Original Article

Investigation on friction stir welding of hybrid composites fabricated on Al–Zn–Mg–Cu alloy through friction stir processing

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**ABSTRACT**

This study presents microstructural and mechanical investigation on friction stir welding of composites fabricated through friction stir processing on a high strength Al–Zn–Mg–Cu alloy by utilizing hybrid reinforcement. Surface composites (SCs) were fabricated via FSP, sliced to the processed thickness and cut-apart through the longitudinal axis of the SCs. They were subsequently, friction stir butt welded by employing varied tool rpm (560–900 rpm). The mechanical properties, microstructural analysis and micro-hardness profile was obtained for the welds. Results of investigation revealed that in comparison to SC samples the reinforcement particle distribution of the welded samples became more homogeneous due to the weld pass. In comparison to SCed samples the micro-hardness was found to be enhanced and more evenly distributed in the welded samples. The microstructural examination indicated that minute tunneling defect was introduced in samples welded at 560 and 900 rpm whereas incomplete root penetration (IRP) defect was observed in all welded samples. The ultimate tensile strength (UTS) of welded samples were found lower than base metal which was attributed to the presence of tunnel and IRP.

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1. Introduction

Aluminium based metal matrix composites (AMMCs) have developed increasing interest in structural applications in aerospace, transportation and defence due to their superior properties in comparison to conventional alloys and materials [1,2]. Generally, AMMCs are largely fabricated via fusion based technologies. Producing AMMCs with fusion based practices leads to some typical problems such as particle clustering, casting related defects that significantly affects tensile strength, non-homogenous and unfavourable microstructure,
inclusions, blow holes and porosity etc. [3]. At the same time, the main barrier preventing AMMCs widespread industrial applications is their difficulty in joining in a reliable manner by conventional fusion based welding processes including tungsten inert gas welding (TIG), gas metal arc welding (GMAW), laser beam welding (LBW), electron beam welding (EBW), vacuum brazing, ultrasonic assisted soldering, resistance spot welding etc. [4]. It is well known that during melting and at high temperatures interfacial reactions and formation of detrimental phases, segregation of reinforcement along the grain boundaries and their clustering occur. In case of high energy rate beam based welding; the formation of deleterious phase is of greater concern. When the molten matrix material comes in contact with the reinforcement it may also react with the reinforcement and form some undesirable interfacial phases [3]. These phase causes the low strength zones along the joint-line [5].

Solid state fabrication is the key of satisfactory in-service performance due lesser imperfections and defects. Recently, friction stir welding and processing (FSW/P) has come out as a popular solid state processes as it is clean, simple, economical, environment friendly and a versatile process [3,6]. Apart from its simplicity and economic benefits this process also improves the microstructure and mechanical properties of materials through dynamic recrystallization (DRX). In FSW/P a rotating cylindrical tool having shoulder and probe is plunged in to plate(s) to be processed. The friction between tool and plate produces frictional heat which is required to soften the material. Under rotational and simultaneous traversing motion of tool; the material experiences complex movement and severe plastic deformation (SPD) which is known as stirring. Further, during stirring, the material undergoes through a simultaneous friction, extrusion and forging action. The side where tool rotational and traverse direction are same is known as advancing side (AS), whereas, the other side is retreating side (RS).The characteristic zones that evolve during FSW/P are identified as nugget or stir zone (SZ), thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ) [6].

Since its inception as welding technique, FSW/P has evolved as a major manufacturing philosophy, and surface composite (SC) fabrication is a fast growing application of this process. Surface composites merit over plain alloys or bulk composites due to synergy of toughness of substrate and strengthening of surface. Numerous works are being reported on surface composites which are fabricated via FSP route. But, most of the work remained focused on non-heat-treated 1xxx, 3xxx and 5xxx series and 6xxx alloy series. The 2xxx and 7xxx series are the age-hardenable high strength aviation/aerospace alloys. Their high specific strength is the main benefactor which makes them favourable for this niche application. Any further strengthening (of course with acceptable levels of fatigue strength and corrosion resistance) via surface composites may be a significant development. So far very few studies report SC fabrication of 2xxx and 7xxx alloys (except some alloys such as 2014, 2024, 2124 and 7075 etc.) [7]. Some work which report composites on 7050 have investigated frictional and tribological properties [8]. These alloys are sensitive to temperature and high temperature exposure time, beyond which their strength drops sharply. Heat input during FSP may adversely affect and may cause softening rather than strengthening.

7050 is a recent heat treatable high strength Al–Zn–Mg–Cu alloy and is popular aerospace structural material due to its lower quench sensitivity, better fracture toughness and resistance to stress corrosion cracking [9]. The MMCs fabrication on this series, however, is very scantily reported. The stir casting method was used by some researchers to fabricate MMCs on this alloy, but in annealed condition [10,11]. It is worthwhile to note that, careful control of temperature and time, age-hardened alloys may also be strengthened. Strengthening of age-hardened alloy (AA7050-T7451) through surface composites via FSP has been reported in detail in the work of authors elsewhere [12]. Recently, Gangil et al. have successfully fabricated composite on this series in T7451 condition through FSP and increased its strength significantly [12]. Materials are not deployed standalone, and eventually they need to be joined at the interface. Topical popularity of SC has opened new opportunities and challenges for their welding too. The joining of SCs by conventional fusion welding route takes away benefits of the SCs due to concerns like segregation of reinforcement and reaction with matrix [13]. It is widely agreed that the solid state processes are more feasible than the conventional fusion based processes for the welding of MMC in general and SCs on age-hardened AMMC in particular. Most researches mainly report microstructure and micro hardness, and also that the micro-hardness of welded zones is slightly smaller than the base metal in case of age-hardened alloys [14]. Interestingly, the MMCs are mostly produced by conventional route such as stir casting. In any case, joining of cast MMCs excellent joint efficiency can be attained as FSW will also improve the casting related defects and imperfections. For example, Vijay and Murugan, welded 10% TiB2 AMMC of unreported grade Al-alloy and reported optimized joint efficiency of 99.47% [15]. The FSW of composites produced by FSP are literally very few; and in the absence of prior imperfections (i.e. casting related) their welding with comparable joint efficiency is really challenging. More so, the joining of MMCs/AMMCs/SCs pose the problem of another dimension, that the ceramic reinforcement particles present in the composites seriously reduce the FSW tool life [16].

It is evident that the literature on FSW of SCs/AMMCs/MMCs is reported less and that on the welding of composites produced by FSP are negligible. Most importantly, to the best knowledge of the authors, FSW of composites on age-hardened 7xxx alloys in general and 7050 in particular is not available. Given that the strengthening on 7050 beyond its T7451-strength by SC via FSP was obtained [12]; feasibility of its welding may come out to be a great enable to its real application. The current study was performed with this primary objective as to investigate and report results, issues and aspects of FSW of 7050-T7451 composites. AA7050 T7451 is solutionized at 477 °C and cold worked using conventional methods. Its aging is performed in two-stage heat treatment. In the first stage it is heated at 122 °C for 3–6 h. For second stage it is heated at 163 °C for 15 h followed by cooling in air. In the present study processing of AMMCs reinforced with TiB2, Al2O3, Mg, and Zn were produced by FSP route and these were friction stir welded at varied tool rotational speed;
Table 1 – Chemical composition of AA7050-T7451 (wt.%).

<table>
<thead>
<tr>
<th>Element</th>
<th>Cu</th>
<th>Mg</th>
<th>Zn</th>
<th>Fe</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Ti</th>
<th>Zr</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA7050-T7451</td>
<td>2.2</td>
<td>2.3</td>
<td>6.2</td>
<td>0.07</td>
<td>0.01</td>
<td>0.03</td>
<td>0.01</td>
<td>0.06</td>
<td>0.1</td>
<td>Remainder</td>
</tr>
</tbody>
</table>

Table 2 – Mechanical and thermal properties of AA7050-T7451.

<table>
<thead>
<tr>
<th>Aluminium alloy</th>
<th>UTS (MPa)</th>
<th>Elongation (%)</th>
<th>Micro-hardness (HV)</th>
<th>Thermal conductivity (W/mK)</th>
<th>Melting point (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA7050-T7451</td>
<td>489.5</td>
<td>6.94</td>
<td>180.3</td>
<td>180</td>
<td>494</td>
</tr>
</tbody>
</table>

Table 3 – Parameters that are constant during FSW.

<table>
<thead>
<tr>
<th>Process parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welding speed</td>
<td>mm/min</td>
<td>100</td>
</tr>
<tr>
<td>Welding pass</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>Tool tilt angle</td>
<td>Degree</td>
<td>2</td>
</tr>
<tr>
<td>Tool shoulder diameter</td>
<td>mm</td>
<td>12</td>
</tr>
<tr>
<td>Tool plunge</td>
<td>mm</td>
<td>2.9</td>
</tr>
<tr>
<td>Tool shoulder surface</td>
<td>–</td>
<td>Flat</td>
</tr>
<tr>
<td>Pin diameter</td>
<td>mm</td>
<td>4</td>
</tr>
<tr>
<td>Pin length</td>
<td>mm</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Fig. 1 – OM image of AA7050-T7451.

![OM Image](image1)

Fig. 2 – (a) FSP tool with scroll, and (b) FSW tool.

![FSP Tool](image2)

and investigation on microstructure, defect formation and mechanical properties of the AMMCs was performed.

2. Materials and methods

The chemical composition, mechanical and thermal properties of base metal (BM) are given in Tables 1 and 2, respectively. BM was 6 mm thick high strength age-hardened Al–Zn–Mg–Cu alloy (AA7050-T7451). The BM plates were cut across the rolling direction as shown in the OM image in Fig. 1. Two sets of experiments were performed. In first set, surface composites (SCs) 3 mm in depth were fabricated via FSP by utilising hybrid reinforcement comprising of TiB₂, Al₂O₃, Mg and Zn in 67.5, 22.5, 6.5, and 3.5 wt.% respectively (details of which are given elsewhere [12]). High-carbon high-chromium (HCHCr) steel tool (Fig. 2a) used for SCs fabrication was selected through previous study [17]. Tool shoulder diameter was 18 mm with anti clock-wise scroll having height of 0.5 mm and width of 0.75 mm, cylindrical pin (3 mm length and 6.5 mm diameter) was employed for FSP. During SCs fabrication the number of FSP pass, tool rpm, traverse speed and tool tilt were fixed to 1, 710 rpm, 63 mm/min and 2°, respectively. In second set of experiments plates with SCs fabricated on them were sliced to processed zone thickness of 3 mm. The so-fabricated SCs were then friction stir welded in butt joint configuration. The HCHCr steel tool (Fig. 2b) of 12 mm shoulder diameter, 4 mm pin diameter and 2.7 mm pin length was employed for FSW. The FSW joints were made at 560, 710, and 900 rpm tool rotation (designated as FSW520, FSW710, FSW900) while keeping other parameters at constant value which are given in Table 3. The fixed and variable parameters were obtained via extensive trial experiments.

Post welding, various test samples were machined from the joints. The samples for microstructural examination were cut across the tool travel direction and polished as per standard metallographic procedure including belt grinding, wet grinding and diamond polishing. The polished samples were subsequently etched using modified Keller’s reagent comprising of 6 ml HF, 6 ml HCl and 3 ml HNO₃ in 150 ml water for 8 s. The micro-hardness of samples was measured on Vickers micro-hardness testing machine at a force of 2 N and a dwell time of 15 s. Tensile test specimens were prepared in accordance with ASTM EBM and the tests were performed on a computer interfaced Tensometer at a test speed 2 mm/min.

3. Results and discussion

Macro and micro-structural analyses along with micro-indentation and tensile tests were carried out to investigate the influence of tool rotational speed during FSP and FSW of fabricated SCs.
3.1. Macro and microstructure

Surface morphology of processed and welded plates is shown in Fig. 3(a,b). The compositied/welded surfaces possessed good surface texture having smooth and uniformly spaced ripples, and they are free of visible defects.

Fig. 3 – Typical overall view of (a) FSPed specimen, and (b) FSWed specimen (FSW710).

Fig. 4(i) depicts the macrograph of cross-section from the fabricated composite and Fig. 4ii(a–e) are the optical micrographs (OM) from indicated regions. Some particle accumulation in RS was observed as shown in Fig. 4ii(a,b). Region depicted in Fig. 4ii(c) shows particle free stir zone (PFSZ). Homogeneous particle distribution was observed on the entire AS with clear interface and good bonding. The SZ comprised of equi-axed grains indicating significant grain refinement as compared to initial grain size. The grain refinement from initial size of 130 μm to 5–8 μm in SZ was produced due to dynamic recrystallization (DRX) during FSP [18]. The macro and micro-structural images of the cross-section of welded SC plates are presented in Figs. 5–7(i and ii). High resolution SEM images were also obtained from regions with particle accumulation. The SEM images of region with accumulation of FSPed SC sample and reinforced region of all the samples is given in Figs. 8(a,b) and 9(a,d) respectively.

Welded samples were found to be free from reinforcement accumulation which was otherwise present in the SC samples. Such better dispersion of particles has actually resulted in uniform contour with enhanced micro hardness. However, tunneling defect was observed in the RS of samples welded at
Fig. 6 – (i) Macro-images of cross-section of FSW710 (ii) OM images from various locations as depicted in (i).

Fig. 7 – (i) Macro-images of cross-section of FSW900 (ii) OM images from various locations as depicted in (i).

Fig. 8 – SEM images of SC showing (a) reinforcement accumulation in RS, and (b) magnified view of encircled accumulation region.
520 and 900 tool rpm as shown in Figs. 5 and 7(ii-g). Tunnel free weld was observed for FSW710 (Fig. 6). Another defect, incomplete root penetration (IRP) seriously hampers the joint strength. IRP was observed in all the welded samples. The IRP was found to decrease from 420 µm to 340 µm with increase in tool rotational speed from 520 rpm to 900 rpm, respectively. Higher rpm creates more heat input which in turn reduces the flow stresses and make material movement better and consequently, IRP (which is present in the low heat region near the bottom of pin) is reduced with the increase in rpm. The reinforcement was found to be homogeneously distributed all over the SZ in all the welded samples. This homogeneous distribution of reinforcement was achieved due to the additional welding pass after SC fabrication through FSP. All the distinguished microstructural zones were clearly visible in welded samples and are marked in the respective figures.

3.2. Micro-hardness

Micro-hardness was traced on the polished and etched samples over entire transverse section of fabricated SC and welded samples. Fig. 8 shows micro-hardness contour maps for Sced and FSWed samples over the entire weld/processed zones. All the weld samples possessed low hardness in the HAZ which is recipient of heat both during SC fabrication as well as welding, but has not been stirred. The effect of high heat in HAZ region changes the characteristic properties associated with softening of matrix due to coarsening of precipitates and increased grain size. In AA7050-T7451 aluminium alloy the improvement in hardness is achieved through fine distribution of η' strengthening precipitates [19]. It is evident from literature that exposure to high temperature for even a few minutes may significantly reduce the hardness of material due to coarsening of precipitates from η' to η phase [20]. The grain size refinement in SZ is produced due to DRX phenomenon during FSP and may result in increase in hardness due to matrix grain size strengthening effect. However, the net effect on SZ hardness value depends on combined effect produced by dispersion condition of reinforcement, matrix grain size strengthening and precipitates conditions in SZ, TMAZ and HAZ [21,22]. The hardness value in FFSZ region is found almost equal and in some cases exceeding the BM hardness in FSPed sample, whereas, it is found somewhat lower in FSWed samples. This fact endorses that the combined effect of grain refinement and reinforcement may outplay the softening effect due to precipitate dissolution/coarsening in RZ region.

![SEM images of reinforced zone of samples](image-url)
A close observation of micrographs (Figs. 4ii(a,b) and 8a,b) and micro-hardness profile presented in Fig. 10 reveals that in SCed sample the reinforcement agglomeration is more on the RS which attributed to the micro-hardness distribution in the RS including in TMAZ being high. Whereas, on the AS of SCed samples the hardness is more uniformly distributed and is greater than the average BM hardness. The hardness near the lower portion of the processed zone is marked with patches of lower hardness which may be due to less even distribution of reinforcement particles.

The hardness profile for all the three welded samples reveal that the additional welding pass over and SCed samples has resulted in more homogenization of the reinforcement distribution (Fig. 9(b–d)) which has resulted in improvement in hardness across entire welded zones with the exception of small pockets of lower hardness in welds performed at 710 and 900 rpm. The welding of composite which was performed at 560 rpm has resulted in overall improvement in hardness over entire welded zones with the exception of slightly lower hardness on RS side of SZ and TMAZ. The micrographs in Fig. 5(ii–c) reveal that the reinforcement distribution is homogeneous in AS whereas RS is marked with particle free stir zone (FFSZ) due to which the hardness is less. Further, the region of TMAZ-HAZ interface has a tiny tunnel (Fig. 5(ii–g)) which is also evident with the steep drop in the hardness in the TMAZ-HAZ (vicinity of the tunnel) of sample welded with 560 rpm.

The weld at 710 rpm offers higher heat input in comparison to the weld at 560 rpm. The island on low hardness in the middle of SZ appeared to have been cause by high heat input associated softening of 7050-T7451 and also that the reinforcement is more homogeneous (although sparse too) and skewed in the AS. This fact would have resulted in the formation of low hardness island in the middle and also slightly lower hardness in the TMAZ-HAZ region on RS. Finally, the weld fabricated at 900 rpm has the largest heat input among all the three welds.

High rpm not only results in high heat input but also causes higher stirring rate [23]. These two factors have resulted in the higher hardness distribution in the entire weld zone caused by better reinforcement particle distribution and at the same time pockets of high temperature (e.g. middle of SZ and shoulder affected zone) were marked with lower hardness values.

### 3.3. Tensile strength

The tensile strength and % elongation (E%) of processed and welded samples were measured and are presented in Table 4. The ultimate tensile strength (UTS) of fabricated SC was found lower than the BM which might be due to accumulation of particles in RS side which acted as stress raiser and resulted in failure of samples during testing. This is attributed to the fact that in-homogeneity in materials microstructure weakens it and reduces load bearing ability of the sample [21]. However, welded samples showed lower UTS than the SCed samples. It is marked that the micro-hardness distribution is enhanced in the welded samples but the microstructural images of welded samples also reveal presence of tunnel and IRP defects which lead to the failure in the vicinity of defects and resulted in lower UTS value. It may be noted that the hardness and mechanical strength are closely correlated and an enhanced hardness naturally translates into increase in strength. But, defects act as the stress raiser, reduce load bearing area and consequently become the cause of failure. This implies that a more homogeneous hardness contour map with enhanced hardness (such as in FSW560) would have contributed to the increase in strength but the sample’s bulk strength reduced due to presence of defects, whereas the strength in the rest of the cross section would have been enhanced. Among all the welded samples FSW710 showed highest UTS, as this sample was free of tunnel defect and could withstand more load during testing as compared to other samples. The highest hardness distribution is evident for sample welded at 560 in comparison to sample welded at 710 and 900 rpm, as shown in Fig. 10. But, micro-structures of FSW560 and FSW710 (Figs. 5 and 6 respectively) reveal that the FSW650 possessed defect where as FSW710 did not. Thus, a lower strength of FSW560 despite higher micro hardness in comparison to FSW710 is attributed to the presence of defect. Due to the similar reason the joint at 710 rpm also showed better %E. The strength could have further improved if the IRP was not present. The tensile test also showed that the samples fractured from the weakest region i.e. either from poor interfacial bond between particles and matrix or from defects.

The results of this investigation demonstrated that the welding of metal matrix composites of age-hardened 7050-T7451 can be be done by FSW with reasonable strength.

### Table 4 – UTS and %E of samples.

<table>
<thead>
<tr>
<th>Sample name</th>
<th>UTS (MPa)</th>
<th>%E</th>
<th>Joint efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite</td>
<td>436.2</td>
<td>6.19</td>
<td>–</td>
</tr>
<tr>
<td>FSW520</td>
<td>208.8</td>
<td>3.84</td>
<td>47.87</td>
</tr>
<tr>
<td>FSW710</td>
<td>303.3</td>
<td>5.06</td>
<td>69.53</td>
</tr>
<tr>
<td>FSW900</td>
<td>203.5</td>
<td>3.72</td>
<td>46.65</td>
</tr>
</tbody>
</table>
4. Conclusions

In this maiden work the surface composites (SC) were fabricated on high strength AA7050-T7451 via friction stir processing (FSP) and they were friction stir butt welded. The results revealed that the surface composites can be successfully fabricated on age hardened Al-alloy via solid state FSP. The results of the investigation also revealed that:

1. In comparison to composites the reinforcement particle distribution is more homogenized during FSW due to weld pass.
2. In comparison to composites the micro-hardness was found to be enhanced and more evenly distributed in the welded samples. Higher rpm was found to develop island of low hardness which might be attributed to high heat input at higher rpm.
3. Minute tunneling defect were present in samples welded at 560 and 900 rpm whereas incomplete root penetration (IRP) defect was observed in all the welded samples.
4. The tensile strength of welded samples was found to be reduced which was mainly attributed to the tunnel and IRP defects. A highest of about 70% joint efficiency was found to be in the samples which was made at 710 rpm.

Conflicts of interest

The authors declare no conflicts of interest.

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