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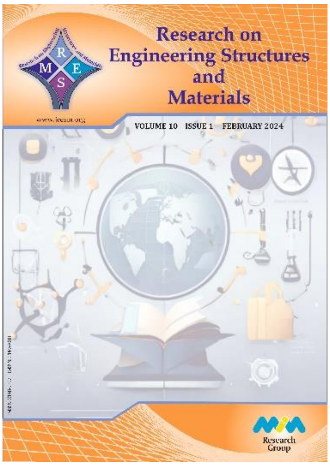

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Research Article

Performance improvement of AA6061-T651 friction stir butt-weldment using particulate addition strategy

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Abstract

The joint quality performance of AA6061-T651 friction stir weldments had been investigated in this study through addition of pulverized waste glass (PWG), palm kernel shell ash (PKSA) and synthetic silicon carbide (SSC) with a bid to enhancing some selected mechanical properties. Optimized processing parameters which include 1120 rpm rotational speed, 40 mm/min traverse speed, 1.5^{o} tilt angle) and optimum reinforcement strategy (parallel hole) established from a preliminary investigation were utilized for the friction stir welding. The mechanical properties such as the tensile strength, hardness and impact energy were then further investigated. The results showed that the mechanical properties of all the reinforced welded joints improved significantly than the unreinforced joint having a relatively reduced joint performance of 132 MPa tensile strength, hardness of 45.3 HRB and impact energy of 39.4 J. The PWG-reinforced friction stir welded joint performed optimally at a tensile strength of 212.7 MPa, 72 HRB hardness and 54.5 J impact energy followed by the SSC-reinforced joint which exhibited 173.7 MPa tensile strength, 54.8 HRB hardness and impact energy of 41.7 J. Hence, 80%, 59% and 38% joint performance was exhibited through tensile strength, hardness and impact energy of PWG-reinforced friction stir weldments of AA6061-T651 against the unreinforced weldments.

1. Introduction

The continuous demand for utilization of lighter, stronger and cost-effective engineering materials with excellent corrosion materials has been on the increase [1-3]. This is specifically for the production of high-speed and low fuel economy automobiles and aircrafts. Hence, aluminium alloys, most especially the 7000 and 6000 series have become choice materials for manufacturing industries since they possess excellent combination of these properties for making of specific parts [4, 5].

For instance, heat-treatable and precipitation hardened AA6061-T651 containing magnesium and silicon as its major alloying constituents is utilized in producing structural components of aircrafts wings and fuselages, car wheel spacers and rims and body frames due to its relatively high strength and high toughness properties [6-8]. The poor quality of weld obtained from this alloy has become a bothering issue resulting from the excessive softening of the strengthening precipitates at temperatures above the solidus temperature

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[9]. In order to address this challenge, several experimental approaches and strategies have been adopted and engaged such as parametric optimization of welding parameters, design and re-design of welding tool pin and shoulder geometries, adoption of post and pre-heat treatment studies, as well as particulate reinforcement strategies [9-12]. However, among the several research efforts previously carried out towards enhancing the deteriorated mechanical properties of friction stir welded joints of AA6061-T651, addition of reinforcement powders, most especially nano and micro-sized ceramic or conventional particles which includes Al_2O_3, B_4C, SiO_2 and SiC have proven to significantly improve the frail friction stir welded joint quality [13-16].

Till date, the utilization of these synthetic particles for reinforcement purposes has become very frequent and popular. Moreover, several works have been reported on the impact of these traditional reinforcement powders on the microstructure, mechanical and tribological properties of friction stir welded joints of AA6061-T651 [17, 18]. Reports from these studies showed that the use of synthetic reinforcement powders gave significant improvement on the mechanical properties as compared to the unreinforced friction stir welded joint of AA6061-T651 weldment. However, these synthetic powders are relatively expensive and not readily available for use [19]. In order to mitigate this challenge, the use of non-crystalline or amorphous powders such as graphite, carbon nanotubes, graphene and copper powder has been investigated and established to have contributed significantly to the enhancement of the mechanical properties of friction stir weldments [20-24]. Several reports from previous works revealed that these amorphous powders gave immense improvements to the joint quality of AA6061-T651 friction stir welded joints thereby making them potential and cost-effective replacements in place of the conventional crystalline and synthetic powders [25-28].

Presently, the utilization of amorphous or non-crystalline powders as reinforcements for friction stir welding (FSW) of aluminium alloys including AA6061-T651 is not popular as research conducted in this area are still very scanty [29]. Moreover, the use of industrial ceramic and agricultural wastes particles are fast gaining acceptance as alternative or replacement powders of choice for use as reinforcements. In previous studies, non-synthetic silica reinforcement powders from rice husk ash was utilized for FSW of AA6061-T6 [30]. The outcome of these studies revealed that hard silica particles hindered grain growth and formation due to the effect of pinning and refinement of grains that resulted from dynamic recrystallization within the aluminium matrix. According to these reports, major improvements were observed in the microstructure and mechanical properties of AA6061-T651 friction stir weldments. In addition, friction stir welding of pulverized waste glass-reinforced aluminium alloy 6061-T651 has been successfully investigated by Ogunsemi *et al.* [31] where the welding processing parameters range (rotational speed between 900-1400 rpm; traverse speed between 25-63 mm/min; tilt angle between 1-2.5^o) were utilized and established to offer optimum mechanical performance of the friction-stir welded joints. The results of the work and other previous investigations by Abioye *et al.* [32] revealed that the addition of reinforcement powders gave significant enhancement to the tensile strength and hardness properties of friction stir weldments of AA6061-T651 in comparison with the unreinforced welded joint under the same welding conditions. However, till date, few works have been reported on the utilization of amorphous or agro-waste powders such as palm kernel shell ash (PKSA) as reinforcement in the FSW of AA6061-T651. Therefore, this present work seeks to investigate the impact of different reinforcement powders such PKSA, Pulverized Waste Glass (PWG and Synthetic Silicon Carbide (SSC) on the joint performance of friction stir weldments of AA6061-T651.

2. Materials and Methods

The materials and research methods utilized in this study are as presented.

2.1. Materials Collection and Equipment

The parent metal for this work is a rolled plate of 6 mm thick heat treatable aluminium alloy6061-T651 ordered from Aluminium Rolling Mill Coy, Malaysia. The plate was cut into 100 mm×50 mm×6 mm dimension. Table 1 shows the elemental constituents of the base metal examined through X-ray fluorescence (Model No: ATX2600) analysis.

A parallel-hole reinforcement strategy was adopted to incorporate the particles along the faying or abutting plate surfaces. This was achieved by drilling 14 parallel holes, each of diameter 4 mm and 4.6 mm depth along the weld line as shown in Figure 2. The total volume of the holes (approximately 810 mm^3) was utilized as the volume of the PKSA powders injected into the holes before FSW. The size of PKSA, PWG and SSC used for this work is < 45 µm. However, the choice of a parallel-hole particle addition strategy was informed by the outcome of the investigation conducted by Ogunsemi *et al.* [33] where the strategy was established among other strategies to produce the optimal mechanical properties of pulverized waste glass (PWG)–reinforced friction stir weldments of AA6061-T651.

Fig. 1. A non-consumable HSS rotating tool mounted on a vertical milling machine for FSW

Table 1. Elemental composition (wt. %) of AA6061-T651 Plate (as-received)

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	97.612

A conventional vertical milling machine (Model No: MC-1007) was adapted to carry out friction stir welding. This was achieved by incorporating a non-consumable tapered high speed steel (HSS) tool with pin. The tool's shoulder is of diameter 20 mm while the pin is of diameter 4 mm and length 4.5 mm. A typical experimental showing the non-consumable rotating HSS tool mounted on a vertical milling machine is presented in Figure 1.

Fig. 2. Parallel hole design strategy

2.2. Friction Stir Welding (FSW)

Figure 3 shows a schematic diagram of the friction stir welding process. A vertical milling machine having a non-consumable high-speed steel (HSS) rotating tool with pin was adapted to produce the weldments. The diameter of the tool shoulder is 20 mm with 4.5 – 4 mm tool pin (tapered) diameter from the shoulder over a 4.5 mm length. Friction stir welding was carried out by utilizing optimized process conditions (1120 rpm rotational speed, 45 mm/min traverse speed and 1.5^{o} tilt angle) and parallel-hole design strategy (for particle addition) already established from a recent investigation by Ogunsemi *et al.* [34] was adopted for optimal results.

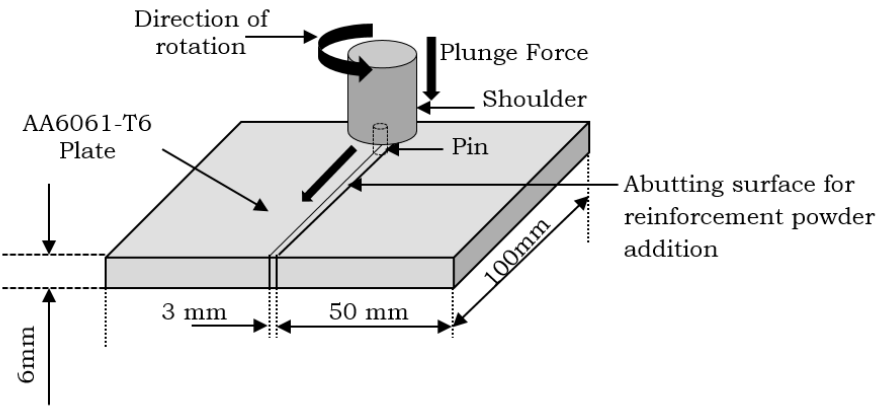

Fig. 3. Schematic of the FSW proces

2.3 Mechanical Tests

Instron 3369 universal tensile testing machine with a x-head velocity or loading rate of 5 mm min^{-1} was used for tensile tests adopting the ASTM-E8M-13 standard as shown in Figure 4. For each experimental run, three (3) samples were prepared and tested to obtain the average value with a view to understanding the level of dispersions or deviations of the results obtained for improved reliability. The hardness values were determined by cross sectioning the surface of the samples and then creating five (5) indentations on each surface using Rockwell hardness tester (Model: RBHT, Sr. No:2011.202). 300gf of load and 10s of dwell time was maintained for the overall test. Charpy impact testing machine was used to conduct the impact energy tests by adopting the ASTM E23 standard. Samples were machined into 55 mm × 10 mm × 5 mm dimension with a 2 mm depth center-notch. A load of 25 kg was impacted on samples at the center at room temperature.

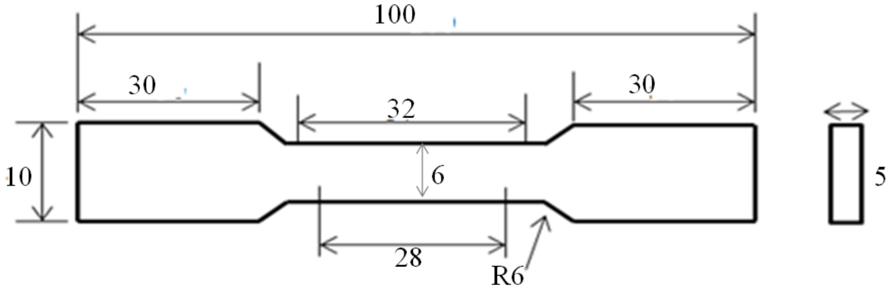

Fig. 4. Schematic of a typical tensile test specimen (dimensions are in mm)

3. Results and Discussion

3.1 Visual Observation of the Friction Stir Welded Joints

Samples of the unreinforced (US), PKSA, PWG and SSC-reinforced friction stir welded joints of aluminium alloy6061-T651 are illustrated in Figure 5. Visual examination of the entire friction stir weldments revealed that the weldments are void of surface defects like porosity and cracks, which shows that selected parameters (1120 rpm, 40 mm/min and 1.5 ^{0}) are suitable for the welding of the material.

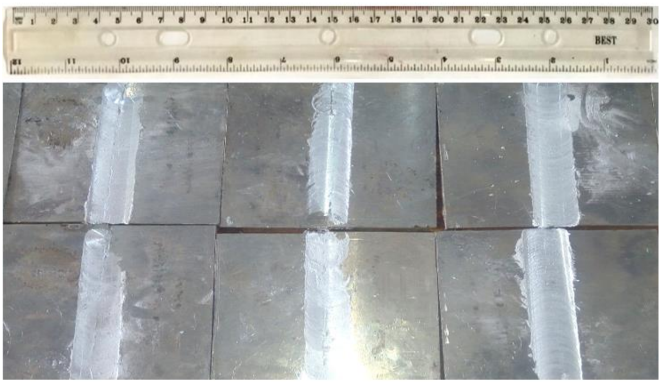

Fig. 5. Some selected reinforced and unreinforced AA6061-T651 friction stir weldments

3.2 Microstructural Examination

Results of the Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) analysis of the PKSA, PWG and SSC reinforcement used in this study are presented in Figure s 6, 7 and 8 respectively.

According to the EDS analyses of the PKSA and PWG, it is evident that the elemental compositions comprise 91% and 81.86% silica respectively while about 12.28% of silicon was present within the SSC microstructure. Silica (SiO_2), being one of the commonly used synthetic reinforcement powders used in previous studies has been established to provide enhancement to the tensile strength of friction stir weldments of aluminium alloy6061-T651 [35]. Hence, inclusion of high percentages by weight of silica within the microstructures of PKSA and PWG indicate that these supposedly agro and industrial waste can serve as potential replacements for the synthetic powders which are more relatively expensive and not readily available. The presence of these high content of silica within the aluminium matrix during friction stir welding is responsible for the restrictions of grain growth resulting from the pinning effect of the reinforcement powders thereby leading to substantial grain refinement within the stir zone (SZ) and the heat affected zone (HAZ) of the FSWed-joints of AA6061-T651 [36]. This results into improved mechanical properties and microstructure of the weldments for better and quality joint performance.

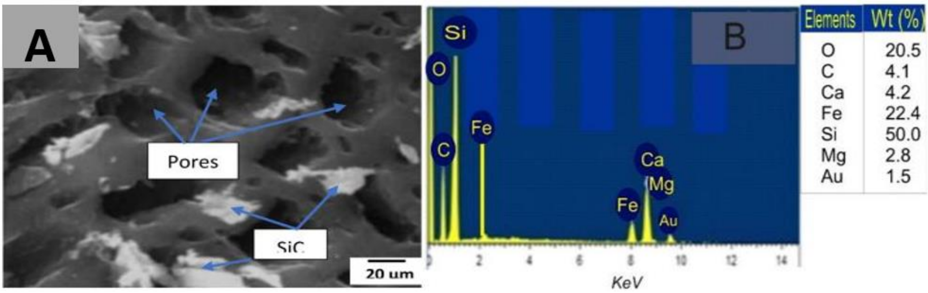

Fig. 6. (a) SEM Micrograph of PKSA (b) The EDS analysis showing the various elemental compositions

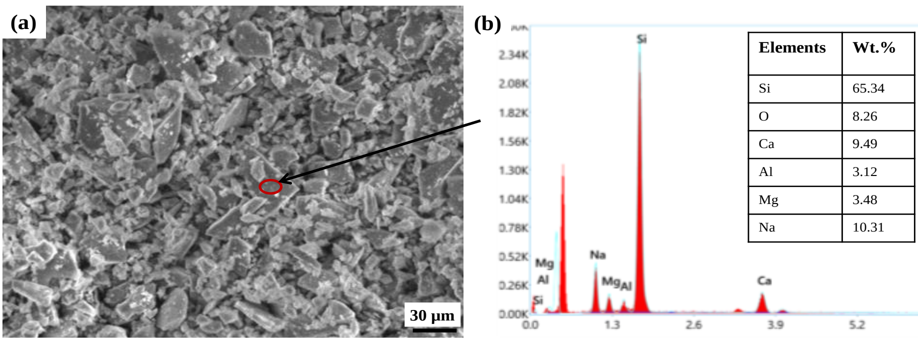

Fig. 7. (a) SEM Micrograph of the PWG (b) Elemental compositions revealed via EDS

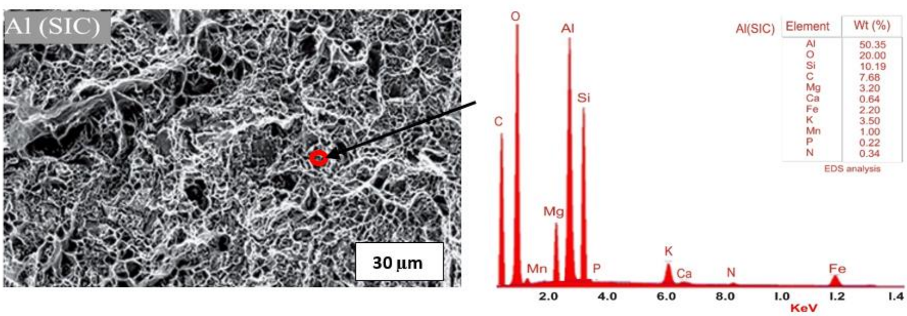

Fig. 8. SEM Micrograph of SSC and the EDS analysis showing the various elemental compositions

3.3. Enhancement of Mechanical Properties FSWed-Joint of AA6061-T651 Using PKSA Reinforcement

Table 2 shows the impact of PKSA reinforcement particles on selected mechanical properties of AA6061-T651 while Figure 9 reveals the interaction between the tensile strength, hardness and impact energy properties of PKSA-reinforced friction stir weldments of AA6061-T651 and unreinforced joint. It can be deduced from Table 2 and Figure 9 that the various reinforcement additions significantly improved the selected mechanical properties of friction stir welded joints (FSWed-joints) of AA6061-T651 as compared to the unreinforced joint. The addition of PKSA reinforcement within the aluminum matrix is adjudged to have imparted substantial grain refinement resulting from pinning effect and dynamic recrystallization mechanisms during FSW [42]. These phenomena are established to have contributed significantly to the high mechanical property value exhibited by all the reinforced joints.

Table 2. Effect of PKSA on the properties of FSWed-joint of AA6061-T651

PKSA	Tensile Strength (MPa)	Hardness (HRB)	Impact Energy (J)
Sample1	181	52.2	37.3
Sample2	148	43.4	44.1
Sample3	164	46.5	45.9
Avg. Value	164.3	47.4	42.4
Unreinforced	132.2	45.3	39.4

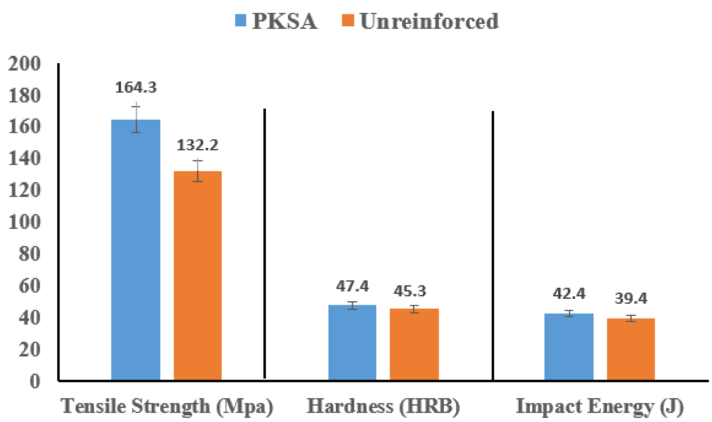

Fig. 9. Relationship between mechanical properties of PKSA-reinforced friction stir weldments of AA6061-T651 and unreinforced joint

3.4 Enhancement of Mechanical Properties FSW Ed-Joint of AA6061-T651 Using PWG Reinforcement

The influence of PWG reinforcement on the selected mechanical properties of AA6061-T651 is illustrated on Table 3 and Figure 10. The interaction between the tensile strength, hardness and impact energy properties of PWG-reinforced friction stir weldments of AA6061-T651 as clearly indicated in Figure 10 depicts significant improvements over the unreinforced joints having relatively low mechanical property values. The inclusion of reinforcement particles PWG within the aluminium matrix is established to have imparted substantial grain refinement resulting from pinning effect and dynamic recrystallization [42]. These phenomena are adjudged to have contributed to the increased mechanical property value exhibited by the reinforced joints.

Table 3. Effect of PWG on the properties of FSWed-joint of AA6061-T651

PWG Reinforcement	Tensile Strength (MPa)	Hardness (HRB)	Impact Energy (J)
Sample 1	210	69.4	55.1
Sample 2	215	75.2	54.2
Sample 3	213	72.1	54.1
Avg. Value	212.7	72.2	54.5
Unreinforced	132.2	45.3	39.4

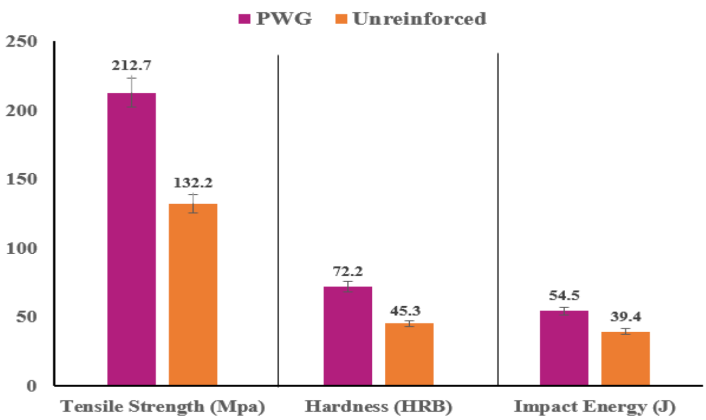

Fig. 10. Relationship between mechanical properties of PWG-reinforced friction stir weldment of AA6061-T651 and unreinforced joint.

3.5 Enhancement of Mechanical Properties FSW Ed-joint of AA6061-T651 Using SSC Powder Reinforcement

Table 4 and Figure 11 reveal the influence of SSC reinforcement on the mechanical properties of AA6061-T651 considered in this study. The interaction between the tensile strength, hardness and impact energy properties of PWG-reinforced friction stir weldments of AA6061-T651 as clearly indicated in Figure 11 shows significant improvements over the unreinforced joints having relatively low mechanical property values. The addition of SSC reinforcement within the aluminium matrix has been established to have greatly imparted substantial grain refinement which resulted from pinning effect and dynamic recrystallization exhibited by the particles [42]. These phenomena are adjudged to have contributed to the increased mechanical property values exhibited by the reinforced joints.

The interaction between the different reinforcement powders and their corresponding influence on the mechanical properties of welded joints of AA6061-T651 has presented on Figure s 9, 10 and 11 shows a similar trend or behaviour with the tensile strength having the highest values, followed by the hardness. Generally, as shown in Figure 12, significant improvement was observed on the mechanical properties of reinforced friction stir welded joints of AA6061-T651 as compared to the unreinforced joint with a relatively low values of 132 MPa tensile strength, 45.3 HRB hardness and 39.4 J impact energy.

Table 4. Effect of SSC on the properties of FSWed-joint of AA6061-T651

SSC Reinforcement Powder	Tensile Strength (MPa)	Hardness (HRB)	Impact Energy (J)
Sample 1	155	60.4	38.8
Sample 2	186	53.8	42.3
Sample 3	180	50.1	44.2
Avg. Value	173.7	54.8	41.7
Unreinforced	132.2	45.3	39.4

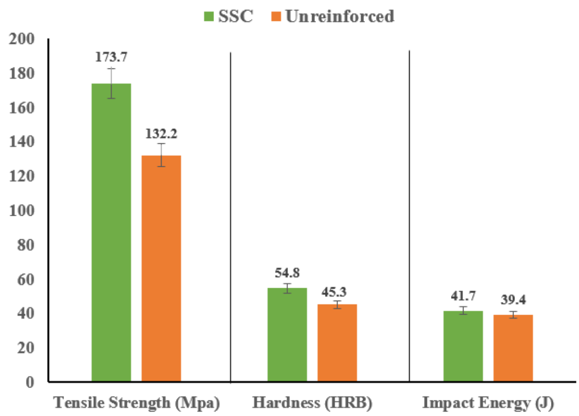

Fig.11**.** Relationship between the mechanical properties of SSC-reinforced FSWed-joints of AA6061-T651 and unreinforced sample

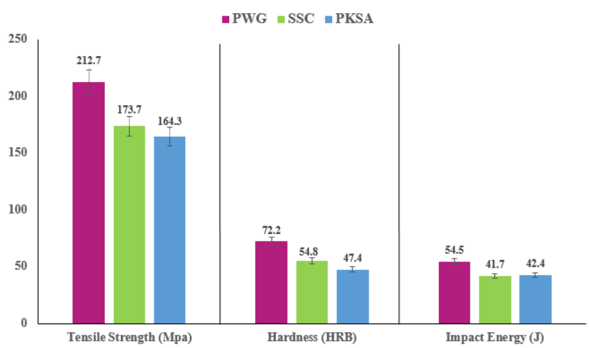

Fig. 12. Main interaction plot showing the effects of the various reinforcement powders on the mechanical properties of FSWed-joints of AA6061-T651

However, as clearly shown in Figures 10 and 12, the PWG-reinforced joint significantly improved the mechanical properties of the joint with the highest value of tensile strength

(212.7 MPa), hardness (72 HRB) and impact energy (54.5 J) as compared to other reinforcement particles, especially PKSA having a relatively higher percentage by weight of silica as shown in Figure 6 and Figure 7. Although the percentage of silica in PKSA is higher compared to that of PWG, the mechanical properties of PWG-reinforced joint are higher compared to those of PKSA-reinforced FSWed-joint. The deduction from this result could be attributed to the high inherent hardness of the ceramic-glass particles and its severe pinning effect on the grain formation that resulted into dynamic recrystallization and more substantial grain refinement within aluminium matrix at the friction stir welded joint region [37].

3.6 Tensile Strength

The tensile strength properties of all aluminium alloy6061-T651 reinforced friction stir weldments were significantly enhanced as observed in their joint efficiencies and performance when compared to the unreinforced joint as clearly presented in Figure s 9, 10, and 11 which represent the PKSA, PWG and SSC-reinforced joints respectively. However, the PWG-reinforced sample gave the optimum tensile strength of 212.7 MPa indicating sound and quality weldment of AA6061-T651 as shown in Figure 12. The deduction from this result could be the influence of the inherent high hardness of the pulverised waste glass which was uniformly dispersed and the homogenous mixture within the aluminium matrix by the rotating tool. This uniform dispersion and homogenous mixture at the stir zone largely contributed to dynamic recrystallization and the pinning effect of the particles which resulted into substantial grain refinement and the eventual improvement of the tensile strength [38]. These phenomena are also adjudged to be responsible for the optimum impact energy of 54.5 J obtained from the PWG-reinforced friction stir welded joint of AA6061-T651 in relation to other reinforced. The tensile strength values of PKSA and SSC-reinforced joints are 164.3 MPa and 173.7 MPa respectively.

3.7 Hardness

The hardness values of friction stir welded joint of PGW-reinforced AA6061-T651 and other reinforced (PKSA and SSC) are presented in Figure 12. All the reinforced joints demonstrated increased or high hardness values as compared to the unreinforced joint but the PGW- reinforced joint gave the optimum value of 72 HRB. This finding is in consonance with recent findings by Abioye *et al* [39] where the AA6061-T651 mechanical strength was enhanced using Al_2O_3, SiC, B_4C as well as Ogunsemi *et al* [40] where PWG was utilized. Results of their studies showed that the reinforced joints experienced higher hardness compared to unreinforced welded joints. The higher hardness observed in the PGW-reinforced joint over the unreinforced is traceable to the high hardness inherent in the PWG. The waste glass which has been established from previous study to comprise mainly 82% by weight SiO_2 has been reported to have an average hardness value of 580 HV [41]. Inclusion of reinforcement particles (PKSA, PWG and SSC) within the aluminum matrix is also established to have imparted substantial grain refinement resulting from pinning effect and dynamic recrystallization [42]. These phenomena are adjudged to have contributed to the high hardness value exhibited by the reinforced joints. Amongst the welded joints reinforced, the weldment produced from the addition of PWG gave the optimum value of 72 HRB. This finding can be attributed to improved homogeneity of particle distribution and mixing by the rotating tool. The pinning effect of the PWG is also adjudged to gain more prominence over other reinforcement powders thereby leading to significantly higher and better grain refinement which results into improved or increased hardness. Other reinforcement particles such as PKSA and SSC exhibited relatively higher hardness of 47.4 HRB and 54.8 HRB respectively compared to the unreinforced joint with the lowest hardness value of 39.4 HRB. The apparent absence of the phenomenal pinning effect and dynamic recrystallization caused by the particles within the unreinforced joint of AA6061-T651 friction stir welded joint confirms the relatively low hardness value and poor weld joint performance [43].

3.8 Impact Energy

The values of the impact energy of the reinforced joints of AA6061-T651 friction stir weldments are given in Figure 12. Average of three (3) measurements was used to achieve the actual value for each sample. The unreinforced joint demonstrated an impact energy of 39.4 J. The joints produced using PWG reinforcement exhibited the highest impact energy of 54.5 J followed by the PKSA-reinforced joint with impact energy of 42.4 J. The relatively higher impact energy observed in the PWG-reinforced joint is traceable to improved nucleation or retention of particle and distribution which is adjudged to have led to improved refinement of grains within the stir zone [44]. It has been established from previous works that grain refinement due to dynamic recrystallization (DR) within the processed aluminium alloy matrix is responsible for the increased impact energy. Nucleation of new grains through DR resulted into refinement of grains which contributed immensely to the increased impact energy exhibited by the weldment [45].

4. Conclusion

The utilization of amorphous or non-crystalline powders as reinforcements for friction stir welding (FSW) of aluminium alloys including AA6061-T651 is fast gaining acceptance as alternative or replacement powders in place of the synthetic ones. In previous studies, non-synthetic silica particles from rice husk ash were introduced for FSW of AA6061-T6 with significant contribution or impact on the mechanical properties. The results from the studies revealed that strong silica powder led to grain formation and growth restrictions due to pinning effect and grain refinement that resulted from dynamic recrystallization of the aluminium matrix within the stir zone (SZ). However, in this study, the enhancement of the tensile strength, hardness and impact energy of friction stir welded joints of AA6061-T651 has been experimentally achieved. Optimized processing parameters (1120 rpm rotational speed, 40 mm/min traverse speed, 1.5^o tilt angle) and optimum reinforcement strategy (parallel hole) established from a preliminary investigation were utilized for the friction stir welding. The mechanical properties such as the tensile strength, hardness and impact energy were then further investigated. The results of this work revealed that the addition of reinforcement particles (PWG, PKSA and SSC) greatly improved the friction stir welded joint properties as compared to unreinforced joints which gave relatively lower values of mechanical properties. The PWG-reinforced joints performed optimally with increased values of 212.7 MPa, 72 HRB and 54.5 J for the tensile strength, hardness and impact energy respectively. Hence, 80%, 59% and 38% joint performance was exhibited through tensile strength, hardness and impact energy of PWG-reinforced friction stir weldments of AA6061-T651 against the unreinforced weldments. Therefore, it is adjudged that this joint performance is traceable to reduced particle sputtering by the rotational tool during friction stir welding and improved grain refinement which is traceable to DR as a result of the pining effect of the uniformly dispersed particles within the aluminium matrix during welding.

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