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ORIGINAL ARTICLE

Investigation on the effects of SiC particle addition in the weld zone during friction stir welding of Al 6351 alloy

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Abstract This study attempts to incorporate SiC particles in the weld zone during friction stir welding of Al 6351 alloy. SiC particles of suitable size (12 μm) were added during welding at the weld zone through a special arrangement, and thus joined Al 6351 alloy plates were evaluated for their mechanical properties under two different conditions, i.e. in the as-weld condition and under annealed condition. The results of the study reveal that the mechanical properties of the SiC particle added Al 6351 alloy welded joints are superior in both as-weld and under annealed condition, compared to their plain Al 6351 alloy welded joints. Microstructural examination of the welded joints reveals that pinning effect of grain coarsening has occurred on account of addition of SiC particles in the weld region.

Keywords Aluminium alloys · Friction stir welding · Grain coarsening · Mechanical properties

1 Introduction

The convention method of joining of aluminium and its alloy is accomplished by brazing, arc welding, TIG welding and MIG welding. However, fusion welding of aluminium and its alloys are usually subjected to defects like porosity, hot cracking and formation of nitrides in the weld zone [1]. It is needless to state that the above defects affect the strength of the welded joints during the service. Hence, presently solid state joining techniques like friction welding and friction stir welding are widely accepted as alternative joining methods for welding of aluminium and its alloys [2]. Friction stir welding is a solid state welding process which uses friction as its main source to form welding with a tool that produces enough heat to plasticise the material. In addition, the tool also helps to move the plasticised material from one side to another to form a strong bonding between the materials to be joined [3]. Friction stir welded aluminium and aluminium alloy joints are generally subjected to post weld treatment "annealing" to relieve the locked up thermal stress [4].

However, this post welding treatment is not recommended for end applications demanding superior mechanical properties at the weld zone [5–7]. Generally, grain coarsening [8] occurs in the weld zone of the friction stir welded aluminium alloy plates subjected to annealing treatment. Moreover, for low-end applications, the loss of strength due to grain coarsening at the weld zone observed on account of annealing must be considered in the joint and component design. Few earlier researchers [9–11] have attempted to mitigate the problem of grain coarsening observed during annealing in the aluminium welded plates by addition of ceramic particles of suitable size in the aluminium plates during casting stage itself. Nevertheless, casting of such ceramic particles reinforced aluminium alloy composite plates is susceptible to flaws like hot pores and solidification cracking [12]. Hence, considering the above aspects, in the present study, an attempt has been made to incorporate ceramic particles in the weld zone during friction stir welding of aluminium alloy plates to overcome the problem of grain coarsening during subsequent annealing treatment. The effect of the addition of ceramic particles in the weld zone during friction stir welding on grain coarsening

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is ascertained by evaluation of mechanical properties and SEM studies of the thus welded aluminium alloy plate joints.

2 Experimental procedure

Al 6351 alloy plates of dimension 100×50×6 mm were used as the material for friction stir welding. Square pin profile tool made of HCHCr tool steel was used to carry out friction stir welding on Al 6351 alloy plates. The diameter ratio of the tool is maintained at 3 (i.e. the ratio of the tool shoulder diameter to the pin diameter [18 mm/6 mm]) based on previous works [13–16]. The tool was hardened and tempered to a range of 56–58 HRC to withstand heat and wear during friction stir welding. The entire friction stir welding operation was carried out in a vertical milling machine, the details are discussed elsewhere [17, 18]. In the selection of SiC particle, finer grain sizes tend to mix poorly relative to coarse particles and also lead to ceramic with lower SiC content [19]. Similarly, when grain size above 12 μ is introduced, the particles do not provide a smoothness and consistency in the mixing of SiC and aluminium alloy [20]. So, SiC particles of 12 μ sizes are selected and are evenly applied on the welding sides of Al 6351 alloy plates. The weight percentages of SiC particles, i.e. 1 wt%, 1.5 wt% which is approximately 0.1 and 0.15 g, respectively, are weighed in a digital weighing scale and used in the experiments. Since the SiC particles are fine powder, it adheres to the welding sides sufficient to perform friction stir welding operation without the need for any adhesives. SiC particles are applied to the welding edges of the Al 6351 alloy plates prior to welding for introduction and uniform distribution of SiC particles in the weld region. Figures 1 and 2 show the welding sides of Al 6351 alloy plates and the presence of evenly applied SiC particles on the welding edge.

Apart from the study on the effects of the addition of SiC particles, in order to systematically record the influence of the chosen process parameters on the final responses, Taguchi's technique is applied. Taguchi's design is an efficient tool as it combines the experimental design theory and quality loss function to improve the performance of a process with reduced time and cost. Therefore, Taguchi's L18 orthogonal array at mixed level scheme used in this study to conduct the experiments is shown in Table 1. Totally, 18 experiments were conducted to evaluate the mechanical properties in as-weld condition, and one more set of replicate experiments of the same were conducted for evaluating the mechanical properties in annealed condition. On the whole variables, SiC wt%, axial load, rotational speed and welding speed were chosen as the factors. Of them, SiC wt% is varied at two levels (low, high), and the other three factors, axial load, rotational speed

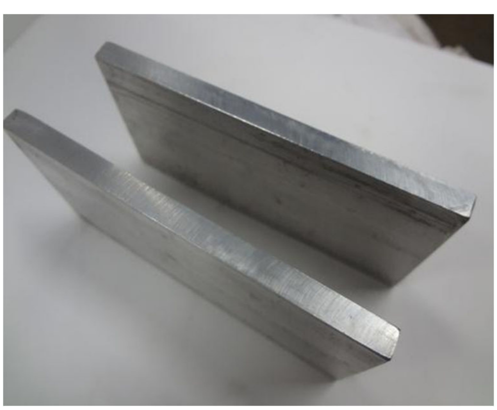


Fig. 1 Welding sides of Al 6351 alloy plates

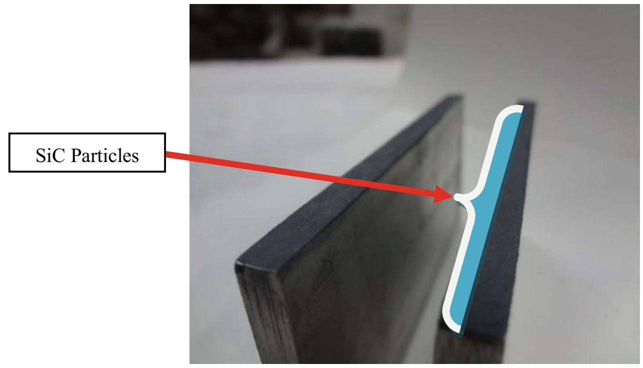


Fig. 2 Evenly distributed SiC particles on the welding sides of Al 6351 alloy plates

Table 1 L18 mixed level orthogonal array

Exp. no.	SiC wt%	*L* (KN)	*S* (RPM)	*F* (mm/min)
1	1	1.5	710	14
2	1	1.5	1000	21
3	1	1.5	1400	29
4	1	2	710	14
5	1	2	1000	21
6	1	2	1400	29
7	1	2.5	710	21
8	1	2.5	1000	29
9	1	2.5	1400	14
10	1.5	1.5	710	29
11	1.5	1.5	1000	14
12	1.5	1.5	1400	21
13	1.5	2	710	21
14	1.5	2	1000	29
15	1.5	2	1400	14
16	1.5	2.5	710	29
17	1.5	2.5	1000	14
18	1.5	2.5	1400	21

Table 2 L18 orthogonal array with responses and S/N ratios of as-weld plates

Exp. no.	SiC wt%	*L* (KN)	*S* (RPM)	*F* (mm/min)	Responses			S/N ratios		
					UTS	Hardness	Impact	UTS	Hardness	Impact
1	1	1.5	710	14	135.5	60	0.84	55.19	48.12	11.04
2	1	1.5	1000	21	141.67	63	0.84	55.58	48.54	11.04
3	1	1.5	1400	29	178.57	62	0.98	57.59	48.40	12.38
4	1	2	710	14	137.5	53	0.84	55.32	47.04	11.04
5	1	2	1000	21	154.47	61	0.84	56.33	48.26	11.04
6	1	2	1400	29	185.8	64	0.84	57.93	48.68	11.04
7	1	2.5	710	21	144	62	0.84	55.72	48.40	11.04
8	1	2.5	1000	29	138.44	63	0.98	55.38	48.54	12.38
9	1	2.5	1400	14	134.72	54.5	0.98	55.14	47.28	12.38
10	1.5	1.5	710	29	141.67	60	0.84	55.58	48.12	11.04
11	1.5	1.5	1000	14	138.21	52	0.7	55.36	46.72	9.45
12	1.5	1.5	1400	21	175	58.5	0.84	57.41	47.90	11.04
13	1.5	2	710	21	147.22	56.5	0.98	55.91	47.59	12.38
14	1.5	2	1000	29	138.89	64.5	1.26	55.41	48.74	14.56
15	1.5	2	1400	14	131.19	59.5	0.84	54.91	48.04	11.04
16	1.5	2.5	710	29	163.89	60	0.84	56.84	48.12	11.04
17	1.5	2.5	1000	14	133.33	54	1.12	55.05	47.20	13.54
18	1.5	2.5	1400	21	129.78	51.5	0.84	54.82	46.79	11.04

and welding speed, were varied at three levels (low, mid and high). Tensile strength, Brinell hardness and impact strength of the welded joints were taken as the responses to evaluate the properties of the welded plates. Annealing of the friction

Table 3 L18 orthogonal array with responses and S/N ratios of annealed plates

Exp. no.	SiC wt%	*L* (KN)	*S* (RPM)	*F* (mm/min)	Responses			S/N ratios		
					UTS	Hardness	Impact	UTS	Hardness	Impact
1	1	1.5	710	14	111.1	41.2	0.7	53.47	44.85	9.45
2	1	1.5	1000	21	104.2	47.5	0.84	52.91	46.09	11.04
3	1	1.5	1400	29	128	46	0.7	54.70	45.81	9.45
4	1	2	710	14	118.05	43.5	0.84	53.99	45.32	11.04
5	1	2	1000	21	108.33	41.8	0.84	53.25	44.98	11.04
6	1	2	1400	29	116.34	42.5	0.84	53.87	45.12	11.04
7	1	2.5	710	21	127.78	43.5	0.84	54.68	45.32	11.04
8	1	2.5	1000	29	129.17	46	0.7	54.78	45.81	9.45
9	1	2.5	1400	14	133.33	42.5	0.98	55.05	45.12	12.38
10	1.5	1.5	710	29	136.11	44.5	0.7	55.23	45.52	9.45
11	1.5	1.5	1000	14	108.40	40.5	0.7	53.25	44.70	9.45
12	1.5	1.5	1400	21	122.22	49.5	0.84	54.30	46.44	11.04
13	1.5	2	710	21	138.9	43.5	0.84	55.41	45.32	11.04
14	1.5	2	1000	29	127.78	44	0.98	54.68	45.42	12.38
15	1.5	2	1400	14	129.17	46	0.7	54.78	45.81	9.45
16	1.5	2.5	710	29	126	45	0.7	54.56	45.61	9.45
17	1.5	2.5	1000	14	130.55	43.5	0.84	54.87	45.32	11.04
18	1.5	2.5	1400	21	123	44.5	0.84	54.35	45.52	11.04

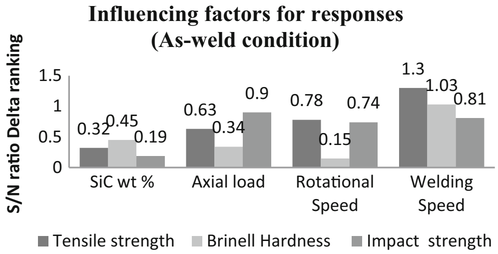


Fig. 3 Influencing factors for responses in as-weld condition

stir welded Al 6351 alloy plates were done in an electrical muffle furnace. The welded plates were soaked at a temperature of 311 °C for 2 h and were then allowed to cool in still air. Tensile test specimens were prepared according to ASTM B557 standard and were tested in 12-tonne UTM testing machine. The Brinell hardness test samples were prepared as per ASTM E10-12 standard and were tested with an applied load of 31.625 kg under 2.5-mm steel ball indenter. For the impact test, samples were prepared as per ASTM D256 standards and were tested on an Izod impact testing machine.

3 Results

3.1 Signal to noise ratio

The assessment of influencing factors on the responses is calculated using S/N ratio. By the appropriate selection of S/N ratio, the goal of the design could be achieved. In the present study, Taguchi's loss function "larger the better" criteria is selected so that the welded joints will have superior properties at the weld zone. It is evident that the larger S/N ratio corresponds to the superior weld quality. In Taguchi's method [21], the signal to noise ratio (i.e. S/N ratio) is used to determine the deviation of the quality characteristics of the desired value. Tensile strength, Brinell hardness and impact strength at the weld section were tested to evaluate the strength of the welded joints. Study of the influence of chosen factors on response was found by calculating

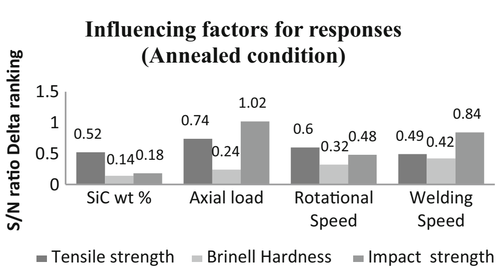


Fig. 4 Influencing factors for responses in annealed condition

Table 4 Mean and standard deviation values for as-weld and annealed condition

	As-weld condition	Annealed condition
Mean value of hardness	58.833	44.194
Standard deviation	4.2357	2.2459

S/N ratios. The S/N ratio of Taguchi's quality loss function is expressed by Eq. (1).

$$SN_L = -10\log\left(\frac{\sum_{i=1}^{n} 1/y_i^2}{n}\right) \quad (1)$$

where n is the number of tests and y_i is the experimental value of the ith quality characteristics of the experiment. The estimated responses and their corresponding S/N ratios of the as-weld plates are given in Table 2 and for the annealed condition in Table 3.

4 Discussion

The influences of chosen factors (process parameters) are determined by ranking the S/N ratios, which is obtained by the average of the calculated values at three levels. Delta (Δ) ranking helps to identify the influencing factors based upon ranking obtained by the differences between the maximum and minimum S/N ratio values of the factor within the three levels (low, mid and high). The analysis of S/N ratios was done for the responses of the friction stir welded Al 6351 alloy plates for both conditions (i.e. as-weld condition and annealed condition). The ranking of influencing factors

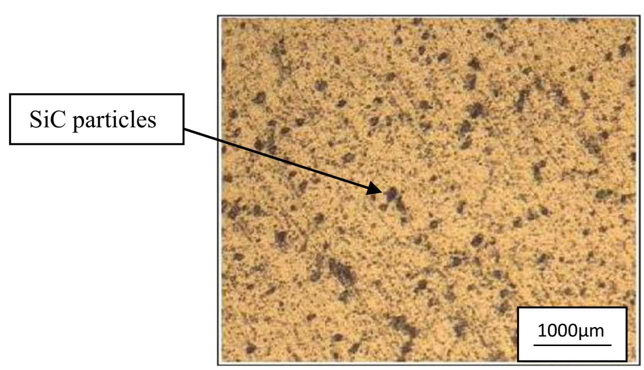


Fig. 5 Microstructure image of the as-weld plates showing uniform distribution of SiC particles in the weld zone

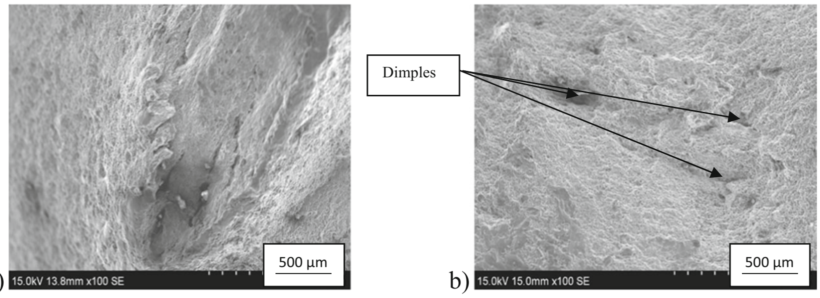
a) b)


Fig. 6 SEM image of FSW plates without addition of SiC particles: **a** As-weld, **b** Annealed

for the responses viz tensile strength, Brinell hardness and impact strength in as-weld condition were charted and given in Fig. 3 and for annealed condition in the Fig. 4.

From Fig. 3, it is evident that the responses viz tensile strength, hardness and impact strength of the welded joint in as-weld condition are mainly influenced by welding speed. Selection of correct welding speed will result in the complete mixing of added SiC particles with the parent Al 6351 alloy. A too high or low welding speed will lead to agglomeration of the added SiC particles thereby resulting in inferior strength and hardness. Similarly, from Fig. 4, it is evident that responses of the welded plate in the annealed condition are mainly influenced by the factor axial load. Proper selection of axial load will result in the introduction of dislocations in the weld zone which will improve the mechanical strength [22]. In Al 6351 alloy welded plates without the addition of SiC particles, grain growth occurs leading to increasing in grain boundaries during annealing. As per Hall-Petch relation, the yield strength has an inverse square root relation with grain size [23]. Table 4 shows the mean and standard deviation values of the hardness of the friction stir welded plates for both as-weld and annealed conditions. The standard deviation value of hardness in as-weld condition is found to be 4.2357 HB, and the value of standard deviation in annealed condition is 2.2459 HB. The deviation from the desired mean value is found at a minimal range in annealed condition. This is due to the addition of SiC particles in the nugget zone which helped to retain the hardness even in annealed condition. The strength and hardness value of Al 6351 alloy plates welded without the addition of SiC particles decreased on annealing due to increasing in grain size which is shown by earlier work [24].

In Al 6351 alloy welded plates with the addition of SiC particles, the introduction of dislocations due to proper selection of axial load and presence of uniformly distributed SiC particles results in pinning effect on grain growth during annealing. Nevertheless, the addition of SiC particles during friction stir welding has resulted in the improvement of tensile strength both in the as-weld and annealed condition due to the uniform distribution of the particles in the weld zone as shown in Fig. 5.

Figure 6a, b is the SEM images of the failed tensile test specimens of as-weld and annealed plates without addition of SiC particles, respectively. The as-weld sample has more cleavage facets fracture which is an indication of brittle failure [25–27]. In Fig. 6b, more ductile dimples are visible on account of grain growth that has occurred during annealing treatment. Figure 7 shows the SEM images of failed tensile test specimen of as-weld and annealed plates with addition of SiC particles. It is evident that the SiC particles in Fig. 7a are uniformly

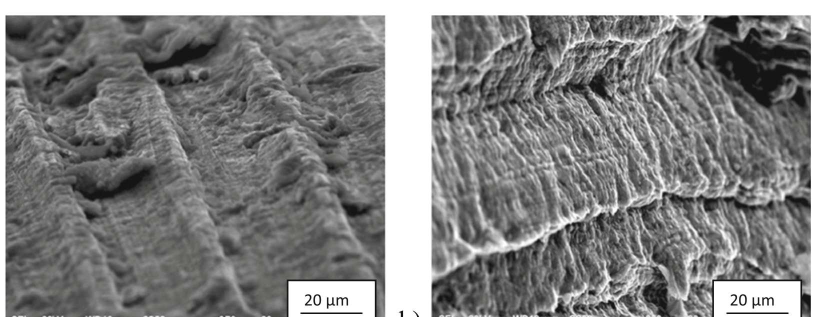
a) b)


Fig. 7 SEM image of FSW plates with addition of SiC paricles: **a** As-weld, **b** Annealed

distributed in the fractured area, and in Fig. 7b, the ductile dimples are reduced in the fractured area compared to annealed plain Al 6351 alloy plates.

Depending on the combination of the parameters chosen and the role of added SiC particles, the failure of the tensile test specimen occurred either at the nugget zone or at the heat affected zone. Specimens which had fairly uniform distribution of SiC particles reported higher values of tensile strength and failure at HAZ. On the other hand, samples with non-uniformly distributed SiC particles due to improper parameter combination failed at NZ. The results of S/N ratio for Brinell hardness characteristics of as-welded Al 6351 plates show that welding speed is the major influencing factor. The second most influencing factor is SiC wt% followed by rotational speed and axial load, respectively. Similarly, in the annealed condition, the hardness characteristic is influenced by the welding speed. Moreover, the factors rotational speed, axial load and SiC wt% have the equal effect on the hardness characteristics of the friction stir welded Al 6351 alloy plates in annealed condition. The addition of SiC particles in the weld zone during friction stir welding of Al 6351 alloy plates have improved the hardness characteristics in the nugget zone due to the uniform distribution of SiC particles than in the base metal. However, the welding speed is considered as the most influencing factor than SiC wt% because it plays a vital role in helping the tool to mix the added SiC particles with the Al 6351 alloy plates thoroughly in the stir zone.

The impact strength of the Al 6351 alloy plates in the as-weld condition and annealed condition is moreover equal. Despite their conditions (i.e. As-weld condition or annealed condition), there is not much notable difference in their property. Added SiC particles in the weld region have improved the impact strength of the welded joints of Al 6351 alloy plates. In other words, the impact resistance has increased to a value of 1.26 kg-m which is higher than the parent metal impact resistance value of 1.12 kg-m. From the above discussion, it is evident that the addition of SiC particles during friction stir welding of Al 6351 alloy plates satisfies the objective. The method and the amount of SiC particles added are found to be valid for implementing it with friction stir welding through this investigation which is also evaluated by means of statistical approach [28] and by the previous work [29] with the statistical modelling for predicting the mechanical properties [30]. In the as-weld condition, the influence of parameters for the responses like hardness, tensile strength and impact strength is also playing a vital role. The interaction effect of the parameter welding speed and rotational speed influences the response at high-level experimentation. This is because when the rotational speed is at a higher level, the frictional heat generated will be high resulting in the higher material flow. During such conditions, the need for the transportation of material with the help of welding speed must be high. So, the interaction of the rotational speed and welding speed results in higher mechanical property of the welded aluminium alloy. Moreover, a proper parameter combination selection is required for obtaining better results in mechanical property characteristics. The parameter combination of rotational speed, axial load and welding speed plays a vital role in the property characteristics as variation in the effects could be clearly seen whenever the ranges are varied. For the overall performance, it is suggested to keep the parameters at mid range except for SiC and welding speed; the range should be kept at a high level for it shows better property characteristics.

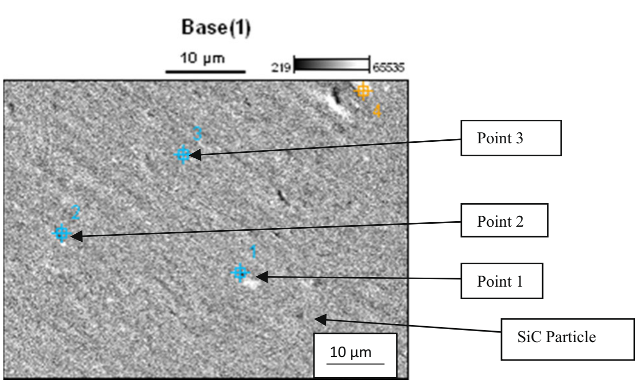


Fig. 8 SEM image of as-weld sample with SiC particles in the weld zone

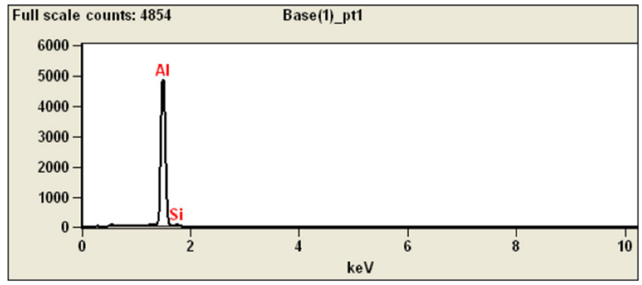


Fig. 9 EDS for the as-weld sample with addition of SiC particles in the weld zone

Table 5 Atom percentages of the spectrum points in as-weld sample

	Mg-K	Al-K	Si-K	Mn-K
Base(1)_pt1		97.32	2.68	
Base(1)_pt2	0.93	93.50	5.11	0.46
Base(1)_pt3	0.38	99.16	0.47	

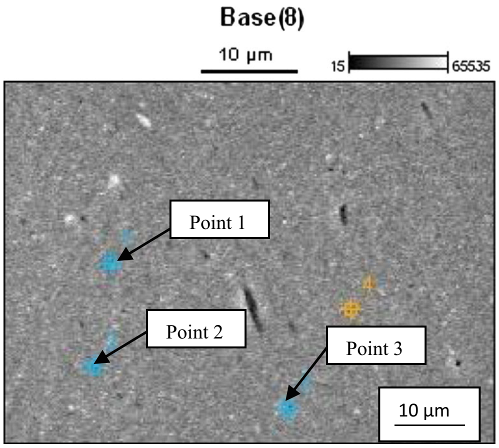


Fig. 10 SEM images of the annealed sample with SiC particles in the weld zone

The energy dispersive X-ray spectroscopy was taken to evaluate the microstructure characteristics of SiC particle addition in the weld zone on friction stir welding of Al 6351 alloy plates. Spectroscopy was taken at an accelerating voltage of 15 kV with a magnification of ×2500.

Figure 8 shows the SEM image of the as-weld sample with the addition of SiC particles in the weld zone. The spectra of the point 1, 2 and 3 are shown in Fig. 9. The spectrum at point 1 clearly shows the presence of silicon and aluminium. The results shown in Table 5 are atom percentages of the spectrum points in the as-weld sample. The result indicates the atom percentages of the various spectral points in which the SiC percentages could be clearly seen. The SiC particle has majorly distributed and mixed with base alloys. This concentration of added SiC particle percentages could be seen in spectra point 2. On account of this mixing of SiC particles, the as-welded samples of the Al6351 have reported a higher mechanical property values.

Figure 10 shows the SEM image of the annealed sample with the addition of SiC particles. The corresponding spectra of the points 1, 2 and 3 are shown in Fig. 11. The spectrum at point clearly shows the presence of silicon and aluminium. The results shown in Table 6 are the atom percentages of the spectrum point in annealed sample. Because of the annealing effect, the aluminium alloy expands its boundary increasing the aluminium alloy atom percentages, and it could be seen in the spectral points. However, it is evident from the spectral points 2 and 3 that the addition of SiC particles restricts the grain boundary growth by pinning effect and maintains the distribution evenly throughout the samples. On account of this pinning action of the added SiC particles, the mechanical property in the annealed condition is maintained with only marginal decrement of values. Therefore, the addition of SiC particles during welding has resulted in increase of mechanical properties to an extent of 33 % in as-weld condition over plain alloy. Similarly, the reduction in the mechanical properties on account of annealing has differed from 29 to 25 % compared to welding of unreinforced alloy plates.

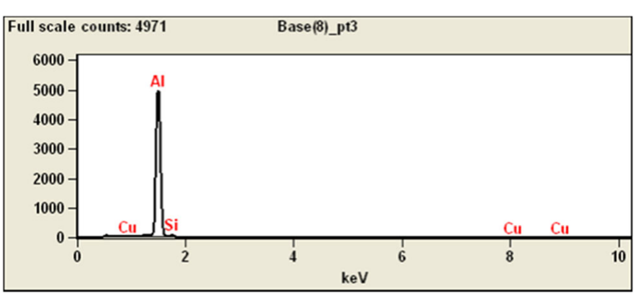


Fig. 11 EDS for the annealed sample with addition of SiC particles in the weld zone

Table 6 Atom percentages of the spectrum point in annealed sample

	Mg-K	Al-K	Si-K	Cu-K
Base(8)_pt1	0.33	98.99	0.46	0.21
Base(8)_pt2	1.53	95.95	2.51	0.00
Base(8)_pt3		97.11	2.57	0.31

5 Conclusion

Based on the investigation of friction stir welding on Al 6351 plates with addition of SiC particles in the weld zone for both as-weld and annealed conditions, the following conclusions are derived.

- The method of addition of SiC particles during friction stir welding of Al 6351 plates is found to be a viable technique.
- SEM-EDX study reveals uniform distribution of SiC particles in the weld zone which is an indication that correct proportion of SiC particles has been added.
- The SiC weight percentages are sufficient enough in the friction stir welding of Al 6351 alloy plates, and the results of the mechanical property are found to be improved by retaining the characteristics when compared to our earlier studies.
- Improvement of 33 % was obtained in mechanical properties of as-welded plates of Al 6351 alloy.
- The reduction of mechanical properties in annealed condition, when compared to the base material to Al 6351 alloy plates welded with SiC particle addition, was reduced from 29 to 25 %.

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