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PAPER

Joint quality enhancement of AA6061-T6 friction stir weldment by reinforcing with pulverized glass waste using different reinforcement strategies

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Keywords: friction stir welding, reinforcement strategies, pulverized glass waste, AA 6061-T6, particle distribution, mechanical properties

Abstract

The purpose of this study is to investigate the effect of different reinforcement strategies on the mechanical properties of pulverized glass waste (PGW) reinforced AA6061-T6 friction stir welded joint. Friction stir welding of PGW reinforced AA6061-T6 was carried out at an optimized processing parameters by using different reinforcement strategies including centre groove, parallel holes, centre holes, zig-zag holes and side holes arrangements. Thereafter, the microstructure and mechanical properties of weldments produced using each strategy were investigated. The results showed that all the reinforcement strategies utilized in this work produced harder joints than the unreinforced joint. The parallel holes (PH) strategy followed by the centre holes (CH) exhibited the highest hardness of 72 HRC_B and 66 HRC_B respectively. Only the joints produced using PH, CH and SH strategies exhibited higher or improved impact energy than the unreinforced. Though the joints produced using PH and CH reinforcement strategies have tensile properties that are close to that of the unreinforced joints, the unreinforced joints show higher tensile properties than the entire reinforced joints. Compared with other reinforcement strategies, better particle distribution was achieved through the use of PH and CH reinforcement strategies. Parallel holes and centre holes arrangements have been established as the most appropriate reinforcement strategies for producing high quality aluminium alloy composite welded joints.

1. Introduction

Aluminum alloy 6061-T6 is a precipitation hardened aluminum alloy which contains magnesium and silicon as its major alloying elements. Due to its combination of favorable properties such as high strength-to-weight ratio, excellent corrosion resistance, high ductility and low cost [1], it is now a material of choice for making structural components such as rims and wheel spacers in automobile and fuselages and wings of aircrafts [2]. However, the major issue of concern is the poor weld quality of this alloy because of the dissolution of its strengthening precipitates at temperatures beyond 250 °C [3–5]. Welding processes including friction stir welding take place at temperatures beyond 250 °C. Hence the loss of weld quality is inevitable at the joint.

Reinforcement's additions into abutting edges of AA 6061-T6 before welding has proven to be an effective method to compensate for its weld quality loss. Hard ceramic particles including SiC, B_4C, Al_2O_3 and SiO has been extensively utilised for enhancing the tensile strength [6], hardness [7] and wear resistance [8] of the welded joint of AA 6061-T6 and other heat-treated aluminium alloys. The particle reinforcement requires prior fabrication of holes or grooves along the weld line in which the hard ceramics are embedded. Past works have revealed that groove size plays a significant role in enhancing reinforced weld joint quality. For example,

Table 1. Chemical composition of the AA 6061-T6 plate as determined by XRF analysis.

Elements	Mg	Si	Fe	Cu	Mn	Cr	Ni	Zn	Ti	Al
Wt(%)	0.891	0.562	0.314	0.265	0.039	0.231	0.014	0.053	0.019	Bal

Ravinder *et al* [9] investigated the effect of varying groove size (width) on the joint strength of SiC-reinforced AA 5053-AA6061 dissimilar friction stir welded joint. It was established that varying the groove size influences the mechanical properties of the welded joint due to the variation of reinforcement's content at different groove widths. The optimal joint strength was achieved at groove width of 2 mm. Also, Abioye *et al* [10] has established a maximum groove width of 2 mm as a benchmark for producing ceramic particles-reinforced AA 6061-T6 friction stir welded joint. Apart from the creation of centre groove, creation of holes on top of the base plate (along and/or around the weld line) has been identified as another method of incorporating reinforcement particles (i.e., reinforcement strategy) in the friction stir welded joint or friction stir processed (FSP) surface [11]. Comparative study on the holes and groove reinforcement strategies in the fabrication of reinforced joint and composite surfaces using friction stir welding/processing has been carried out by Sharma *et al* [12]. It was found that hole reinforcement strategy produced higher quality joint which was attributed to improved homogeneity of particle distribution.

So far, holes and groove reinforcement incorporation strategies have been very much investigated in the FSW and FSP of aluminium alloys. Investigation of the effects of different hole patterns on the mechanical properties of reinforced aluminium alloy friction stir welded joint is still scanty. Also, the use of amorphous particles such as pulverized glass waste (PGW) as a cheaper reinforcement replacement for synthetic ceramic particles has rarely been tried in the fabrication of friction stir composite welding. In this work, the effects of different hole reinforcement strategies (Parallel holes—PH, Centre Holes—CH, Side Holes - SH and Zig-Zag Holes - ZZ) and centre groove reinforcement strategy on the mechanical properties of PGW reinforced AA6061-T6 friction stir welded joints were investigated.

2. Materials and methods

2.1. Materials

AA6061-T6, obtained from Aluminum Rolling Mill Coy., Malaysia, was used as the base metal. The material was machined into dimension 100 mm × 50 mm × 6 mm. The chemical composition of the material, as obtained via x-ray fluorescence (XRF) analysis, is presented in table 1. In order to investigate the effect of different reinforcement strategies. First, centre groove reinforcement strategy was made by machining a centre groove of dimension 90 × 2 × 4.5 mm (L × B × H) along the weld-line. Thereafter, 14 blind holes of diameter 4 mm and depth 4.6 were machined along and near the weld line in different patterns including zig-zag, parallel, centre, side holes to form another 4 reinforcement strategies in four different samples. The reinforcement strategies were prepared such that the centre groove volume is approximately equal to the total volume of the 14 holes in each of the other 4 samples. The volume of the centre groove (~810 mm^3) and the total volume of the 14 holes in other reinforcement strategies (about ~810 mm^3) were taken as the volume of the PGW injected into the joints because the groove and holes were properly and fully filled with the reinforcement particles prior welding. Figure 1 shows the schematic of the five reinforcement strategies utilised in this work. The reinforcement particles (<45 μm size) used is pulverised glass waste (PGW) which is a borosilicate glass. The elemental analysis of the PGW, as determined by energy-dispersive x-ray (EDX) analysis, is presented in figure 2.

2.2. Friction stir welding

Prior to the friction stir welding (FSW), the groove and the holes in each sample were manually filled with the PGW. Thereafter, the filled grooves and holes (except the side holes) were sealed by single-passing pinless friction stir welding tool over the grooves and holes. This was done so as to prevent or minimise sputtering of the reinforcement particles during FSW. In the case of the side holes, the holes were carefully sealed with the aid of transparent tape so as prevent falling off of the PGW prior the welding. As shown in figure 3, FSW was performed by using a non-consumable rotating high-speed steel (HSS) tool with pin. Single pass FSW was done in all cases so as to prevent excessive localised heating of the joint which may further deteriorate the joint quality. The tool shoulder is of diameter 20 mm while the tool pin (tapered) is of diameter 4.5–4 mm from the shoulder over a length of 4.5 mm. The experiments were performed on an adapted conventional vertical milling machine. The entire holes and groove in each of the samples were designed in such a way to have an almost equal volume fraction of reinforcement particles. The utilised process parameters were the optimum values previously discovered [13] which are rotational speed of 1120 rpm, traverse speed of 40 mm min^{-1} and tilt angle of 1.5^0.

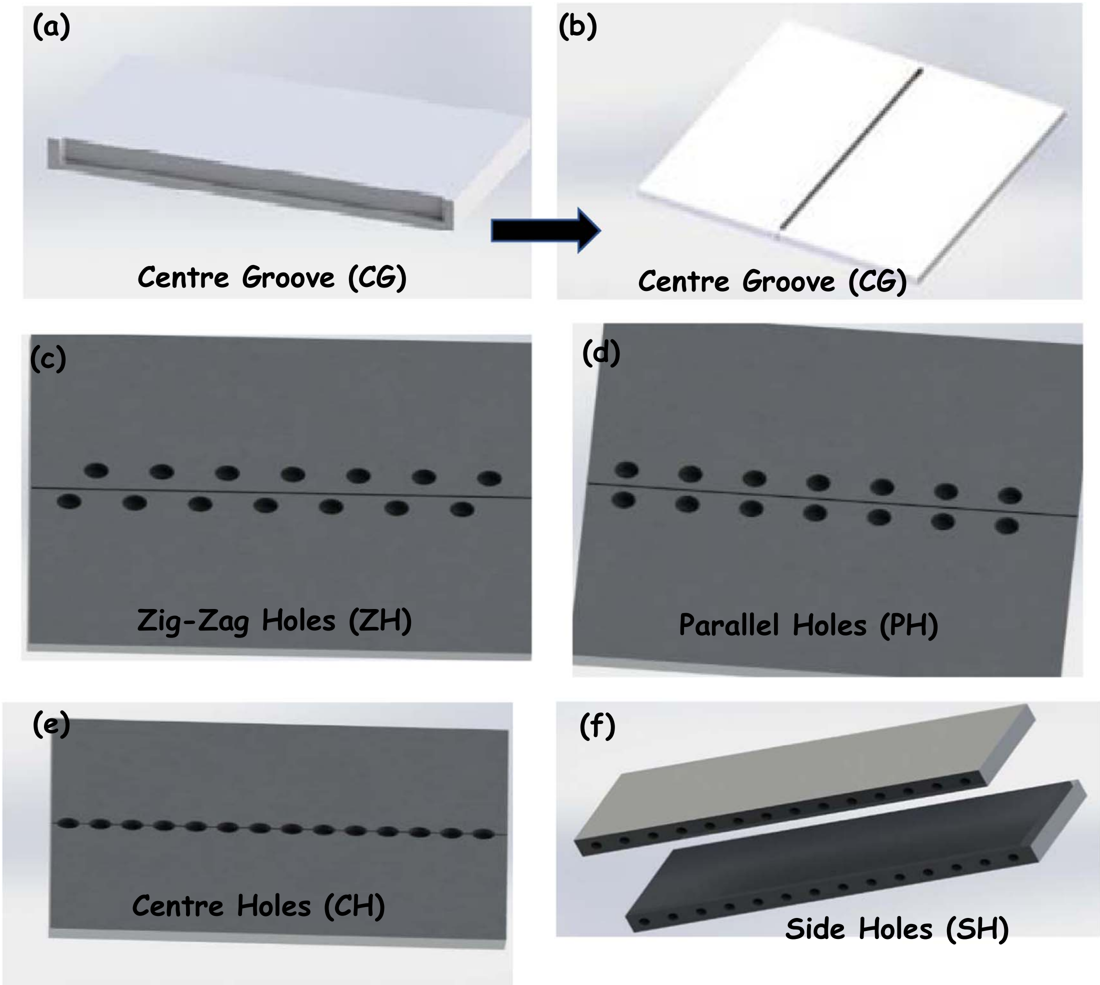
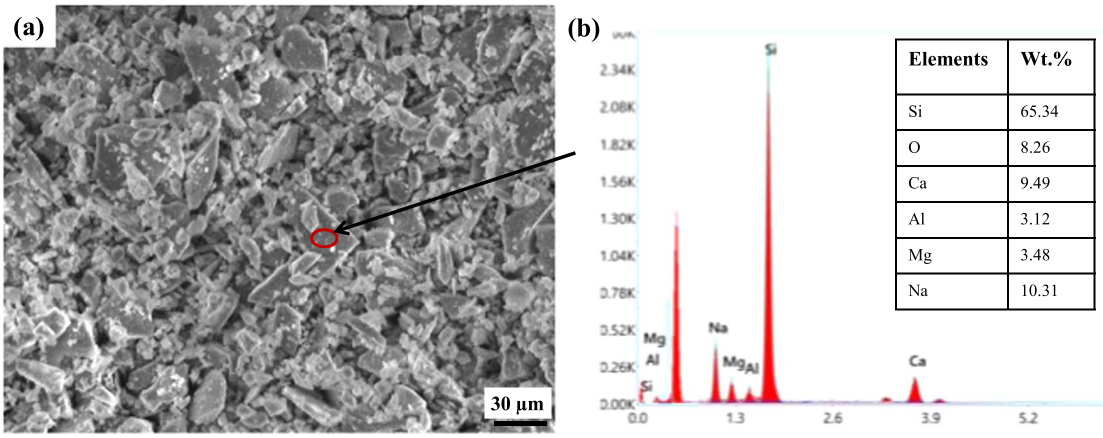


Figure 1. Schematic of the utilised five reinforcement strategies.



Elements	Wt.%
Si	65.34
O	8.26
Ca	9.49
Al	3.12
Mg	3.48
Na	10.31

Figure 2. (a) SEM micrograph of the pulverised glass powder (b) EDS analysis showing the various elemental compositions.

2.3. Microstructural characterization

In order to investigate the microstructure of the welded joints, the weldments were cross-sectioned along the joints and samples were taken in the middle of the joint. The samples were ground and polished. Thereafter, the samples were etched using modified Poulton's reagent (50 ml Poulton's reagent + 25 ml HNO_3 + 1 ml HF + 1 ml H_2O) for about 5–7 s. Subsequently, the microstructure of the joint was studied using a scanning electron microscopy equipped with energy dispersive spectroscopy (EDS).

Figure 3. A picture showing the friction stir welding process.

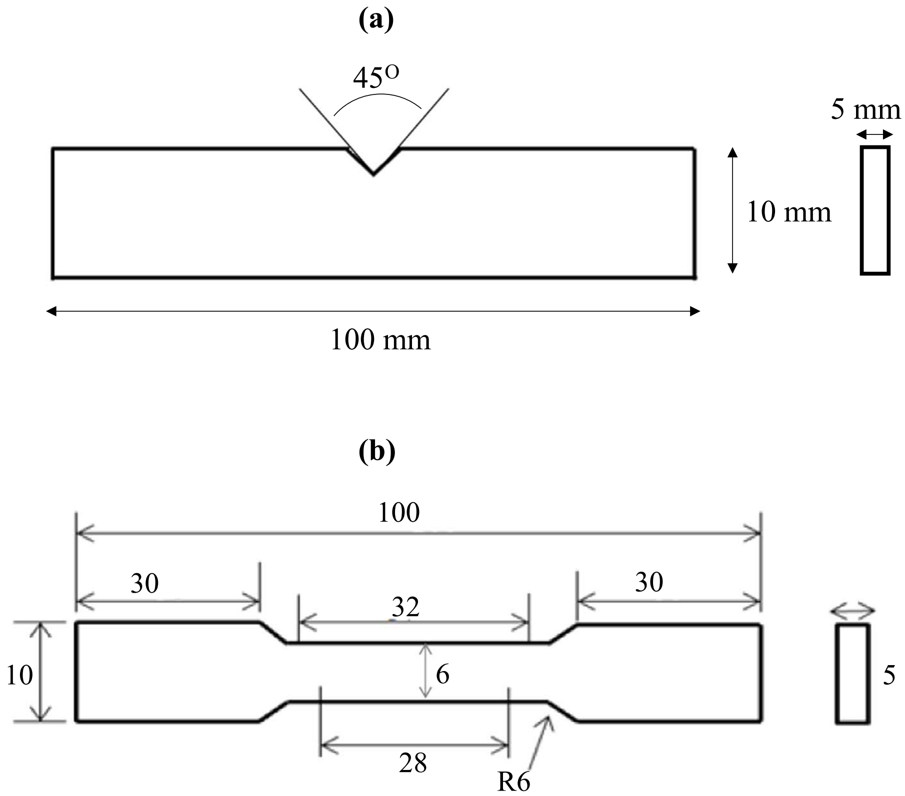


Figure 4. Schematic diagram of (a) tensile and (b) impact test specimens (all dimensions in mm).

2.4. Mechanical tests

The micro-hardness was measured by making five indentations randomly on the cross-sectioned surface of the samples using Rockwell hardness tester (Model: RBHT, Sr.No:2011/202). A load of 300 gf and dwell time of 10 s was used for the entire test. Adequate spacing was allowed in-between two consecutive indentations to avoid potential effect of strain fields developed by adjacent indentations. The impact strength test was conducted using a Charpy impact testing machine, following ASTM E23 standard. The samples were cut into the dimension 55 mm × 10 mm × 5 mm with a centre-notch of 2 mm depth (see figure 4(a)). The sample was impacted at the

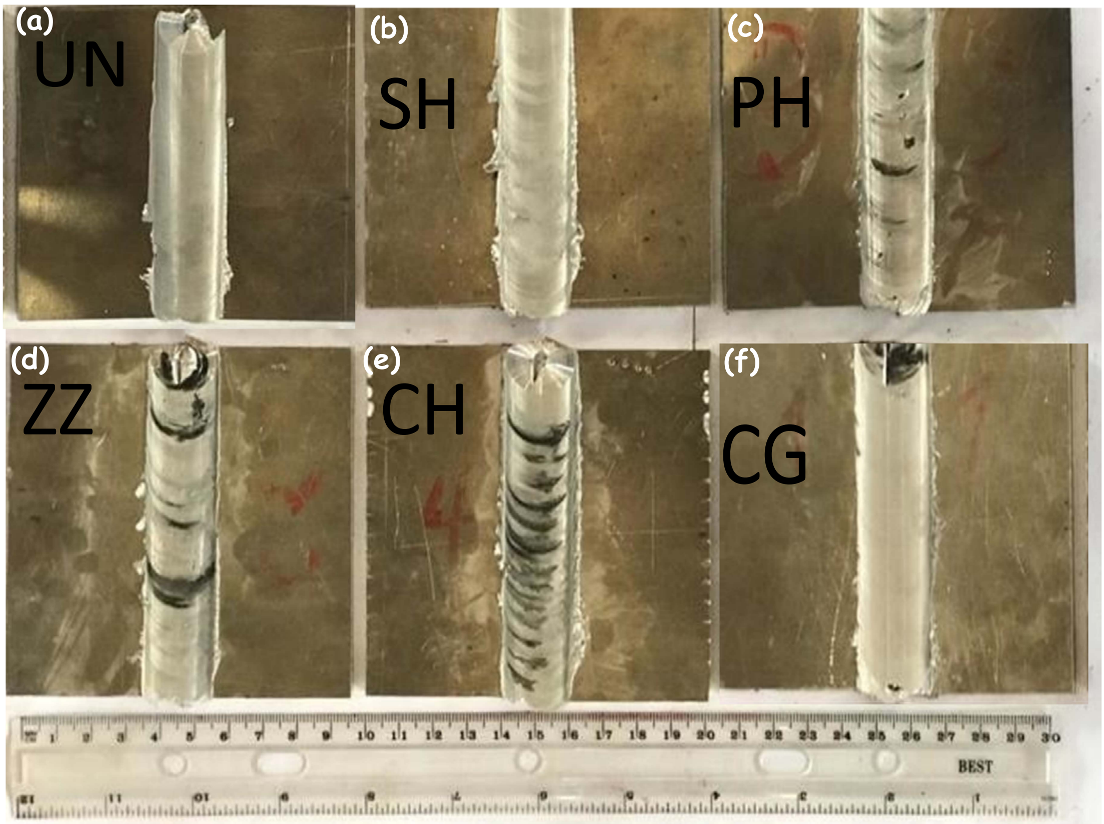


Figure 5. A picture showing the (a) unreinforced and reinforced friction stir weldments produced using (b) Side holes, (c) Parallel holes, (d) Zig-Zag holes, (e) Centre holes, (f) Centre groove reinforcement strategies.

centre with a load of 25 kg at room temperature. In order to measure the tensile properties of the joints produced using different reinforcement strategies, samples were cut across the welded joints. The cut samples were then machined and prepared based on the ASTM-E8M-13 standard (see figure 4(b)). The tensile test was carried out using Instron 3369 universal tensile testing machine. Tensile tests were done using the x-head velocity or loading rate of 5 mm min^{-1}. Three (3) samples were prepared and tested for each experimental run so as to obtain the average value of the three measurements, thereby enhancing the reliability of the results obtained.

3. Results and discussion

3.1. Visual examination of welded joints

Figure 5 shows an unreinforced and the five PGW-reinforced AA6061-T6 friction stir welded joints. Visual observation of the entire weldments revealed that the joints are smooth and free of visible crack which indicates that the parameters used are suitable for the welding of these materials. The dark lines in the samples are as a result of powder spreading on the surface while filling the holes and groove. The surface regions having some spread of PGW on them appeared darkened after undergoing FSW.

3.2. Microstructural investigation

SEM images presented in figure 6 shows the stir zones of the joints produced using the five (5) different reinforcement strategies. A typical observation of the reinforced joints revealed that the joints comprise mainly two distinct phases. The first is a continuous dark contrast phase spotted 'A' which is believed to be the aluminum matrix while the second is white contrast angular-shaped phase marked 'B' in figure 6(b). EDX analysis was conducted on the two phases. The results, as shown in figure7(a), revealed that the phase spotted 'A' comprises mainly of Al (97.99 wt%) and Mg (2.23 wt%). Comparing this composition with the original composition of the as-received AA 6061-T6, it can be adjudged that the dark continuous phase is AA 6061-T6 (Al–Mg–Si Alloy).

The EDX spot analysis conducted on the white contrast angular-shaped phase (B) is presented in figure 7(b). The phase is found to be rich in Si (34.22 wt%) and has other contents similar to that of the pulverized glass waste including Mg (39.96 wt%), Na (3.48 wt%). With this result, it is adjudged that the white angular phase is the

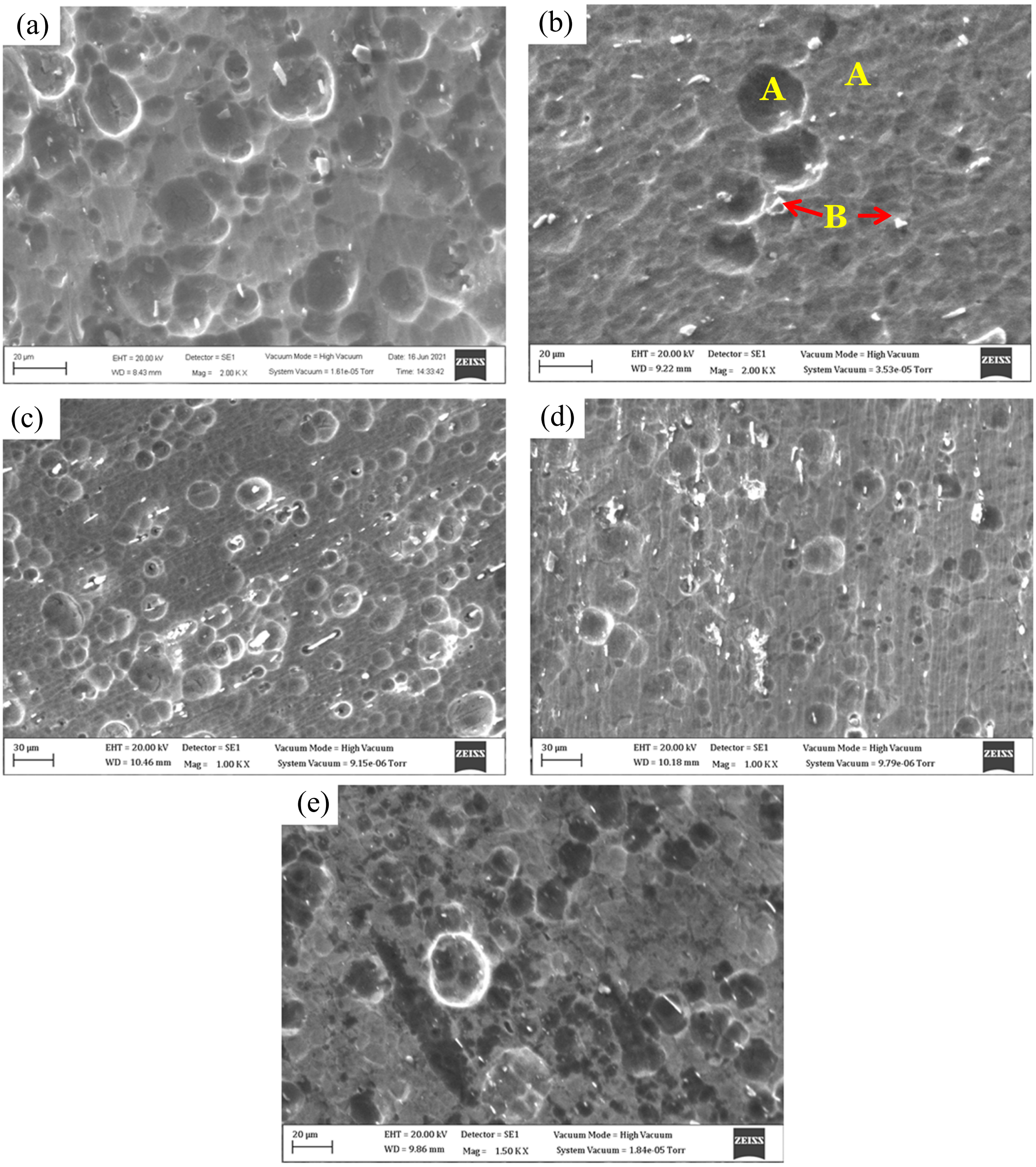


Figure 6. SEM images showing the AA6061-T6 friction stir welded joints produced via (a) centre groove (b) Zig-zag holes (c) parallel holes (d) centre holes and (e) side holes reinforcement strategies.

PGW that is randomly dispersed in the continuous aluminum matrix. A critical observation of all the reinforced joints revealed that the joint produced using centre groove reinforcement strategy appears to have the lowest volume of PGW dispersed in the matrix. The lowest PGW retention observed in the CG joint can be traced to particle sputtering observed during the FSW of the joint despite the prior sealing of the groove. The joints formed using PH and CH strategies are found to have the highest number density of PGW well dispersed in the aluminum matrix. The particles distribution is also found to be more uniform in the joints produced using PH and CH strategies.

3.3. Hardness

The microhardness values of the PGW-reinforced AA6061-T6 friction stir welded joint and the unreinforced joint are presented in figure 8. The value for each sample is an average of five measurements. The hardness of the PGW-reinforced samples ranged between 56.1 ± 0.78 and 71.2 ± 1.1 HRC_B while that of the unreinforced was found to be 55.7 ± 3.6 $HRC_{B.}$ The fact that the reinforced welded joints demonstrated higher hardness than the unreinforced is in agreement with the finding of Abioye *et al* [14] where AA6061-T6 welded joint reinforced with SiC, Al_2O_3 and B_4C exhibited higher hardness than the unreinforced joint. The reason for the higher hardness

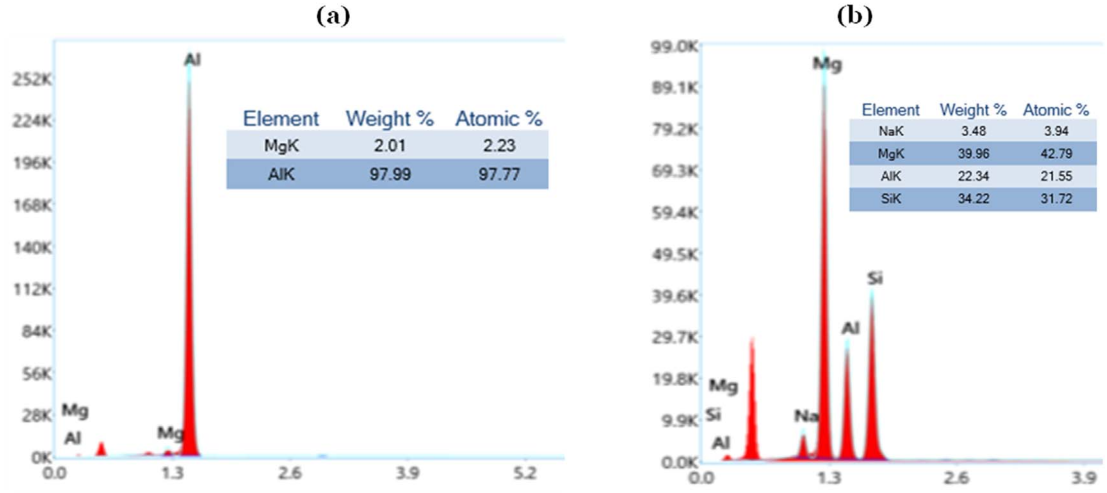


Figure 7. EDX spot analysis conducted on the phases marked (a) A and (b) B.

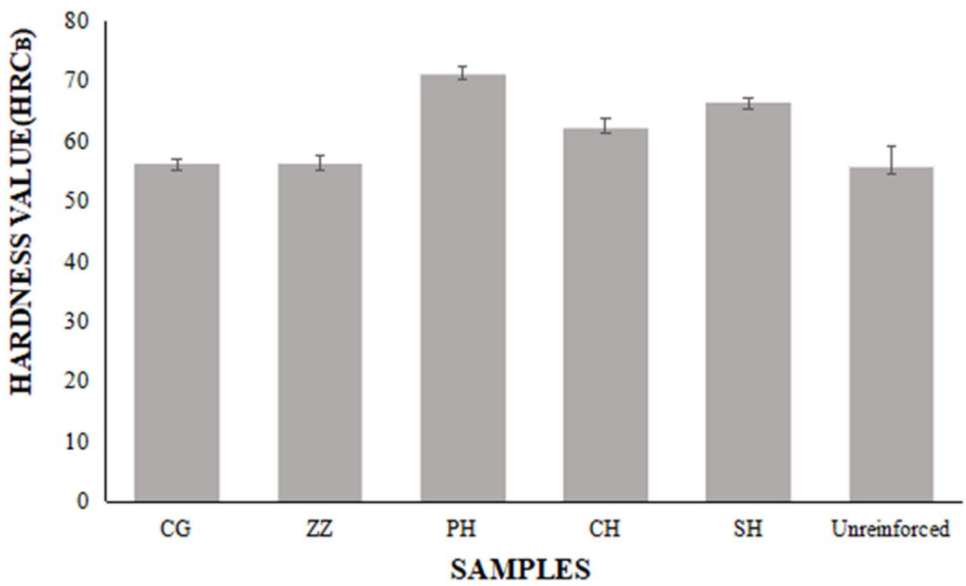


Figure 8. Microhardness of an unreinforced and PGW-reinforced AA6061-T6 friction stir welded joints produced via different reinforcement strategies.

exhibited by the PGW-reinforced joint over the unreinforced can be traced to the inherent high hardness of the pulverized glass waste. The glass waste which comprises mainly SiO (88% by weight) has been reported to have an average hardness value of 580 HV [15]. Also, the addition of the PGW is adjudged to have caused substantial grain refinement resulting from dynamic recrystallization and pinning effect [13]. This is believed to have contributed to the high hardness of the reinforced welded joint. Among the reinforced joints, the joint produced using centre groove strategy has the least hardness. This observation was confirmed by earlier finding of Sharma *et al* [12] who discovered that hole reinforcement strategy is better than the groove reinforcement strategy. This can be explained by improved homogeneity of particle distribution and high particle retention exhibited by the hole reinforcement strategies, compared with the centre groove strategy. The low particle retention found in the joints produced using centre groove reinforcement strategy is due to the sputtering of the PGW from the centre groove during the welding process. Joints produced using parallel hole (PH) strategy showed the highest hardness of $71.2 \pm 1.1\ HRC_B$. This is not unconnected with the high particle retention and improved particle distribution found with the holes pattern especially, parallel hole reinforcement strategy. Hence, the pinning effect is adjudged to be more prominent leading to significantly high grain refinement. Other strategies such as centre holes and side holes also exhibited relatively high hardness of about 66.4 ± 0.9 HRC_B and 62.2 ± 1.7 HRC_B respectively.

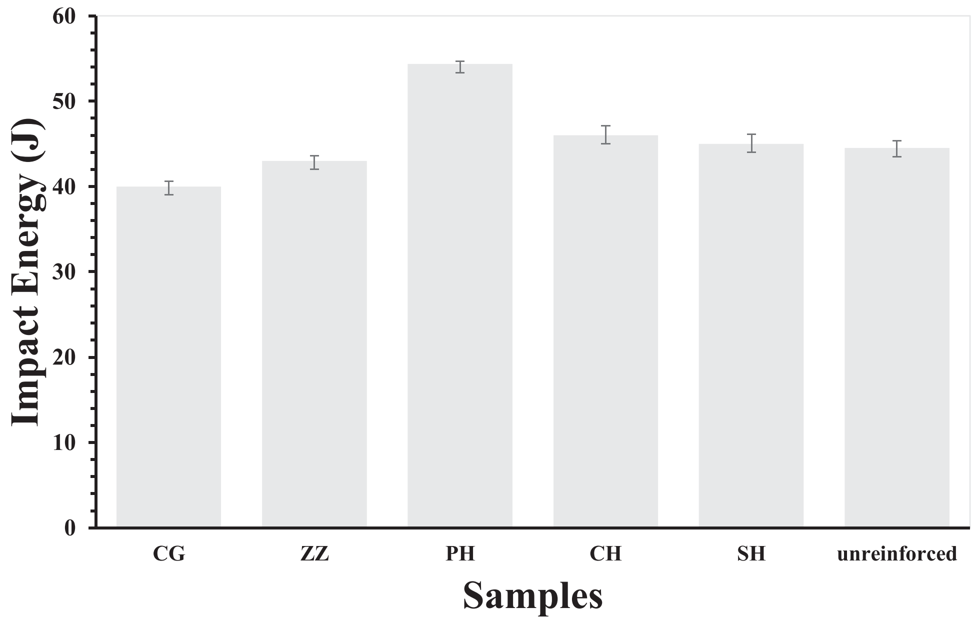


Figure 9. Impact energy of an unreinforced and PGW-reinforced AA6061-T6 friction stir welded joints produced via different reinforcement strategies.

3.4. Impact strength

The impact energy values of the unreinforced and five pulverized glass waste reinforced AA6061-T6 friction stir welded joint are presented in figure 9. The value of the impact energy for each sample (unreinforced and five pulverized glass waste reinforced) of AA6061 friction stir welded joints was gotten from an average of three measurements. The unreinforced joint exhibited impact energy of 44.5 ± 0.9 J. All the PGW-reinforced friction stir welded joints except the joints made using centre groove and zig-zag reinforcement strategies exhibited higher impact energies more than the unreinforced joint. PH strategy followed by CH reinforcing strategies has impact energies of 54.3 ± 0.3 J and 46 ± 1.2 J respectively. Among the PGW-reinforced joints, the zig-zag holes method and the centre groove methods showed the least impact energy with values of 43 ± 0.6 J and 40 ± 0.6 J respectively. The higher impact energy found in the samples made using PH, CH and SH reinforcement strategies can be attributed to improved particle retention and distribution which is believed to have produced increased grain refinement in their welded joints [16, 17]. In the past, grain refinement in the friction stir welded or processed aluminium alloy matrix has been establsihed to increase with the addition of the reinforcement particles [10, 14]. Through dynamic recrystalisation, new grains are nucleated. Hence, grains are refined. However, the growth of the new grains are often hindered by the reinforcement particles resulting in increased grain refinement [18, 19]. As a result, the toughness (i.e., impact energy) of the reinforced friction stir welded joints is adjudged to have increased as a result of finer grain size. Joints with high impact energy can be traced to have more percentage weight of the reinforcement as there was escape of powder during the FSW process in some of the reinforced joints. Increase in weight of the reinforcement increases the degree of resistance offered to the motion of dislocation, resulting in increased toughness [20].

3.5. Tensile strength

The ultimate tensile strength (UTS) and percentage elongation of all the welded joint samples are presented in figure 10. It was observed that the PGW reinforced AA 6061-T6 friction stir welded joints (96–146 MPa) demonstrated a noticeable decrease in UTS and percentage elongation (3.2–9.3%) compared to the unreinforced AA6061-T6 friction stir welded joint (156 ± 1.4 MPa, 21.1 ± 1.1%). However, the UTS of the joint made using CH strategy was close to that of the unreinforced joint. This result showed that the addition of the PGW reinforcement showed no significant improvement and could not overturn the strength loss in the welded joint caused by the dissolution of strengthening precipitates [21]. The base metal (as received AA6061-T6) exhibited a tensile strength of 293 ± 1.2 MPa and elongation of 24.6 ± 0.8%.

As shown in figure 11, all the reinforced joints exhibited relatively poor joint efficiency as compared with the unreinforced joint. The tensile property and joint efficiency of the centre groove sample was exceptionally low. During the friction stir welding process, escape of the PGW-reinforcement is likely to have occurred especially, in the centre groove sample which gave the lowest UTS value (96 ± 3.1 MPa). In addition, the low tensile

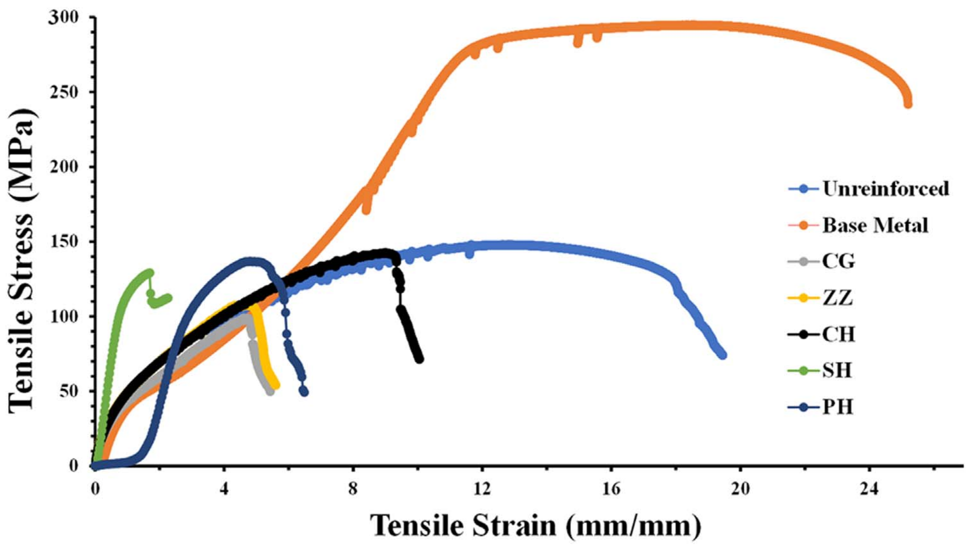


Figure 10. Tensile properties of an unreinforced and PGW-reinforced AA6061-T6 friction stir welded joints produced via different reinforcement strategies.

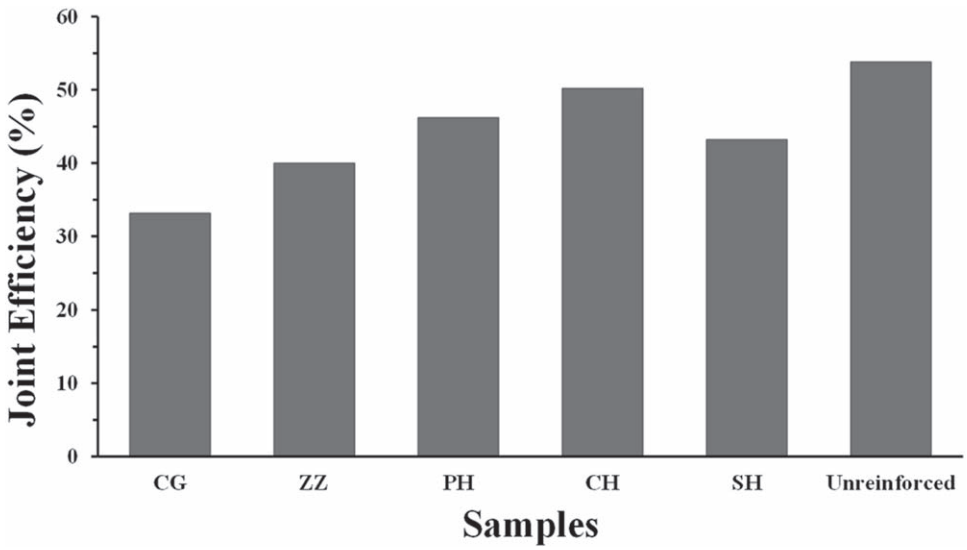


Figure 11. Joint efficiencies of the unreinforced and PGW-reinforced AA6061-T6 friction stir welded joints produced via different reinforcement strategies.

properties of the reinforced samples can be attributed to some formation of particle clustering. This observation is in tandem with Singh [22] in the study of mechanical and microstructural characterization of friction stir welded AA6061-T6 joints reinforced with nano-sized particles, it was reported that decrease in tensile property is related to reinforcement particles cluster formation. According to Ozden *et al* [23], high brittleness of the reinforcement particles could also have played a role.

4. Conclusion

The effects centre hole (CH), parallel holes (PH), zig-zag holes (ZZ), side holes (SH) and centre groove (CG) reinforcement strategies mechanical properties of the pulverized glass waste (PGW) reinforced-AA 6061-T6 friction stir welded joints were successfully investigated. The joints produced using PH and CH reinforcement strategies have more particle retention and better particle distribution in the aluminium matrix. All the reinforced joints exhibited higher hardness (ranging from 56.1 to 71.2 HRC_B) than the unreinforced joint (55.7 HRC_B). The PH reinforcement strategy followed by the SH strategy exhibited highest hardness of 71.2 and 66.1 HRC_B respectively. Only the joints produced using PH, CH and SH strategies exhibited improved impact energy of 54.3 ± 0.3 J, 46 ± 1.2 J and 45 ± 1.2 J respectively than the unreinforced joint (44.5 ± 0.9 J). The unreinforced joint shows higher tensile properties than the entire reinforced joints. Therefore, the PGW additions using all the reinforcement strategies did not improve the tensile properties of AA 6061-T6 friction stir welded joint.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare that there is no conflict of interest.

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