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Review On Friction Stir Processed TIG And Friction Stir Welded Dissimilar Alloy Joints

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Abstract

There is an increase towards reducing the weight of structures through the use of aluminium alloys in different industries like aerospace, automotive, etc. This growing interest would lead towards using dissimilar aluminium alloys which would require welding. TIG and friction stir welding are the well-known techniques that are currently suitable for joining dissimilar aluminium alloys. The welding of dissimilar alloys has its own dynamics which impact on the quality of the weld. This then suggests that there should be a process which can be used to improve the dissimilar alloys welds post their production. Friction stir processing is viewed as one of the techniques that could be used to improve the mechanical properties of the material. This paper reports on the status and the advancement of FSW, TIG and FSP technique. It further looks at the variation use of FSP on TIG and FSW welded joints with the purpose of identifying the knowledge gap.

KeyWords: *Tensile analysis; Microhardness; Friction stir welding; TIG welding; Friction stir processing; Aluminium alloys; Microstructure.*

1 Introduction

Aluminium alloys are known to be good candidates for different applications in various fields like aerospace, food packaging, automotive industries, etc. Their good candidacy comes from the fact that these metals are light in weight, have good mechanical properties, good corrosion resistance, etc. Various aluminium alloys possess different mechanical and thermal properties and these differences are influenced by the alloying elements used in producing each alloy [1, 2]. Most industries are opting towards using dissimilar alloys in producing various components. This option is meant to reduce the costs that are involved in using similar alloys [3]. In as much as this approach is a cost saving measure, however, there are also challenges associated with it. This includes the welding technique suitable at welding dissimilar alloys. The mostly used welding techniques involves tungsten inert gas (TIG) welding and friction stir welding (FSW). The TIG welding technique has been dominating in joining similar and dissimilar aluminium alloys until the birth of FSW.

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There have been some challenges that were involved in joining dissimilar alloys through TIG technique. Those challenges include porosity, solidification cracking, thermal residual stresses, etc. These challenges have led to the discovering of the post processing technique called friction stir processing. Friction stir processing (FSP) is a technique used to modify the microstructure of a metal through the use of non-consumable rotating tool. FSP originated from friction stir welding which was initially established by The Welding Institute. FSP uses the same principle as FSW but does not join metals rather modifies the local microstructure in the near-surface layer of metals [4].
FSP works by plunging a specific cylindrical non-consumable tool into the plate and kept stationary for a few seconds. This is done so as to allow the stabilization in an input temperature required for processing. The rotating tool gets released so that it travels along the surface of the metal being processed. The tool travels from the start to the end of the plates resulting in the attainment of the processing. When the processing is finished, the tool is then unplunged, leaving a small hole or rather travels to an offset distance to avoid leaving a hole. The side in which the tangential velocity of the tool surface is parallel to the traverse direction is called the advancing side, and the non-parallel side is called the retreating side [5-6].

This paper is aiming at reviewing the works that deals with the processing of similar and dissimilar joints produced by the TIG and FSW welding techniques.

2.1 Friction Stir Welding of Similar/Dissimilar Alloys/Metals

The recent studies have revealed that the material positioning during FSW of dissimilar plays an important role towards the strength of the weld. The good weld is produced when the hardest material is positioned on the advancing side while keeping the softer one on the retreating side during welding [7,8]. In an attempt towards analysing the impact of material positioning during FSW dissimilar alloys, various studies have been performed in this regard. Dilip et al. [9] have performed the FSW of AA2219-T87 and AA5083-321 with the aim of performing the microstructural analysis of the joint. The weaker material (AA2219-T87) was positioned on the advancing side while the stronger material (AA5083-H321) was kept on the retreating side. The microstructural analysis revealed that the joint and the retreating side were dominated by the material which was placed on the advancing side (AA2219-T87). The microhardness value corresponding to the weaker material was observed on the retreating side where most tensile failure occurred.

Friction stir welding of the 3mm thick AZ31B magnesium alloy and AA5052-H32 aluminium alloys was performed by Taiki et al. [10]. The aluminium plate was positioned on the advancing side and Mg plate on the retreating side during welding. There was a variation in welding speed and tool speed.

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The microstructure analysis revealed that the joint was dominated by the AA5052-H32. It was also noted from the microstructural analysis that the dominating AA5052 had refined grains compared to parent material although the hardness value dropped compared to AA5052 base metal. Hardness distributions of the cross-section revealed that the intermetallic compounds (IMCs) partly existed in stir zone (SZ). All the samples failed at the center of the joint during tensile tests analysis. This failure location showed that the joint was dominated by the material that was positioned on the advancing side during welding.

Cavaliere & Panella, [11] conducted a study on the effect of tool position on fatigue properties of dissimilar 4mm thick AA2024 and AA7075 plates joined by FSW. The AA2024 was positioned on the advancing side while AA7075 situated on the retreating side. The joint attained when the tool was positioned 1mm off the center (towards AA7075) had higher hardness value compared to the joint attained when tool was 1.5 mm off the center of the weld. The maximum tensile properties of both joints were lower than the parent materials. Both joints revealed ductile failure mode characterized by the presence of very fine dimples. The strong effect on fatigue crack growth was attributed to the positive Kr value measured on the cross-section of the different welds.

Peng et al., [12] have performed friction stir welded on the 5mm AA5A06-H112 and 6061-T651 aluminium alloys. This welding was performed under controlled cooling conditions i.e. forced air cooling (FAC) and natural cooling (NC) conditions. The AA5A06-H112 was positioned on the advancing side while AA6061-T651 on the retreating side. The 0.5MPa pressure was used to blow the air towards the welding direction which then intersected the surface of materials at angle of 30°. The microstructural analysis and microhardness test results for the joint produced under FAC were found to be higher compared to those that of the joint produced under NC condition. The tensile results for the joint produced under FAC condition were 10% higher than those produced at NC condition. The joint produced under NC condition had coarser grains compared to the joint produced under FAC condition. Both joints had ductile failure mode but the dimple size for the joint produced under FAC were higher than the joint produced under NC condition.

In as much as the material positioning plays a significant role towards the joint quality involving dissimilar alloys, Shah et al. [13] have further investigated the influence of the tool eccentricity towards the joint quality. They discovered that placing the stronger material on the advancing side improves the tensile strength and the percentage elongation of the joint. Their metallurgical analysis revealed that the tool eccentricity also plays a vital role towards the material flow however, there are some limitations when it comes to material mixing. The analysis of the joint formed when two dissimilar alloys are used in friction stir welding normally focuses on the mechanical properties. However, Giraud et al. [14] have gone to the extent of analysing the compounds that are being formed during the FSW of dissimilar alloys. They have discovered that there are intermetallic compounds (IMCs) that are formed during FSW of dissimilar alloys. These IMCs have a brittle nature which could lead to a greater mechanical weakness.

Khodir and Shibayanagi [15] have assessed the joint formed when AA2024-T3 was friction stir welded with AZ31 magnesium alloy. Their study involved the variation of welding speed at a constant rotational speed. The AA2024-T3 was located on the advancing side for all the welding. The microstructural analysis revealed that the increase in welding speed impacted the phase redistribution in the stir zone. The AA2024-T3 was distributed towards the lower regions of the stir zone while the AZ31 dominated the upper regions below the tool shoulder of the stir zone. The microstructural analysis also revealed a consistent formation of laminates structures in the SZ near the advancing side boundary between SZ and TMAZ which were independent from welding speed variation. There were also intermetallic compounds that were formed in the SZ which contributed towards the fluctuation of the hardness distribution.

Rodriguez et al. [16] have friction stir welded AA6061-T6 and AA7050-T7451 with the purpose of assessing the microstructure and mechanical properties of the dissimilar welded joint. Their study involved the variation of rotational speed while keeping the welding speed constant. The AA7050-T7451 was positioned on the advancing side while AA6061–T6 was kept on the retreating side during welding. The tensile analysis revealed that the joints produced at lower speed were weaker than the base metals hence the fracture occurred at the SZ. The joints that were produced at higher rotational speed were stronger than AA6061-T6 base metal hence the fracture occurred consistently towards the AA6061-T6. The variation in fracture location was found to be directly linked with the material mixing at the SZ. The microstructural analysis revealed the ductile mode of failure. Moreover, the EDS results reveal the existence of three distinct layers where layer 1 had a nominal composition of AA6061, layer 2 had a composition of AA7050 and layer 3 had the combination of the two. Similar results were reported by Gou et al., [17] when they performed FSW on dissimilar AA6061-AA7075.

Mofid et al., [18] performed a study on the friction stir welding of the 3mm thick AZ31C-O magnesium alloy to 5083 aluminium alloy in air and under nitrogen liquid. Their study involved the tracking of the temperature profile during welding and they attained this through the installation of thermocouples. There was a notable decrease in IMCs formation for the joints produced under liquid nitrogen compared to joints produced through air. The XRD analysis results exhibited the intermetallic phases of Al_3Mg_2, $Al_{12}Mg_{17}$ and Al_2Mg_3. The stir zone of the welds produced under nitrogen atmosphere showed a smoother interface compared to welds produced through air atmosphere. The attained maximum temperature during the welding was 676K and 651K respectively during air weld and under water weld.

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FSW dissimilar aluminium alloys 2024-T365 and 5083-H111 was performed by El-Hafez and El-Megharbel [19]. Variation in process parameters and pin profiles were employed with the purpose of analysing their influence to the microstructure and tensile properties. The stronger material (AA2024-T365) was positioned on the advancing side throughout the welding. The combination of the highest speeds of 1120rpm and 1400rpm with 80mm/min achieved the best strength and joint efficiency of 90% and this was due to sufficient heat being generated. Square pin profile produced higher strength joints compared to triangular and stepped profiles. Placing AA2024 on the advancing side (AS) played a significant role towards joint strength improvement. Cole et al., [20] also reported that the material placed on the advancing side dominates a major portion of the weld zone.

Vivekanandan et al. [21] have used vertical milling machine to friction stir welding of aluminium alloys 6035 and 8011 with the aim of evaluating the mechanical properties of the dissimilar weld joint. The varying welding speed at a constant rotational speed was employed throughout the welding. The welds produced at the welding speed of 60mm/min were found to be the best results compared to other speed combinations. This parameter combination produced fine grains at the center of the weld which contributed to the increase in hardness value. The dissimilar friction stir welding of undiluted copper and 1350 aluminium alloy sheet with a thickness of 3mm was investigated by Li et al. [22]. The AA1350 was placed on the advancing side throughout the welding performance. The microstructural results in the nugget zone showed the vortex-like pattern and lamella structure. There was no formation of IMCs in the nugget zone. The hardness dispersion revealed that the hardness on the copper side was higher than that on the AA1350 side and the hardness at the bottom of the nugget was generally higher than those previously mentioned. The tensile properties of the dissimilar welds were all lower than those of the base metals. A ductile-brittle mixed fracture surface was observed on the dissimilar joints of the tensile tested specimens.

The 6mm thick sheets of aluminium alloys 6061 and 5086 were friction stir welded together to analyse the evolution of microstructure in the stir zone and its influence on tensile properties of the joints [23]. The welding parameters used were the rotational speed of 500rpm, traverse speed of 35mm/min and the axial force of 4.9kN. The tensile properties of the joints correlated with microstructural features and microhardness values. The dissimilar joint exhibited a maximum hardness of 115HV and a joint efficiency of 56% which was higher than the hardness of the base metals. This was attributed to the defect-free stir zone formation and grain size strengthening.

2.2 TIG Welding of Similar/Dissimilar Alloys/Metals

One of the most critical factor to consider for TIG welding is the filler metal, which mainly depends on the alloys to be welded. Ishak et al., [24] investigated the welding of dissimilar aluminium alloys 6061

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and 7075 using different filler metals namely ER4043 (Si-reach) and ER5356 (Mg–reach). The depth analysis revealed ER5356 penetrated deeper compared to the ER4043 and the depth of penetration plays an important role towards the strength of the weld or joint. The microstructural analysis revealed the existence of fusion zones that are normally identified on dissimilar TIG joints. The grain size at fusion zone (FZ) for filler ER5356 specimens was finer than that of filler ER4043. Average hardness values for filler ER5356 specimens were higher compared to filler ER4043 ones. TIG welding using the ER5356 filler yielded better joint compared to ER4043.

Borrisutthekul et al. [25] have evaluated the feasibility of using TIG welding technique in joining the dissimilar materials i.e. steel plate and aluminium alloy plate. The microstructural analysis reveal that there was an existence of FZ and HAZ which are the characteristics of the TIG welding. All the specimens were fractured on the same location during the tensile analysis i.e. HAZ of aluminium alloy side. This type of behaviour was due to the growth of grain sizes that was observed through microstructural analysis. The existence of intermetallic reaction layers was also observed during the microstructural analysis.

Most studies that are studying different aspects of welding seem to be dominated by mostly two dissimilar aluminium alloys i.e. 5083 and 6061 [26 -31]. Waleed and Subbaiah [26] have evaluated the effect of using ER4047 filler rod in welding aluminium alloys 5083-H111 and 6061-T6. Similar analysis was also performed by other researchers with the focus on different aspects and different welding parameters on different grade of 5083 [27 - 31]. Waleed and Subbaiah focused on analysing the mechanical behaviour of the joint formed through the use of ER4047 filler rod. The tensile strength of the joint was lower than that of the base metals. The hardness value of the joint was varying in each side of the joint. This variation was caused by the formation of the magnesium-silicon (Mg2Si) precipitates on the AA6061 side. The microstructural analysis showed the elongation of grains towards the rolling direction. There was also an existence of cavities and micro-pores at the intersection point of the weld. There was a notable decrease in ductility and this decrease was caused by the presence of columnar grain.

Narayanan et al., [32] have evaluated the impact of TIG welding parameters variation on the aluminium alloy 5083 joints. The welding current and the shielding gas flow rate were the two parameters that were being varied for the duration of the study. The tensile results and the hardness value for the joint was lower than that of the commercial base metal. The microstructural analysis showed that the grains in the HAZ region were coarser compared to the base metal hence the brittle failure. The welding quality improvement of AA6031 plates using an automated TIG welding system was performed by Mohan, [33]. The mechanical analysis showed that the joint performance was found to be way lower than that of the base metal. There was an inverse proportionality that was observed

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between the welding speed and the tensile strength of the joint. There was also a variation of hardness value across the weld.

Automated pulse TIG welding using 5083 and 6061 dissimilar aluminium alloy was conducted by Baghel & Nagesh, [34]. The main purpose was to evaluate the mechanical behaviour of the joint formed through this technique. The radiographical analysis revealed the presence of porosities which were caused by the lack of proper penetration. The tensile results for the joint were lower than the base metal. There was a variation of hardness value which was caused by non-uniformity of the grain sizes across the weld. The surface fracture exhibited the ductile failure mode. The impact of the welding speed variation towards the quality of the AA5083 TIG welded joints was analysed by KumarSingh et al., [35]. All the other parameters were kept constant but only the welding speed that was varying. The tensile results showed a linear relationship with the welding speed until 100 mm/min. The notable decrease in tensile results was observed at the welding speed beyond 100 mm/min. The microstructure of the weld pool showed a refined grain size in comparison to the base metal.

TIG welding of dissimilar aluminium alloys 2014 and 5083 was investigated by Sayer et al., [36]. One-sided TIG welding was applied with two passes. The microstructural analysis results in the weld region showed nonhomogeneous less equiaxed grain distribution with bigger diameters when compared to AA2014 and AA5083-O base metals. The grain size increase was said to be due to severe heat input. The tensile test results were lower than those of base metal. The tensile test specimens fractured in the welded region revealing brittle mode of failure. There was a variation in hardness across the weld with a sharp decrease at the center. This sharp decrease at the center was reported to be caused by the high Si content in the filler material which dominated the center of the weld. Singh et al., [37] reported the mechanical properties of TIG welding at different parameters with and without the use of flux. The welding parameters used were all varied with the purpose of determining the optimal welding parameter combination. The variation of current effected the decrease in hardness value of the joint. The hardness values for joint formed with flux were higher compared to those formed without flux. AA7075-T651 and AA6061-T6 were TIG welded with the aim to investigate the hardness of the centre weld joint of the dissimilar aluminium alloys [38]. The Al-Si alloy filler wire type was used in performing all the welding. The maximum hardness value for the joint was found to be lower than that of the base metals. There were voids that were observed through microstructural analysis.

2.3 Friction Stir Processing of Similar/Dissimilar Alloys/Metals

Friction stir processing is a fairly new material processing technique. This then suggests that there are many works that are still in progress focusing in different aspects of this new technique. This involves the processing of plates and welded joints. The evaluation of the mechanical properties of

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the friction stir processed dissimilar AA2024 and AA6061 welded joint was performed by Hameed et al. [39]. The friction stir processed joints used were formed through the use of FSW technique. The authors did the mechanical analysis of the processed joint in comparison with the unprocessed joints. The parameters used in performing the processing were similar to those used to perform FSW. The tensile properties of the processed joint were higher than the unprocessed joint. The hardness value for the processed joint was higher than the unprocessed joint. The microstructural analysis for processed joint reveal finer grain sizes compared to the unprocessed one.

Karthikeyan and Kumar, [40] studied the relationship between process parameters and mechanical properties of a single pass friction stir processed 6063-T6 aluminium alloy plate. Processing was performed at different axial forces, traverse speeds and tool rotational speeds. The tensile results revealed a linear relationship with the axial force than any other parameter used. The improvement in ductility was found to be linearly depending on the axial force than on the other parameters. The application of the FSP on 6mm AA6056-T4 plates was performed by Hannard et al. [41] with the purpose of improving the ductility of the said material. It is well known that the ductility of each material plays a very crucial role towards the formability of the material and the chosen material is mostly used in forming different components and structures. Hannard et al. discovered that the ductility of the plate increased with the increase in number of processing pulses. The existence of pores from the base metal was suppressed completely by the increase in multi-pass FSP. The multi-pass FSP was found to be the method in breaking the intermetallic particles and to redistribute them homogenously. Hannard et al. work have proven that the proper processing of the material occurs when the multi-pass FSP is used.

Mazaheri et al., [42] have shown the capabilities of FSP in producing surface composites. This capability was tested when they used the FSP technique to produce the A356/A_2O_3 surface composites. The microstructural analysis results of the A356/A_2O_3 indicated that A_2O_3 particles were well distributed in the aluminium matrix, and good bonding was also observed. The nanoindentation technique revealed that the microhardness for A356/A_2O_3 and A356–nA_2O_3 surface composites is higher than the samples processed without A_2O_3 particles and the as –received A356 material. A similar study was performed by Kalashnikova and Chumaevskii [43] where they used the FSP technique to develop surface composite between TiC and AA6082. The microhardness of the composite was found to be higher compared to the AA6082 metal. The tensile properties of the composite were found to be matching those of AA6082.

The effect of FSP on AA2024-T3 was studied by Hashim et al. [44]. The performance of the FSP was based on the pin-less cylindrical shoulder. The hardness results revealed that the application of FSP increased the hardness of the processed sample compared to the base material. There was also a notable increase in tensile properties of the processed sample compared to the base metal. The

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microstructural grain size was also refined compared to the base metal and this was found to be in correlation with tensile results.

The impact of FSP technique on the mechanical properties of cast Al-Si base alloy was analysed by Tsai and Kao [45]. The tensile properties of cast AC8A alloy were improved after FSP, particularly the tensile elongation, which increased from < 1% to 15.4%. FSP resulted in improvement of the tensile strength as the result of a combination of dissolution, coarsening and strengthening precipitates, which were attained by the FSP parameters. Jana et al., [46] investigated the FSP effect on fatigue behaviour of the cast Al–7Si–0.6 Mg alloy. The results showed five times improvement in fatigue life for a hypoeutectic Al–Si–Mg cast alloy. FSP eliminated the porosities and refined the Si particles resulting in a decrease of the crack growth rate. In addition, FSP resulted in both break-ups of the dendritic microstructure and complex material mixing.

Kurt et al., [47] performed FSP on the aluminium alloy 1050 to improve respective mechanical properties. Samples were subjected to the various tool rotating and traverse rates with and without SiC powders. The optimum processing parameters that were found to give better results were the rotational speed of 1000rpm and traverse speed of 20mm/min. The results revealed that FSP reduced the AA1050 grain size which subsequently increased its hardness. A good dispersion of SiC was obtained and a good formation of composite layer. The hardness of the formed composite surfaces was improved significantly compared to that of base metal. Bending strength of the produced metal matrix composite was significantly higher than that of the processed specimen and untreated base metal.

The impact of using various Cr-Mo steel tool profiles in performing the FSP on AA2014 was studied by John et al. [48]. The hexagonal profile was found to be the best profile in producing good mechanical properties of the processed sample. The highest value for the hardness was also achieved through the hexagonal pin profile. The hexagonal pin profile was found to be suitable in producing highly refined grains compared to other profiles tested in the study. The influence of FSP on the microstructure and mechanical properties in terms of hardness for AA6061 sheet was investigated by Prakash and Sasikumar [49]. The cylindrical shaped high steel tool was employed in performing the multi-pass FSP. The microstructural evaluation reveal that the grain size of the processed specimens was 70% smaller than the base metal. There was also a linear relationship between the hardness value and the number of pulses used. The tensile properties were found to be linearly depending on the number of pulses used during FSP.

Sinhmar et al. [50] have analysed comparatively the mechanical properties of the processed and unprocessed AA7039. The modified surfaces were characterized in respect to macrostructure, microstructure, hardness and tensile properties. The results showed an increase in ductility from

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about 13.5% to 23.6% while the ultimate and yield strength were adversely affected. The results showed higher ductility on the longitudinal direction than in traverse direction. The multi-pass friction stir processing produced higher hardness than the single pass one. Santella et al. [51] showed that FSP created a uniform distribution of broken second-phase particles of A319 and A356 and eliminated the coarse and heterogeneous structure of the alloys. The study was performed to assess the mechanical properties and reported that the tensile and fatigue behaviour of the material were improved with friction stir technique. The TEM observations revealed the generation of a fine-grained structure of 5 to 8µ for FSP A356. Furthermore, TEM examinations revealed that the coarse Mg_2Si precipitates in the as-cast A356 sample disappeared after FSP, indicating the dissolution of most of the Mg_2Si precipitates during FSP.

Wrought aluminium alloy 5059 was friction stir processed by Izadi et al. [52] with the purpose of finding the best tool profile suitable for such class of aluminium alloy. Amongst the profile tested, the 3-flat threaded pin profile outshine the profile in all aspects. The microstructural analysis reveal that the average grain sizes was about 1.24um and this size was far less than the grains of the base metal. This grain size contributed towards the improvement of the microhardness. The yield strength and the ultimate tensile stress were also found to be higher than the base metal. The percentage elongation was also found to be higher than 25%. Ni et al. [53] have used FSP to modify the surface of cast Mg-9Al-1Zn alloy. The processed specimens were found to be defect free with fine-grain microstructure dominated by fine β-Mg17Al12 particles. The fatigue properties of the processed specimens were found to be higher than the base metal. The employment of FSP resulted to the transformation of quasi-cleavage fracture to dimple fracture. It was also found that the employment of FSP brought about the suppression of porosities and coarse β particles.

Sakurada et al. [54] were the first to perform a study on underwater FSW on AA6061. Their results showed that it was possible to generate enough friction for processing even though the workpieces were underwater. The stirred region of the underwater weld joint showed a finer microstructure in comparison to the one exposed to room temperature air conditions. The hardness of the underwater specimens was found to be relatively higher than those of the room temperature based specimens. Hofmann & Vecchio [55] studied the effect of submerging FSP on the grain size of AA6061-T6 compared to in air FSP. Their results showed that more grain refinement was attained under submerged conditions due to a faster cooling rate. They also demonstrated the feasibility of predicting the grain size of the processed specimens through the use of boundary migration model.

Zhang et al. [56] performed the joint analysis produced through the processing that was performed under water. They used variation in rotational speed in assessing the joint quality. They discovered that the fracture of the underwater joints was mostly dependent on the tool rotational speed. Their tensile analysis results showed a linear relationship with the rotational speed. Darras & Kishta [57]

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investigated the friction stir processing of AZ31 magnesium alloy in normal and submerged conditions. There were three condition used in performing the analysis of the joints i.e. air, hot underwater and cold underwater. The grain size for the cold underwater specimens was relatively smaller than the specimens produced at different conditions. The thermal results revealed that the highest peak temperature for weld was in air-based processing compared to the other conditions. The longest processing duration was found when the processing was performed on air. Sabari et al. [58] have performed similar study on different material and processing parameters. They reported that the higher temperature gradient (along transverse and longitudinal weld axes) and higher cooling rate in underwater friction stir welds were a result of uniform heat absorption capacity of water when compared to the air-cooled welds.

El-Danaf et al. [59] have used commercial AA5083 rolled plates in analysing the impact of FSP towards the ductility and the grain size of the processed specimens. The microstructure analysis showed a fine grain and an average disorientation angle of about 24º. Ductility was enhanced with a facor ranging between 2.6 and 5 when compared to the base metal. The strain rate sensitivity of the processed material was 0.33 while for the base metal was 0.018. Akinlabi et al., [60] investigated the effect of the tool rotational and traverse speeds as well as the number of passes on tribological characteristics of the modified surfaces. The FSPed samples exhibited lower wear rates than the as-cast A390 hypereutectic Al–Si alloy. The wear rates were found to be decreasing by reducing the tool rotational speed while increasing the tool traverse speed. There was a notable inverse correlation between the wear rate and the number of FSP passes.

Toma et al., [61] investigated the effect of FSP tool cutting depth on the mechanical properties of AA6061-T6. The cylindrical tool without the pin was employed in performing this analysis. The hardness was found to be increasing with the increase in cutting depth. The engineering flaws granules became smaller and the size of these granules increased with cutting depth. The tensile properties of the processed specimens were found to be improving with the increase in cutting depth. Abrahams et al. [62] investigated the properties and microstructure of friction stir processed 7075-T651 aluminium alloy using various tool designs. Trials were conducted on AA5005-H34 with the aim of determining the most suitable FSP tool design out of all the considered pin profiles. Fully recrystallized fine microstructure and a defect free processed zone were achieved through the use of some of the FSP pin profiles. The grain sizes were reduced from the initial 192µm pancake-like microstructure for AA5005-H34 base material to the range between 10 and 20µm in the processed regions. The similar behaviour was also observed on the case of AA7075-T651. The traverse speed had a greater influence on the microhardness and mechanical properties compared to the tool rotational speed. It was also discovered the traverse speed suppressed the precipitates free zones which have negative impact towards the mechanical properties of the material.

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Effect of the processing parameters of friction stir processing on the microstructure and mechanical properties of 6063 aluminium alloy was performed by Zhao et al. [63]. Post FSP produced fine equiaxed α-Al grains formed in the weld nugget of 6063 Al alloy. The size of those α-Al grains was increasing with the increase in rotational speed. Tunnel defects were observed in the TMAZ region for a low tool rotation speed. When the rotational speed exceeded 700rpm, a good combination interface was formed between the WN and the TMAZ. Electron backscatter diffraction results showed that the fraction of the high-angle grain boundary was increased after FSP in the WN. The TEM analysis results showed that the densities of needle-shaped precipitates were reduced in the WN. There was an observed linear relationship between the UTS and the tool rotational speed.

Rouzebehani et al. [64] have used AA7075 plate to perform FSP underwater and room temperature with the purpose of analysing the metallurgical and mechanical properties. The variable process parameters were used. The temperature during FSP was monitored and recorded using the K-type thermocouple placed underneath the plate close to the abutting line of the workpiece. The average grain and precipitate sizes of the weld nugget zones were significantly reduced by the submerged conditions. The best metallurgical and mechanical properties were achieved when the processing was performed under water. There are numerous attempts that are being reported where the FSP technique is being utilized to produce surface composite. These attempts look into different alloys of aluminium and different dopants. Singh et al. [65] have produced surface composite through the use of FSP technique. The approach used by Singh et al. was to deposit SiC particles inside the holes drilled on the surface of AA6063 plate. The microhardness of the fabricated composite was relatively high compared to the one for the base metal. It was discovered that the increase in microhardness was due to the pining effect of hard SiC particles. The good bonding between the SiC particles and AA6063 results to the improvement of tensile strength of the composite when compared with base metal.

The microstructural modification of AA206 through the use of FSP was also reported by Sun et al. [66]. This modification was performed so as to comparatively evaluate the mechanical properties of processed and unprocessed AA206 material. A 6.26mm and 16mm thick plates were used for tensile and fatigue test respectively. The two key processing parameters were tool rotation speed and tool traverse speed. The results showed an increase in both yield strength and UTS after FSP when compared to those of the base metal. There was a notable improvement in yield strength and UTS on the processed plates compared to the base material. The percentage of elongation and fatigue strength also increased compared to the unprocessed ones.

Thakral et al., [67] used FSP to enhance the tensile properties and hardness of the TIG welded AA6061-T6 joint. Tensile results showed that the average UTS value for the base metal was 299MPa, 85MPa for the TIG weld joint and 125MPa for FSP TIG joint. An increase of 48% was reported on the

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UTS on the TIG welded joint. The hardness values of FSP TIG specimen ranged from 72-74HV which was almost similar to that of base metal which was 74HV whereas in TIG specimen hardness value ranged from 66-68HV. Microstructural analysis was performed on the weld zone to evaluate the effect of welding parameters on welding quality and grain structure. The microstructure of FSP TIG joint showed very fine equiaxed recrystallized grains compared to the microstructure of TIG joint.

The effect of a single pass FSP on the mechanical properties and microstructure of the commercially pure aluminium was investigated by Yadav and Bauri [68]. The grain size of the FSPed specimens were way smaller than those of the base metal. The TEM results showed fine grains with well-defined boundaries. The tensile results showed UTS increase of about 25% while the ductility decreased by about 10%. The impurity particles observed in TEM resulted in the yield strength decrease. The hardness also improved substantially compared to the base metal.

Feng et al., [69] investigated the effect of SFSP on the microstructure of the AA2219 sheet. The grain size on the stir zone was less than that of the base metal. The area fraction of the ultra-fine grains in the stir zone increased as heat input decreased. The results showed a decrease in microhardness of the SFSP stir zone compared to that of the unprocessed BM. The processed zone exhibited microhardness that was higher than that of the base metal. The 6mm thick aluminium alloy 6082 was subjected to underwater FSP to test the changes in the UTS [70]. The High Carbon High Chromium Steel rod of diameter 20mm material was used as the processing tool for this investigation. The result revealed that the maximum tensile strength of the underwater joints was higher than that of the normal air. The effect of SFSP on the mechanical and microstructural properties of 10mm thick AA7075 was investigated by Nourbakhsk and Atrian [71]. A thermocouple was used to record the temperature of water during the processing. The single pass FSP was used in carrying out the analysis. The results obtained from the submerged processing were similar to those obtained by other researchers [56-57,64].

2.4 Mostly Processed Welded Structures

Based on the literature cited the most friction stir processing is performed to enhance the properties of the base metal rather than welded joints. Few literatures [39, 52] reports on post processing the friction stir welded joints, while only [68] reports on using FSP as a post processing of the TIG welded joints. No other searchable literature obtained on post processing for both FSW and TIG welded joints. This then suggest that there are more opportunities of exploring the impact of employing FSP technique on TIG welded structures.

2.5 Mostly Processed Grades

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The most processed aluminium alloy series based on the presented literature was 6xxx (6061, 6082, 6063, 60560), with 6061 taking a lead. Following the 6xxx was the 7xxx (7075, 7039), 2xxx (2024, 2219, 2014) and the 5xxx (5005, 5083, 5059).

3 Conclusions

In all the work that has been performed thus far, it has been noted that all the focus has been on FSP as an enhancement technique on aluminium alloys, magnesium and other alloys. It is also noticed that the common mechanical properties analysed include the tensile test, fatigue and microhardness. These properties are studied correlatively with the microstructure. Very few works thus far, which considers FSP as a post weld processing technique for TIG dissimilar alloy welded joint. There is minimal to no trace of any literature on submerged friction stir processing of TIG and FSW welded dissimilar alloy joints. This therefore opens an opportunity for the exploration on the impact of FSP and SFSP towards the properties of the FSW and TIG welded dissimilar joints.

Supplementary Materials

There is no supplementary material for this manuscript.

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Author Contributions

Both authors have fully contributed equally to all the work produced.

Conflict of Interest

The authors would declare no conflict of interest. The authors declare there is no funding involved in this study.

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