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Post-weld friction stir processing of AA5083-FTIG welds with scandium added fillers

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Abstract

TIG welded marine grade AA5083-F/ER5356 and AA5083-F/ER5356+Sc joints were friction stir processed with a pin less FSP tool, to explore the impact of the process parameters on the mechanical and metallurgical characteristics of the weldments and enhance the weld strength. The microstructure of the welds was observed using optical and SEM and subjected to mechanical tests like impact toughness, tensile, microhardness and fractography, to evaluate the strength of the weld. A microstructural improvement was observed in the FSPed weld joints, with an average grain size of 4 μm for TIG welds and 2 μm for Sc added TIG welds, in comparison to the TIG-welded joints, which showed an average grain size of 12 μm and 8 μm when Sc was added. The ultimate tensile strength (UTS) of the FSPed joints were higher than the tensile strength of the base metal, with values of 288 MPa for the FSPed joints and 331 MPa for the Sc added FSPed joints. The FSPed joint’s elongation range decreased to 7.1% but showed a marked improvement for the Sc added FSPed joints, up to 20.5%. There was a marked improvement in the maximum hardness compared to TIG welded joints, with the FSPed TIG-welded joints giving a value of 90 HV1, while the maximum hardness of Sc added FSP joints showing 95 HV1. The study revealed that FSPed and Sc added joints improved the mechanical and microstructural properties of the TIG welded joints significantly.

1. Introduction

The non-heat treatable Al-Mg alloy 5083, possesses good weldability, formability, anti-corrosive property and high specific strength [1–3] and therefore makes it an excellent material for ships, vehicles, pressure vessels and other structural applications [4]. In general, fusion welding approaches like Metal Inert Gas (MIG) and Tungsten Inert Gas (TIG) have been the choice for joining aluminium plates and have been reported to be cost-effective and the most suitable welding procedure for joining AA5083 plates [2, 4, 5]. TIG welding produces weldments that are stronger, more ductile, and more reliable than MIG welding [6, 7]. As a form of arc welding, TIG welding, involves the application of heat produced by an arc struck among a non-sacrificial tungsten electrode and a material with the aid of a shielding gas [8]. Also, TIG welding processes are likely to result in the formation of coarse-grain structures and defects such as porosity, entrapment of impurities, microstructural cracks etc., [9, 10]. The high weld temperature cycle that metal goes through during welding is the primary cause of mechanical properties and microstructural variation [11, 12]. To overcome such an undesirable phenomenon and to refine the grain size, reinforcing master alloys like Br, Ti, Er, Sc, and Zr to the alloy melts and filler melts have been attempted. Specifically, aluminium alloys are refined using Al-Sc-Er, Al-Sc, Al-Ti, and Al-Zr, which creates an intermetallic compound on the surface of aluminium, providing an ideal substratum for nucleation during recrystallization [13]. It has been reported that adding Sc to filler material improved the strength of the weld through grain size reduction [14].
Table 1. Chemical composition of AA5083−F, ER 5356 and ER5356 + Sc (Wt.%).

| Material        | Mg      | Mn | Si | Fe | Ti | Cr | Zn | Cu | Zn | others | Sc | Al |
|-----------------|---------|----|----|----|----|----|----|----|----|--------|----|----|
| AA5083          | 4.6     | 0.64 | 0.08 | 0.14 | 0.03 | 0.06 | 0.03 | 0.03 | 0.03 | 0.05 × 3 | —  | rest |
| ER5356          | 4.5 ~ 5.5 | 0.05 ~ 0.2 | 0.25 | 0.4 | 0.13 | 0.14 | 0.1 | 0.1 | 0.1 | — | — | rest |
| ER5356 + Sc     | 4.5 ~ 5.5 | 0.05 ~ 0.2 | 0.25 | 0.4 | 0.13 | 0.14 | 0.1 | 0.1 | 0.1 | 0.55 | rest |

FSW is a solid-state welding technology that welds the material below the solidus temperature, removing a number of defects and irregularities associated with fusion welding, and producing welds of exceptional strength and ductility. FSW is referred to as green technology because it is significantly more environmentally friendly and energy efficient than modern FW procedures [15, 16]. FSP is like friction stir welding but does not produce weld joints, it only alters the microstructure of the materials [10, 17]. Therefore, FSP would be a surface modification method intended to enhance surface quality. FSP on TIG welding is another technique which induces local microstructural changes and enhances weldment’s mechanical as well as metallurgical characteristics. The FSP technique involves inserting a spinning tool (pinned or pin less) into the material which offers mechanical mixing and frictional heating [18] leading to severe plastic deformation that changes the structure of the grains microscopically to improve the joint strength of fusion welds in both similar and dissimilar materials. FSP also overcomes the limitations in fusion welds such as pores in the weld, hot cracking during solidification, residual stresses and high heat produced during welding which reduces weld strength [19, 20]. Throughout the process, frictional heat is created, due to which material undergoes intense plastic deformation leading to microstructural distortion [21, 22].

Silva [23] reported the impact of FSP on MIG weld of AA6082-T6 alloy, where a 6 mm plate is first MIG welded with ER5356 filler wire at voltage 26.6 V and current 160 amp and a V notch is made at an angle 90° and shielding was achieved with argon gas and found an enhancement in the fatigue properties due to the modification in the geometry of grain, grain size reduction and removal of defects. Msomi and Mabuwa [24] in their FSP on TIG welding of AA5083-H111 alloy, reporting on the formation of coarse grains in the unprocessed weld joints and very fine grains in the processed joint, concluded that the processed joints possessed improved tensile characteristics than unprocessed ones and the failure occurred at the center of the weld for unprocessed joints while it occurred at various locations on the stir zone (SZ) for processed joints.

Fuller and Mahoney [15] studied the use of FSP on GMAW butt welded 5083-H321 focusing on weld toe and weld crown FSP and observed a considerable change in grain size between welded and FSPed nuggets, the FSP tool caused substantial deformation, which removed porosity within the FSPed zone and found an improvement in tensile strength, grain-size strengthening, as well as precipitate strengthening due to fragmentation resulting in the formation of a greater number of precipitates in the arc-WN. Kianezhad and Raouf [25] studied the single-pass welds utilizing GTAW with fillers comprising various concentrations of nano-Al₂O₃, and showed that the specimens were welded with filler having nano alumina particles followed by FSP revealed rise in yield as well as tensile strength contrasted with the weld made by the ER5183 filler.

From the reviewed literature it is obvious that FSP has been effectively used to enhance TIG welded joints. However, a very few attempts were made on conducting FSP of AA5083−F TIG welded samples in which TIG welds were produced with filler rods containing rare Earth Sc. The TIG welded joints have poor weld quality and low mechanical characteristics. By introducing Sc as well as FSP techniques, the welds’ mechanical strength and quality can be increased.

2. Materials and methods

The AA 5083 plates were used as base metal (BM) with chemical constituents as shown in table 1. The 12 mm thick plates of dimensions 100 mm × 50 mm × 12 mm were butt welded. Water and acetone were used to properly clean the filler rods and BM plates. The plates were wire brushed before welding to guarantee complete clean-up. The 5356 + Sc filler rods were prepared by adding Sc at a concentration of 0.5 wt% to the industrial filler alloy ER5356 (cast). A certain quantity of Al 2% Sc master alloy was added to the molten base metal alloy to create the cast filler rod. The alloy was made by chill casting it in a copper mould, then it was cut into four parts. The melting process was used to create the filler ER5356 + Sc.

The joints were fabricated engaging a constant current TIG welding technique, and the filler rods created complete penetration welds. The V-groove joint design of 45° included angle was made for each weld. The filler rods ER 5356 and ER 5356 + Sc (0.5 wt %) of 2.4 mm diameter at voltage 20 V and current 200 amp are used to form the welds. The modified filler rods ER5356 + Sc preparation is based on the method mentioned in the previous study [14]. Readily accessible argon gas had been used to shield this molten weld pool. The configuration of the TIG welding is shown in the figure 1(a).
After TIG welding, FSP was performed with the 3-axis friction stir processing machine (central workshop, Anna University, Chennai, India) and the configuration of the FSP machine is shown in figure 1(b), which has provisions to control the tool rotational speed and table traverse rate. A non-consumable probe fabricated with H13 tool steel, less than 15 mm shoulder diameter [26] tool has been swept over arc weld-bead, through one pass at 1100 rpm as well as 30 mm min⁻¹. The FSP has been performed on tool advancing side (AS) countering its weld, by gently plunging into the intersection of two BM up to the shoulder surface and brought to contact with the work-piece surface. Figure 2(a) demonstrates the pin-less tool schematic diagram employed in FSP and figure 2(b) shows the real picture of the FSP tool used in the process. Figure 3 shows the schematic diagram of samples for tensile, hardness, impact, and microstructure observation on the weld plate. The figure 4 shows the cross-sectional view of (a) TIG joint (b) Sc added TIG welded joint (c) FSP on TIG welded joint (d) FSP on Sc added TIG welded joint.

After post-processing, approach plates were cut along the weld in cross-section by a wire EDM machine. The microstructural examination was completed using an optical microscope (OM) and scanning electron microscopy (SEM). The workpieces were polished with SiC polishing paper diamond compounds prior to microstructural analysis. Following ultrasonic washing in methanol to eliminate extra polishing chemicals and blown air drying, the surface layer of workpieces was removed using a fresh Keller’s reagent to expose the grain structures microscopically. OM was conducted using De-Winter inverted trinocular metallurgical microscope with magnification 50 X to 1000 X. Utilizing OM, the grain’s size and shape were assessed. SEM micro-graphs and fractography were captured with backscattered electron images using Carl ZEISS EVO 18–Germany at 15 and 20 kV with magnification up to 75000 X and resolution of 70 Å. EDAX analysis was used to map the elements of the welded surface using AMETEK Team V.4.3 EDS detector.

The tensile, impact toughness as well as microhardness examination were subjected on the specimens. The tensile evaluation has been done on a universal Tensile testing Machine (UTM)- (Associated Scientific
Engineering Works, New Delhi) according to ASTM E8 standard. The machine’s load range is up to the max. 5 Ton and gear rotation speed −0.5. 1.0 & 1.5 mm min⁻¹. The 12 mm thick specimens were tensile tested at gauge length with widths of 25 mm mm min⁻¹. The average value of 3 readings is presented for all samples. The impact toughness was conducted using a manual Charpy notch impact device (Model-XJJU-50) to measure impact absorption energy and to evaluate the influence of the patch on the impact with respect to ASTM D256. The microhardness tests were conducted by employing a Wilson Wolpert - Germany Vicker’s hardness tester, according to ASTM E384-11 standard. A 1 mm spacing was measured from the weld’s center to the sample’s AS or retreating side (RS). A 100-grams load and a 10 s dwell duration were used during the microhardness test.

3. Results and discussion

3.1. Microstructure in the weld zone
The figures 5(a) and (b) illustrates optical MICROSTRUCTURE of WN’s from unprocessed and FSPed TIG welded joints, respectively. In the TIG weld micrograph fine precipitates especially Al₂Mg₃, Mg₅Si and Alₓ(Fe,
Mn) were segregated along the grain boundaries (GBs) [19, 27]. From the figure 5(a) it can be seen that the $\text{Al}_6(\text{Mn, Fe})$ particles appeared as gray granules in the shape of flakes and dark comma shaped particles are said to be $\text{Mg}_2\text{Si}$. The black particles are recognized as $\beta$ phases $\text{Al}_3\text{Mg}_2$ [4]. TIG weld made with Sc added filler rods results in the formation of $\text{Al}_3\text{Sc}$ intermetallic along with other precipitates. In this study 0.5 wt% of Sc is added, which is more than the necessary minimum concentration of 0.4 wt% Sc [28], $\text{Al}_3\text{Sc}$ particles are seen in the fusion zone as well as non-continuous in the GBs. The $\text{Al}_3\text{Sc}$ must precipitate first in the melt during grain refinement because its L12 crystal structure is very close to that of face-centered cube (FCC) Al. This must happen before Al solidifies. Small compositional changes in the weld pool are possible due to higher Sc levels in the weldments. On application of FSP over the TIG welds a significant drop in grain size was noticed as depicted in the figures 5(c) and (d). Fine grains with a consistent distribution pattern are observed in the FSPed weld nugget as a result of intense plastic deformation and frictional heating. The dynamic recrystallization that propagated during FSP is responsible for the uniform pattern formed by grains [19, 29]. Fine equiaxed grains are produced in the weld nugget as a result of intense plastic deformation and frictional heating during FSP. During FSP, $\text{Al}_3\text{Sc}$ particles can also significantly slow down the dislocation movement and migration of grain or sub-GBs, resulting in finer grains and a higher proportion of small angle GBs related to the substructure in weldments. Additionally, a larger volume intermetallic phases were produced after the FSP in TIG welds, also improves the strengthening process [30].

From the figures 6(a) and (b) the SEM images shows the grain sizes of unprocessed TIG welds are larger for both without and with Sc addition than that of the FSPed welds, which has smaller grains revealed in the figures 6(c) and (d). WN grain sizes of the TIG weld are 9–12 $\mu$m. The addition of Sc to the welds indicated a reduction in grain sizes to an average of 8 $\mu$m in WN. After performing FSP on the TIG welds a further reduction in grain size was noticed. The TIG welded FSPed specimen’s grain size has been between 2–4 $\mu$m in SZ. Also, the Sc added welds showed grain size closer to the TIG welded FSPed workpieces. Because of the FSP tool’s stirring effect the large size $\text{Al}_3\text{Mg}_2$, $\text{Mg}_2\text{Si}$, $\text{Al}_6(\text{Fe, Mn})$ and $\text{Al}_3\text{Sc}$ precipitates are also broken into fine particles and are distributed along with the matrix [15]. Figure 7 represents the plot of the grain sizes of the processed and unprocessed samples. When the FSP technique was used on TIG welds, the weld’s strength increased as a result of the work-hardening and Orowan strengthening by $\text{Al}_3\text{Sc}$ particles [31]. The Hall-Petch relation governs the

![Figure 5. Optical microscopic images of (a) weld center of TIG joints (b) Sc added TIG welded joint (c) FSP on TIG welded joint (d) FSP on Sc added TIG welded joint.](image-url)
grain refinement of FSPed welded joints, and suggests that the UTS enhances as the grain size decreases. The hardness of the material increases due to grain size reduction in the WNZ [19, 32].

Particle morphology and compositions as determined by EDS is depicted in figures 8(a) and (b). The presence of precipitates such as Al2Mg5, Mg2Si and Al6(Fe, Mn) is seen in figure 8(a). The presence of Sc intermetallic, Al3Sc scattered on the aluminium matrix is confirmed from the figure 8(b). As the volume percent
of precipitates increases, the source of dislocation increases, ensuring a considerable rise of dislocation density in the joints, resulting in a notable spike in mechanical strength of weldments.

3.2. Mechanical characterization

3.2.1. Impact toughness

Generally, reliable, or fail-safe design in components can be ably predicted by impact toughness and fracture characteristics, especially in Aluminium-based alloys [33, 34]. In particular, the Charpy impact test-based design strategies are frequently used to avoid brittle fracture [35] and are extensively used because of their ease of use and low cost. In this high strain rate test, the energy required to rupture a material in elastic deformation is computed. The amount of energy absorbed determines the material’s notch toughness. The pendulum which is attached to the equipment is dropped from a specified height and strikes the notched sample. The material’s absorbed energy is determined using the height of the apparatus prior to breaking and the height of the device after the break. The impact samples before and after the impact toughness test are shown in the figures 9(a) and 9(b).

With welding, the impact strength in respect with the BM drastically decreased. The specimens’ impact resistance is depicted in figure 10. The impact energy of FSP over TIG welded joints is like that of BM. This could be associated with the grain refinement, pores removal along with weld imperfections, as well as uniform distribution and fragmentation of intermetallics in the aluminium substrate after FSP. When compared to TIG welded joints, applying FSP on the weld region enhanced impact toughness by around 13%. Also, the impact energy of Sc added TIG weld and FSP on Sc added TIG weld showed a considerable increase to about 4% and 8%, respectively in comparison to that of the TIG weld.

3.2.2. Tensile strength

The table 2 presents the outcomes from the tensile strength for scandium added, FSPed and unprocessed welds in terms of the weld efficiency, and the ratio of weld tensile strengths to base material tensile strengths. The unprocessed TIG welded, and the scandium added samples have strength lower than the base metal and depicted fracture interfaces between the weld and HAZ. Whereas the FSPed and Sc added FSPed samples showed strength...
greater than the BM and their fractures occurred in the HAZ, the enhanced strength of the WN area is caused by
the grain size reduction as well as porosity recovery due to FSP [15].

Figure 11 shows the tensile specimen after the analysis. The welds’ tensile strength and elongation have
reduced from 262 MPa and 33% (for BM) to 242 MPa and 17.50% (for TIG weld), respectively because of the
cast microstructure produced due to slow cooling in TIG welding. Large-sized grains, residual stresses, porosity
and other weld defects are accountable for inferior mechanical characteristics of the weld. When using ER5356
filler, TIG welded specimens showed an increase in micro-hardness. The intermetallic phases Al-Fe and Al-Fe-
Mg helped to raise the hardness of the weld center [36]. However, the grains formed after recrystallization are
said to coarse that is why the interface between the fusion zone and HAZ is said to be the weakest part of the weld
and fracture occurs at that region. The most frequent issue with TIG welding of AA5083 alloys is porosity
formation [4]. Porosity might minimize the tensile strength in the fusion region and decrease the efficacy of the
welded joint. Weldments made by Sc added filler rods showed a slight rise in tensile strength as well as elongation
(nearly 7% and 1% respectively), which is almost comparable to the BM strength. When Sc is added to the

| Joint efficiency based on UTS (%) |
|-----------------------------------|
| BM                               |
| TIG                              |
| TIG + Sc                          |
| TIG + FSP                         |
| TIG + Sc + FSP                    |
| 262                              |
| 242                              |
| 260                              |
| 288                              |
| 331                              |
| 33                               |
| 17.50                            |
| 18.50                            |
| 7.1                              |
| 20.5                             |
| —                                |
| 92.3                             |
| 99.2                             |
| 109                              |
| 127                              |
aluminium alloys, there is a rise in recrystallization temperature above annealing temperature, resulting in a non-recrystallized pattern accompanied by greater strength.

The stress strain curve is depicted in the figure 12, which indicates UTS of all the specimens. The introduction of FSP to the weld zone improved the tensile strength in both TIG welded and Sc added TIG-welded specimens (288 MPa and 331 MPa), which is beyond the BM’s tensile strength. This strength increment of FSPed weldments is because of the formation in dislocation density as well as lattice deformation which induces nucleation of new fine grain during re-crystallization. The dynamic recrystallization that occurred during FSP, because of the heat caused through friction together with severe plastic deformity is responsible for fine and equiaxed grains produced in the Al matrix [37]. During re-recrystallization, modification of the alloy’s microstructure occurs resulting in strengthening its mechanical properties [38]. The elongation to fracture has increased from 17.5% to 20.5% for TIG-welded specimens reflecting an increased ductility. But for Sc added TIG welded joints the elongation has reduced to 7.1% caused due to the vigorous stirring of the FSP process where the precipitates formed by the TIG welding are fragmented into small particles. The TIG + FSPed showed reduced elongation percentage when compared to the other samples and similar results were observed by Kianezhad [25] the ‘simple weld + FSP’ specimen showed elongation reduced by 42%. The elongation of the FSP samples tended to decrease with decreasing grain size [39, 40]. On administering FSP to the welded area the precipitates were supposed to be equally diffused in the matrix added by a decrease in the size of the reinforcements [25, 41]. The coherent Al3Sc particles with good heat endurance are evenly dispersed throughout the FSPed joint and may effectively pin sub-GBs and dislocations during the FSP without visibly coarsening of Al3Sc intermetallics. Consequently, Al3Sc particles can greatly strengthen FSPed joints through effective work hardening and Orowan strengthening. Also adding Sc increased the elongation percentage of the material as it is.

Figure 11. Tensile specimen (a) TIG weld (b) TIG + FSP (c) TIG + Sc + FSP (d) TIG + Sc.

Figure 12. Stress strain curve for the all the samples.
shown in the figure 9(c) and severe plastic deformation had resulted in necking amidst tensile test. And thus, the fracture had occurred in the interface between HAZ and BM. During FSP, the material’s plastic deformation was greater, and the material that has been stirred was more easily distorted, equally distributing the precipitates in the SZ. The severe plastic deformation may be responsible for the uniform dispersion and fragmentation of precipitates. FSP over TIG welds resulted in defect-free microstructure, the porosity and other weld defects have been eliminated which was validated by the SEM micrographs exhibited in figures 4(c) and (d). It is observed that FSP over TIG weld has resulted in grain refinement caused by dynamic recrystallization and intense plastic deformity at joints, elimination of porosity and other weld defects, strain hardening due to interaction of dislocations with precipitates and precipitation strengthening because of the abundance of precipitation, and a rise in the welds’ tensile strength [19].

3.2.3. Micro-hardness

The hardness value of BM is about 80 HV1, while a decrease in hardness was identified in TIG joints. However, weld with Sc added filler material showed hardness at the weld to about 87.9 HV1, which is greater than that of the BM [14]. Figure 13 depicts the hardness graph of FSPed samples, where the hardness profiles of FSPed workpieces indicate an improvement in hardness higher than that of BM and un-FSPed welds. The hardness value of FSP on TIG-welded samples is around 90 HV1 and FSP on Sc added TIG welded joints is 95 HV1 is observed. Fine grains, substructure, and precipitate dissolution define the stir zone’s microstructure. As a result, the GB strengthening and precipitate strengthening in this zone is higher due to Al₃Sc intermetallics, increasing the hardness. The stir zone exhibits the highest microhardness than the HAZ and TMAZ, due to the presence of fine equiaxed grains which are formed during the FSP [9]. The microhardness value decreases significantly from the center of SZ to either AS or RS until the deformed zone or heat affected zone, where it increases again. This could be partly related to the difference in the size of grains and their vulnerability to heat in various regions. The HAZ produces larger grains to have relatively low hardness, hence failure is more likely to occur in this zone during tensile stress [42]. The TMAZ is characterized by significant deformation, grain coarsening, and temperature variance. As a result, both TMAZ and HAZ are known as zones with the lowest hardness range. The hardness values were shown to be related to the tensile strength results. It is observed that the FSPed joints had greater microhardness values compared to the BM because of the modifications in grain sizes as well as grain distribution.

The top, middle, and bottom hardness values were measured, with thickness taken into consideration. Microhardness gradients for all the four specimens (TIG, TIG + Sc, TIG + FSP, TIG + Sc + FSP) were measured. The top, intermediate, and bottom zones’ hardness values are illustrated in the figures 14(a)–(d). The TIG welded samples showed decrease in hardness from top to bottom this may be due to the variation in cooling time. The top surface of the samples was cooled very fast compared to the bottom layer. Longer cooling time may lead to grain coarsening, which results in decrease in hardness. When FSP is conducted on the top layer of TIG joints, the tool’s stirring action causes intense heat and severe plastic deformation, which encourages dynamic recrystallization and creates enormous, high-angle fine grains in the SZ [43]. The hardness of aluminium weldments follows the Hall–Petch ratio; it claims that when grain size declines, hardness rises. In the intermediate region the heat generated due during FSP and forging pressure induced by the FSP tool may be responsible for changes in the microstructure. Coarse grains are formed when compared to the top surface as there is no direct interaction amid the FSP tool and the material. The bottom hardness of the material remains the same as–TIG welded because very little heat may be dissipated to the bottom of the material as well as stress caused by the FSP tool has no effect on the bottom of the material.
3.3. Fractographic studies

3.3.1. Fractography of tensile specimens

The tensile fractographs are shown in figure 15. The fractures are in shear mode, according to visual observation and this eliminates necking while avoiding unnecessary stress in the necked zone. The elongation created during tensile deformation would be limited within the weld region, and the specimen’s test gauge length could remain unchanged. The microstructural evaluation done during SEM analysis focuses on understanding the fractographs of welded materials. The weld joints made by TIG produced large-sized dimples as shown in figures 15(a) and (b). A ductile dimple form of fracture was noticed in TIG joints with significant micro void volumes. The transgranular cracks are initiated by two sources during deformation. One is due to the voids formed by some inclusions that were able to grow and coalesce. Generally, nucleation of void takes place at the interfaces of second-phase particles. As the plastic deformation progresses, the size of the voids grows larger. Neighbouring voids are connected by localized plastic strain in the inner void matrix and thus final fracture surface is formed. Another aspect is the grain boundary segregation owing to Mg diffusion and the constant increase in the size of intermetallics that occur in the grain boundary region. These large precipitates act as stress concentrates and fasten crack propagation, therefore cleavage facets are also seen in the figure 15(a). Addition of Sc to the welds reduced the size of dimples to a certain extent is noticed in figure 15(b). The FSPed tensile test fractured specimen contains a considerable measure of dimples as depicted in figures 15(c) and (d). Dimples size is very fine owing to the production of ultra-fine grains and breakage of precipitates since the stirring activity of the FSP tool. The strength improves on reduction in the size of the dimples [44]. During deformation due to small dimples the centre of the dimples is free from particles therefore micro-voids are developed in the matrix.
rather than in the particles. Thus, the final failure occurs because of the coalescence of voids. The size of dimples also determines the strength and ductility of the material [3]. Finer the dimple, the material shows maximum ductility.

3.3.2. Fractography of impact specimens

The impact fractographs are shown in figure 16. Impact specimens exhibited sheared grains in the impact load direction thus varying from the tensile specimen. The ductile mode of fracture prominently occurred in the impact specimens. The unFSPed TIG-welded sample (figure 16(a)) exhibited large and shallow dimples. The addition of Sc to the welds reduced the size of the dimples just like it reduced the grain sizes (figure 16(b)). The size of the dimples was further reduced after FSP (figures 16(c) and (d)). The dimples of the FSPed samples were equiaxed and the presence of micro-voids was negligible. Fragmentation of the secondary particles during FSP is responsible for the initiation of the micro-crack nucleation. Even though the post-FSPed showed a ductile mode of fracture, quasi cleavage facets are also present which are formed due to the fragmentation of the intermetallics [25]. Porosity is noticed in unFSPed TIG weld samples in contrast to other samples. Porosity inside the FSP zone is minimized due to the severe distortion caused by the FSP tool, however, porosities directly underneath the FSP region are compressed because of major localized tension formed along FSP [15].

4. Conclusions

The impact of FSP on AA5083-F TIG joints, with/without the addition of scandium was undertaken and the conclusions are as follows:

Figure 15. SEM fractographs of tensile samples (a) weld center of TIG joints (b) Sc added TIG welded joint (c) FSP on TIG welded joint (d) FSP on Sc added TIG welded joint.
1. In contrast to the FSPed TIG joints, unprocessed TIG joints showed poor mechanical qualities. The Sc added FSPed TIG-welded specimen showed a maximal tensile strength of 331 MPa, supreme to the BM’s UTS of 262 MPa.

2. The FSPed TIG welded joints had the same impact resistance as the BM, which perhaps because of the drop in the grain size, removal of pores and weld flaws, as well as the homogeneous distribution and fragmentation of the intermetallic phase in aluminium matrix during FSP.

3. The use of FSP increased the ductile nature of TIG-welded joints as well and the surface structure of the FSPed samples showed the smallest dimple sizes.

4. The metallographic examination revealed that the FSP approach can be utilized to improve the weld joints. The heat generated while stirring in the SZ altered the mechanical and microstructural characteristics of processed joints significantly. In both FSPed TIG and Sc added joints, the grain size refinement appeared noticeable. Owing to the severe dynamic recrystallization encountered throughout FSP, the Sc added FSPed joints had the most refinement.

5. The FSP approach had a remarkable effect on the microhardness in the Sc added FSPed joints, resulting in a maximum microhardness of 95 HV, due to the fine microstructure and precipitation strengthening mechanism.

6. The tensile and impact fracture was caused by the coalescence of voids and the size of dimples also determines material’s strength as well as ductileness.

Figure 16. SEM fractographs of impact samples (a) weld center of TIG joints (b) Sc added TIG welded joint (c) FSP on TIG welded joint (d) FSP on Sc added TIG welded joint.
Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Declarations

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The authors declare that they have no conflict of interest.

Availability of data and material

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Author contributions

R. Aarthi - Conceptualization, Investigation, Writing- Review and Editing, K. S. Vijay Sekar - Resources, Supervision, and Validation.

Ethics approval

Not applicable.

Consent to participate

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Consent for publication

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Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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