⁻¹ of each sample were determined from weight loss.
(W_t) using Eqs. (1) and (2) respectively. The friction coefficient was recorded automatically by the wear testing machine. The worn surfaces of the samples were analysed using SEM. £ in Eq. (1) is the density of each sample in g cm⁻³.

\[ V_L = \frac{W_t \times 1000}{\ell} \]  
\[ W_R = \frac{V_L}{S_d} \]  

3. Results and discussion

3.1. Microstructure of the friction stir welded joints

Fig. 4 shows the optical images of the BM and unreinforced FSWed-joint (i.e. friction stir welded joint without particle reinforcement (FSW-WP)) at varying magnifications. The unreinforced FSWed-joint distinctly shows the stir zone (SZ), thermo-mechanical affected zone (TMAZ) and heat affected zone (HAZ). Unlike the BM, the grains in the unreinforced FSWed-joint were stretched and obvious bending of the grains was observed in the TMAZ (see Fig. 4g). This was due to the stirring action of the FSW tool in the joint. The grains in the joint, compared with the BM, are smaller in size. The grains significantly decreased in size from the BM to HAZ to TMAZ and then to the SZ, for example, as shown in Fig. 4d and e. This observation showed that grain refinement which is probably due to the occurrence of dynamic recrystallization [19] occurred in the FSWed-joint. The severe plastic deformation in the welded joint (especially the SZ) resulted in the nucleation of new grains. Hence, finer grain structure was formed.

Reinforcing the FSWed-joint with SiC, B₄C and Al₂O₃ particles addition, as respectively shown in Fig. 5, produced different microstructure in the welded joint. The added particles were fairly homogeneously distributed within the SZ. Compared with other reinforced FSWed-joints, B₄C reinforced FSWed-joint (FSW- B₄C) showed the best particle distribution at the joint, as shown in Fig. 5b. This can be attributed to the fact that B₄C has the biggest average size among the three particles. Therefore, the number of B₄C particle in the groove will be the lowest compared with other particles.
the beginning, tool stirring of materials is believed to be most effective during the FSW with B\textsubscript{4}C addition because minimal resistance would be offered since the number of particles is smaller compared with other reinforced joints. After some time, fragmentation of the big particles into smaller size particles occurred. Hence, homogeneous distribution of particles was achieved and agglomeration of particles was significantly absent. B\textsubscript{4}C fragmentation is obvious in the SEM images presented in Fig. 6 where the average size of the B\textsubscript{4}C after FSW (see Fig. 6d) is smaller compared to the as-received size shown in Fig. 1b. Fragmentation of particles also occurred during the FSW processes with SiC and Al\textsubscript{2}O\textsubscript{3} addition however, it is adjudged to be less significant because of the relatively smaller sizes of the as-received SiC and Al\textsubscript{2}O\textsubscript{3}.

In addition, the relatively lowest density of B\textsubscript{4}C (2.52 g cm\textsuperscript{-3}) is believed to have enhanced the mobility of the fragmented particles during the FSW. However, a tunnel in the centre was observed in SZ of the FSW-B\textsubscript{4}C. The SZ of the SiC reinforced FSWed-joint (FSW-SiC) comprises the SiC particles rich (i.e. SiC agglomeration), moderately dispersed SiC particle and SiC particle free regions. Similarly, the addition of Al\textsubscript{2}O\textsubscript{3} (specific density = 3.95 g cm\textsuperscript{-3}) produced FSWed joint (FSW-Al\textsubscript{2}O\textsubscript{3}) that is characterised with agglomeration of particles, region with moderately dispersed particles and particle free region. However, it was observed that particle free region in the SZ of FSW-Al\textsubscript{2}O\textsubscript{3} is larger than that of the FSW-SiC.

In order to further investigate the effect of the particles reinforcements on the microstructure of the FSWed-joint, the grain size in all the FSWed-joints was measured and compared. Fig. 7 presented the average grain size in the SZ of all the welded joints. The SZ of the FSW-WP (unreinforced joint) has an average grain size of 19.1 ± 1.4. The addition of particles showed better grain refinement as average of values 13.7 ± 2.6 μm, 9.5 ± 2.2 μm and 16.8 ± 2.9 μm were found as the grain size in the SZs of FSW-SiC, FSW-B\textsubscript{4}C and FSW-Al\textsubscript{2}O\textsubscript{3} respectively. This observation is consistent with the findings of Paidar et al. [21]. The reduction in the grain size found in the SZ of the reinforced FSWed-joints is as a result of pinning effect (i.e. reinforcement particles obstructing grain growth at the boundaries). Comparing the average grain size in the SZs of the reinforced welded joints, the lowest average grain size found in the FSW-B\textsubscript{4}C joint and highest value obtained for FSW-Al\textsubscript{2}O\textsubscript{3} are indications that homogenous particle distribution aided the grain refinement. Grain refinement due to pinning effect was adjudged to be reduced in FSW-Al\textsubscript{2}O\textsubscript{3} because of large particle free region in its SZ.

3.2 Hardness

The micro-hardness results, as presented in Fig. 8, revealed that all the FSWed-joints (reinforced and unreinforced) exhibited lower hardness than the BM (113.6 ± 0.6 HV\textsubscript{0.3}). The unreinforced joint (FSW-WP) exhibited the least hardness of
Fig. 5 – Optical microscopic images showing the welded joints of the friction stir weldments reinforced with (a) SiC, (b) B₄C and (c) Al₂O₃ particles.

Fig. 6 – SEM images showing the microstructures of the centre of the stir zone of the friction stir welded joints reinforced with (a, b) SiC, (c, d) B₄C and (e, f) Al₂O₃.

about 65.1±1.5 HV₀.₃ in the SZ and 71.05±0.2 HV₀.₃ in the TMAZ. Compared with the BM, the lower hardness exhibited by the unreinforced FSWed-joint was expected as similar findings had been reported in the literature for both the friction stir welding [23] and friction stir processing [24] of AA 6061-T6. This is due to loss of T6 condition (strengthening precipitates) during FSW. The partial dissolution of the strengthening precipitates in the TMAZ was responsible for its higher hardness compared with the SZ.

As seen in Fig. 8, the addition of all reinforcement particles produced increase in hardness in the FSWed-joints. Average hardness values of 79±2.4 HV₀.₃, 87±3.6 HV₀.₃ and
92 ± 2.6 HV0.3 were found in the Szs of the FSWed-joints reinforced with SiC, Al2O3 and B4C respectively. The TMAZ hardness of all the reinforced FSWed-joints ranged between 74 and 78 HV0.3. The hardness property enhancement can be partly traced to the pinning effect. This resulted in increased grain refinement which eventually resulted in higher hardness property. Also, the inherent property of each of the reinforcement particles played a significant role. The hardness values of SiC, Al2O3 and B4C are very high. Consequently, the addition and distribution of these particles in the AA 6061-T6 matrix has compensated for the hardness loss in the unreinforced FSWed-joint. Among all the three reinforced FSWed-joints, FSW-B4C joint showed the highest improvement in hardness. 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 than the FSW-SiC joint. This observation is consistent with the findings of Sahraeinejad et al. [4] during the friction stir processing of AA 5059 with B4C, SiC and Al2O3 particles addition.

3.3. Wear resistance

The wear resistance of the FSWed-joints with reference to the BM at varying sliding distances using low (30 N) and high (50 N) loads were investigated using pin-on-disk method. As presented in Fig. 9a and b, increasing the sliding distance resulted in increase in volume loss and increase in wear rate. The trends are similar for low and high load tests except that more volume loss was found when 50 N load was applied. Fig. 9c presented the wear rate for all samples as the applied load increased from 30 to 50 N. At both low and high load conditions, the unreinforced FSWed-joint showed significantly higher volume loss and wear rate (see Fig. 9c) when compared with the BM. At low load condition, the wear rate of the BM (1.58 × 10−3 mm3 3−1) is by a factor of 2.1 lower than that of the unreinforced FSWed-joint (3.33 × 10−3 mm3 3−1). At high load condition, the BM exhibited wear rate of 3.24 × 10−3 mm m−1 which is by a factor of 1.6 lower than that of the unreinforced FSWed-joint (5.02 × 10−3 mm m−1). The increased wear rate demonstrated by the unreinforced FSWed-joint is obviously due to the softening of the welded joint after FSW giving significantly lower hardness as already established in Section 3.2. According to Dubey et al. [25], surface hardness has a direct relationship with the wear resistance of the surface.

As shown in Fig. 9, all reinforced joints showed significant improvements because there is reduction in volume loss and wear rate at varying sliding distances when compared
with the unreinforced FSW-ed-joint. At low load condition, the BM exhibited the lowest wear rate. The wear rates of FSW-B4C (2.0 × 10⁻³ mm³ m⁻¹), FSW-Al₂O₃ (2.2 × 10⁻³ mm³ m⁻¹) and FSW-SiC (2.34 × 10⁻³ mm³ m⁻¹) reinforced joints are by factors of 1.7, 1.5 and 1.4 lower than that of the unreinforced FSW-ed-joint (FSW-WP). This trend correlates with the hardness of the joints as previously discussed in Section 3.2. However, at higher load, FSW-SiC joint exhibited the least wear rate followed by the FSW-Al₂O₃ joint. The wear rate of the FSW-SiC joint (2.67 × 10⁻³ mm³ m⁻¹) is by a factor of 1.9 lower than that of the FSW-WP (5.02 × 10⁻³ mm³ m⁻¹). The BM exhibited lower wear rate than the FSW-B₄C joint while the FSW-WP still demonstrated the highest wear rate. This was confirmed by the coefficient of friction (COF) automatically recorded (see Fig. 10) during pin-on-disk wear test because lower COF is an indication of reduced wear rate. All the FSWed-joints with particle reinforcement demonstrated lower COF compared with the unreinforced FSWed-joint.

As revealed in Fig. 11a, the worn surface of the unreinforced FSW-ed-joint is characterised with large and deep pit confirming the huge volume loss during the wear test. The presence of large and deep pits indicates that the joint suffered severe plastic deformation which led to deep cutting of the soft aluminium matrix (low hardness). However, the presence of wear tracks and no significant pit formation was evidenced in the base metal. This confirmed the fact that the wear damage was reduced. This was due to much higher hardness of the base metal giving it higher resistance to plastic deformation as it rubbed against the disk. With the addition of the reinforcement particles, the pins formed in the worn surfaces of reinforced FSW-joints (especially Fig. 12a and e) appear to have reduced in size. This is probably an evidence of the improvement shown by the reinforced FSW-joints over the unreinforced FSW-ed-joint.

The presence of pits and wear debris in varying degrees in all the samples is an indication that that abrasive wear mechanism was dominant. The main abrasive wear mechanism in metals and metal matrix composites have been identified as (i) micro-cutting of the matrix binder, (ii) plastic deformation due to ploughing action and (iii) fracture of the reinforcement particles [26–28]. Usually, the extent of abrasive wear damage depends largely on the hardness of the matrix and the hard surface rubbing against it. Micro-cutting of the matrix had been identified as the most prominent abrasive wear mechanism because the harder surface (which is often the disk) often degrades the softer matrix [27]. This is the reason for the occurrence of large pits in the unreinforced FSWed-joint. In the base metal, the effect of the micro-cutting action was reduced because of its high hardness. In the reinforced joint, prolong micro-cutting action eventually resulted in the dislodgement of the hard particles after the surrounding matrix binder (i.e. soft aluminium) have been severely degraded. Therefore, the pits seen in the reinforced FSWed-joint are results of the hard particles dislodgement (i.e. ploughing out action).

According to Eftekharinia et al. [29], the addition of the particles decreases the pressure contact between softer alu-
The aluminium matrix and harder wear disk because the load on the pin (samples) is shared between the reinforcement particles and the metal matrix. More so, the hardness of the aluminium matrix in the reinforced FSWed-joints has been improved due to enhanced grain refinement. Unlike the unreinforced FSWed-joint, the harder phase (reinforcement particles) protected some portion of the softer aluminium matrix from being exposed to wear damage. Therefore, the wear rate reduced. At 30 N load condition, the lowest wear rate demonstrated by the BM followed by the FSW-B4C joint and then other reinforced FSWed-joints indicated that the hardness of the reinforcement particles and aluminium matrix played significant roles. However, the effect of the aluminium matrix hardness was more significant. The least wear rate exhibited by the BM is an indication that the sliding contact pressure is low at 30 N. The load did not produce sufficient sliding contact and adequate frictional resistance to cause significant material removal from the BM (hardest among the aluminium matrix). However, the softer metal matrix in the reinforced FSWed-joints suffered higher wear damage because higher volume loss was recorded for them. The higher wear damage is believed to have been enhanced by fairly homogeneous distribution of the reinforcement particles in the matrix which would have likely produced large matrix binder mean free path (i.e., average distance in-between the reinforcement particles in the matrix binder). This would have eventually caused larger exposure of the softer aluminium matrix to wear damage. B4C reinforced FSWed-joint has been previously established to have the highest hardness and the most homogeneous particle distribution. Consequently, FSW-B4C joint demonstrated the least wear rate after the BM. The next is FSW-Al2O3 joint which exhibited higher hardness than FSW-SiC and then FSW-WP joints.

The lowest wear rate demonstrated by the FSW-SiC joint (followed by FSW-Al2O3) at high-load condition shows that the effect of the reinforcement particles was significant at
at high load condition can be traced to the average particle size of B₄C (highest among the three utilised particles).

4. Conclusion

Friction stir welding of AA 6061-T6 resulted in grain refinement in the welded region. The grain refinement was enhanced with the addition of the reinforcement particles. B₄C reinforced joint has the most uniform particle distribution with no noticeable particle agglomeration. SiC and Al₂O₃ reinforced friction welded joints contain agglomerations of particles, moderately dispersed particle region and particle free region in the stir zone. The hardness of the unreinforced joint (65 HV₀.₃) was significantly low compared with the base metal (114 HV₀.₃). However, the hardness improved with the addition of the reinforcement particles. B₄C, Al₂O₃ and SiC particles reinforcements produced improvements of about 42%, 34% and 22% in hardness property respectively. The hardness was influenced by the extent of grain refinement and inherent properties of the reinforcement particle. Under 30 and 50 N load conditions, unreinforced AA 6061-T6 friction stir welded joint exhibited lower wear resistance compared with the base metal and the entire particle reinforced joints. Base metal demonstrated the highest wear performance at 30 N load. The base metal wear rate is by a factor 2.1 lower than that of the friction stir welded joint. Particles reinforced joints showed significant improvements over unreinforced joint as the wear rates are by factors of 1.7, 1.5 and 1.4 lower with the addition of B₄C, Al₂O₃ and SiC respectively. At 50 N load condition, SiC followed by Al₂O₃ reinforced joints produced the highest wear performance because the effect of particle reinforcement was predominant due to increased sliding contact
pressure. B$_4$C reinforced joint suffered more wear damage at high load due to the dislodgement of the reinforcement particles which was enhanced by large particle size.

**Conflicts of interest**

The authors declare no conflicts of interest.

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**References**


