Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 44 No. 4 (2023)

Optimization of process parameters for producing AA6061/SiC nanocomposites by friction stir processing Optimization of process parameters for FSW AA7075/TiC, B4C, Al2O3 nano Hybrid composites by Taguchi technique

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Abstract: A significant area of research now being pursued by the foundry industry is how to enhance the mechanical properties of aluminium alloys by reinforcing them with micro ceramic particles. The mechanical and Microstructural studies of commercial AA 7075 stir die castings reinforced by various weight ratios of titanium carbide (TiC), boron carbide (B_4C), and aluminium oxide (Al_2O_3) have been examined in the current study. Further, friction stir welding (FSW) process has been carried out based L_{16} Orthogonal Array (OA). Optimal decision making approach for the improvement of Friction Stir Welding (FSW) process was performed by Taguchi method. Investigations were conducted on the effects of three variables on UTS, including rotating speed, transverse speed and tilt angle. The maximum ultimate tensile stress was found to be around 162 M Pa for sample 8 (1.5 wt% TiC, 0.5 wt% B_4C and 0.8 wt% Al_2O_3) welded at speed 900 rpm, feed 45 mm/min, and Tilt angle 2.5^0.
Keywords: Reinforcement, FSW Process, AA7075, Ultimate Tensile strength(UTS), Tilt angle, Taguchi Technique.

1. Introduction

Aluminium alloys hold great promise for structural applications in the aerospace, defense, and transportation sectors because to their low density, high specific strength, and ability to resist corrosion, particularly in light of the high energy costs. The environment, handling dynamics, greenhouse gas emissions, and fuel efficiency are all improved when vehicles are lighter. To lessen the weight of a vehicle, lighter metals and polymers, such aluminium and magnesium, can be utilized in favor of heavy steels. In the aircraft industry, a lightweight structure is a crucial design element [1–2].

Aluminium matrix composites reinforced with ceramic phases display better strength and stiffness, enhanced Tribological properties, and increased resilience to creep and fatigue when compared to unreinforced aluminium alloys. Large ceramic particulate composites are vulnerable to cracking under mechanical loading, which causes early failure and limited ductility of the composites [3]. By reducing the size of ceramic particles and/or matrix grains from micrometer to nano scale level, the mechanical characteristics of metal matrix composites (MMCs) can be improved even more. According to MA et al. [4], the yield strength of the 1% (volume fraction) Si3N4 (15 nm)/Al composite is significantly higher than that of the 15% SiCp (3.5 m)/Al composite, while both have comparable tensile strengths. According to KANG and CHAN [5], the hardness of the metal was comparable to that of a 10% SiCp (13 m)/Al following the addition of a tiny amount (1%) of nano-particulate in the Al. The potential creation of innovative composites with distinctive mechanical and physical properties has generated significant scientific interest in the use of nanoparticles to strengthen metallic materials in recent years. Reinforcing nanoparticles must be dispersed equally throughout the metal matrix of the nano-composites in order to attain the appropriate properties for mechanical strength. However, it is challenging to obtain homogenous dispersion of ceramic nanoparticles in metals. Ex-situ ceramic nanoparticles can be incorporated into a matrix by using either the powder metallurgy (PM) or liquid metallurgy technique for developing metal matrix nano hybrid composites (MMNHCs).In this research work MMNHCs were fabricated by friction stir casting method.

There are various flaws in the joint quality of AMCs welded using traditional fusion welding techniques. Fusion welding causes the production of detrimental phases in the joint region as a result of excessive heat, cracking, deformation, porosity, and the settling of hard particles at the bottom of the weld zone as a result of the difference in densities [6-7]. An advantageous joining approach for AMCs appears to be a solid state welding process. The Welding Institute (TWI) created and patented friction stir welding as a solid state welding method in 1991 to join aluminium alloys [8]. Finding the ideal levels of speed, feed, and tilt angle for maximizing UTS, Elongation, and Micro Hardness was the goal of a study by K. Jitender et al. [9] that investigated the optimization of process parameters in FSW of AA5083 alloy using Taguchi grey analysis. High strength-to-stiffness ratios are possible with metal structures, and reinforcing particles can produce unique features [13-16]. To clarify particular concerns, such as the frictional contact conditions at the tool-work piece interface, essential experiments must be carried out. It would be ideal to use simulations to accurately forecast the impact of tool geometry and weld settings on the material flow fields [17]. Numerous bonding techniques can enhance the quality of welded materials and alloys, according to recent study. Due to its capacity to join and process thermo-mechanical lightweight metallic materials, friction stir welding and processing (FSW/P) is currently regarded as a well-known application. Four main factors—tool geometry, plunging depth, rotating and traverse speed, and tool tilt angle—have a significant impact on the FSW/P [18]. Grain refinement was visible in all three layers of the nugget zone, with smaller grains in AA7075. Tensile strength increases at the dissimilar joints as heat input is reduced. Alloys like AA6061 and AA7075 have undergone dynamic recrystallization and when welding speed increases, grain size falls dramatically. Compared to their respective base metals, the tested specimens showed a little decrease in micro hardness at the weld. The joints with the lowest heat input have a greater minimum hardness profile [19]. To determine how pin geometry affects their macrostructure, microstructure, and mechanical properties, Bahrami et al. looked into friction stir welds reinforced with Sic nanoparticles. Material flow in the vicinity of the pin tool reveals stir zones without flaws. By using a threaded tapered pin, the high consistency of particle distribution was achieved. A well grained microstructure was created within the stir zone by plastic deformation and frictional warming during the operation. The key welding characteristics to consider, according to Pasha et al., are tool speed, weld speed, weld tilt, and weld pin form. Dynamic recrystallization produces minute, equiaxed grains (DRX), according to microstructure studies. Al2O3 particles stop grain growth by impeding grain boundaries and so limiting their motion. In the FSW and PWHT specimens, abrasive and adhesive wear were the mechanisms of wear. The uniform dispersion of Al2O3 particles turned out to be an ideal value for travelling speed [20].

In order to evaluate process variables while taking into account statistical procedures and evaluating how process parameters affect mechanical characterizations, the current research integrated friction stir welded characterization of AA7075 with titanium carbide, boron carbide, aluminium oxide(TiC, B_4C, Al_2O_3) nano particles as a strengthening factor . With requirements taking into account rotating speed, welding speed, and tilt angle, an experiential evaluation was carried out. To precisely assess the variables affecting the process parameters, experiments were designed.

2. Materials and Experimentation

2.1 Work materials

For this study, Aluminium alloy, namely AA 7075, have been selected as a base metal for the specimen preparation in this investigation as shown in Table.1. Titanium carbide nano powder (TiC), boron carbide (B_4C) and aluminium oxide (Al_2O_3) taken as reinforcement ceramic particles which will influence the grain structure and mechanical properties of base alloy. The term titanium carbide nano powder (TiC) describes extremely small fragments of titanium carbide, a substance comprised of titanium and carbon atoms.

Small particles with a diameter of 1 to 100 nano meters are known as nano powders. The size of Titanium carbide nano powder (TiC) was taken as 50 nm. "Black diamond" is another name for boron carbide. The boron carbide nanoparticles are roughly 50 nm in diameter. At 2600 ° C, graphite and boric acid are combined in order to produce it. One of the toughest materials ever known, boron carbide has an exceptional hardness and wear resistance. It has hardness that is only surpassed by diamond; it is ideally suited for applications that require resistance to abrasion and wear. The material possesses high strength, hardness, crushing efficiency, and elastic modulus as well as thermal resistance and anti-oxidation properties. Aluminium oxide is derived from mainly two sources, bauxite mineral and recycled Alumina. It can be prepared by the hydrolysis of the alkoxide of Al_2O_3 and calcinations of particles in the presence of stabilizing agents. The size of aluminium oxide (Al_2O_3) was taken as 30 nm.

Table 1: Chemical composition of Al -7075 alloy (mass %)

Al	Zn	Mg	Cu	Si	Fe	Mn	Ti	Cr
90	**5.6**	**2.1**	**1.1**	**0.3**	**0.3**	**0.2**	**0.2**	**0.2**

2.2 Tool material

Joints of metal matrix nano composites (MMNCs) are welded by FSW using tapered conical threaded tool. A tapered conical threaded is made up of HSS, H13 tool steel was used for welding the experiment. Fig.1. It is having high temperature, good thermal conductivity and high strength.

2.3 Design of experiments

In this research, the design of experiments has been prepared by the Taguchi approach. In this approach, the selection of significant process parameters is the most important stage, which is generally set by the experimenter's experience. Based on previous investigation [18] on optimization of the FSW process, mainly three process parameters such as rotational speed, feed and tilt angle which are significantly influences the friction stir welding process are recognized as the FSW process parameters in the experimental design in order to yield the optimum strength in joint by minimizing fusion weld defects of the metal matrix castings. Taguchi provided a well-organized approach to estimate the optimal levels of significant input process parameters with the help of the L_{16} orthogonal array system. The selected levels for these input parameters are given in table 1. With respect to the L_{16} orthogonal array, experimental design for the fabrication of casting samples and Friction Stir Welding at different levels of welded process parameters has been prepared.

2.4 Experimental design using Taguchi methods

Taguchi's approach is a static tool for improving design problem performance processes with to respect cost and time, and the number of experiments is significantly decreased. [10]. Utilizing this method, the ideal conditions for a product or process can be determined, the most important factors are found, and the best response of the process parameters can be predicted. Using the experiment approach known as DOE, we can examine the impact of changing many process factors at once at various levels. This allows us to understand how many components interact with one another. Three three-level parameters (rotation speed, transverse speed, tilt angle) are selected for this study using L16 orthogonal array design. It should be mentioned that only the main factor effects are taken into consideration and not the interactions. A total of sixteen runs of the experiment need to be conducted using the combination of levels for each process parameters. The full factorial experimental design would have required 4*4*4=64 runs. Thus using Taguchi experiment design, we have eliminated 48 FSW runs. This helps to save a lot of time and resources. The experimental design carried out with the help of MINITAB 18 software.

Table 2. Welding process parameters and their levels used in the experiments

Parameter destination	Input parameters	Parameter range	Level 1	Level 2	Level 3	Level 4
A	Rotational Speed (RPM)	800 - 1100	800	900	1000	1100
B	Feed (mm/min)	30 - 45	30	35	40	45
C	Tilt angle (^{0})	1 - 2.5	1.0	1.5	2.0	2.5

2.5 Friction Stir Welding

For this investigation, total nine (based on L9 OA) metal matrix composites were fabricated at different weight percentages of ceramic nano particulates (TiC, B_4C and Al_2O_3) as shown in table 3, with the help of a new automated stir casting gadget with a connected electrical induction furnace and a bottom side pouring configuration has been hired to create base alloys more advantageous with nanoparticles. Out of nine castings, one is pure base metal i.e without adding nano ceramic particles. Remaining eight castings were prepared at different weight percentages of nano particles . From these eight castings, 16 samples (i.e two samples from each casting) have been prepared for Friction Stir Welding process based on L16 orthogonal Array (OA).

Friction Stir welding has been conducted on 16 samples at various levels of process parameters (speed, feed and tilt angle) as in Table.4

To evaluate the tensile strength properties of the fabricated samples joined by Friction Stir Welding (FSW), specimens were prepared according to ASTM: B557-15 standard using the CNC wire cutting machine. Tensile strength values for 16 samples were obtained from the universal testing machine as shown in Table. Microstructure and extracted inter-metallic particles of the Al-7075 alloy reinforced with nano particles were examined by -SEM.

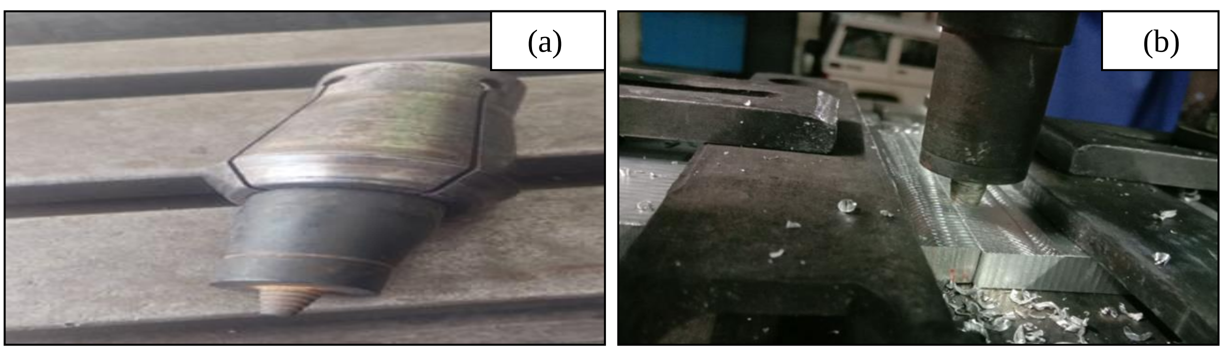

Fig 1: (a). HSS H13 Tool with holder for FSW; **(b)** Friction stir welding process setup with tool holding fixture

This process generates strong forces that act on the base plate and cause the plates to separate. The tool then plunges into the work pieces that need to be welded. The joint must be held together by a rigid clamping mechanism; otherwise, plasticized material will be driven through the joint and harm it. To stop work plates from moving longitudinally, fixtures were utilized as clamps. A friction stir welding configuration for experimental conduction is shown in Table 4. The process generates substantial forces that act on the base plate and cause the plates to separate. The tool then plunges into the components of work that need to be welded. To keep the joint together, a rigid clamping device is required; otherwise, plasticized material will be driven through the joint and ruin it. The plates experience thermal expansion and buckling tendency during the welding process when friction stir welding is used. This can be constrained with the right clamping. Mild steel plates are used to construct the fixture components for the current project

Table 3. Metal matrix composites fabricated at different weight percentages of ceramic nano particulates (L9 OA)

Sample No	Temperature	TiC Wt%	B_4C Wt%	Al_2O_3 Wt%
1	720	0	0	0
2	720	1	0.8	0.5
3	720	1.5	0.5	0.5
4	750	1	0	0.8
5	750	0	0.8	0.5
6	750	1.5	0.5	0.5
7	780	0	0.5	0.8
8	780	1	0.8	0
9	780	1.5	0.5	0.8

Table 4. Tensile strength values of Friction Stir Welding samples at different levels of process parameters

Sample Number	Input process parameter			Output parameter
	Speed	Feed	Tilt Angle	Ultimate Tensile Strength
1	800	30	1.0	103.6
2	800	35	1.5	142.3
3	800	40	2.0	137.8
4	800	45	2.5	140.2
5	900	30	1.5	148.0
6	900	35	1.0	132.0
7	900	40	2.5	154.0
8	900	45	2.0	162.0
9	1000	30	2.0	134.0
10	1000	35	2.5	141.0
11	1000	40	1.0	152.0
12	1000	45	1.5	138.0
13	1100	30	2.5	145.0
14	1100	35	2.0	135.0
15	1100	40	1.5	138.0
16	1100	45	1.0	150.0

3. Results and Discussion

*3.*1Mechanical properties of die casting AA7075

Table 3 shows the output characteristics such as tensile strength values of Friction Stir Welded samples which are obtained from the 8 experimental Friction Stir castings prepared in two sets at different weight percentages of ceramic nano particles (TiC, B4C, Al2O3) The significant effect of grain refinement by reinforcement particles on the mechanical properties of the commercial AA7075 alloy such as ultimate tensile strength (UTS) have been observed here. The UTS values of the AA7075 alloy are improved by the addition of the ceramic particles which are act as equiaxed grain refining sites. From Table 3, it has been observed that the maximum Tensile Strength was attained for sample 8, which was performed Friction stir welding at 900 rpm, 45mm/min feed and 2.0 ^{0} tilt angle. Also, it was noticed that less tensile strength occurred for sample 1 such as 122 MPa.

3.2 Optimization

The welding experiments have been conducted on vertical milling machine available at Private Industry, Hyderabad, Telangana State, India. Experimental data are traditionally used to analyze the mean response. The Taguchi method stresses the importance of studying the variation of the response using the Signal-to-Noise (S/N) ratio . The reason for this is to minimize the variation in the quality characteristics due to uncontrollable parameters. Hence, the tensile strength is a "Higher the better" type of quality characteristic, so the S/N ratio was used for that type of response. For next step, the S/N ratios were computed for 16 samples. The values, the mean values for each parameter at different levels and the S/N ratios of each test are shown in Table 4. The average values of tensile strength for each parameter at levels 1 to 4 are given in Table 5 and are plotted in Figs. 2(a)−(c). Average values of S/N ratio of varies considered parameters at four levels are given in Table 6 and plotted in Figs. 3(a)−(c). The main effects in terms of S/N data are also given in Table 6.Residual plots for ultimate strength are shown in Fig 4.

Table.4 Tensile strength mean values and S/N ratios against sample numbers at various levels of parameters

Sample No	Speed	Feed	Tilt Angle	Ultimate Strength	S/N ratio	Mean
1	800	30	1.0	122.0	41.7272	103
2	800	35	1.5	135.0	42.6067	142.3
3	800	40	2.0	137.8	42.7850	137.8
4	800	45	2.5	140.2	42.9350	140.2
5	900	30	1.5	148.0	43.4052	148.0
6	900	35	1.0	132.0	42.4115	132.0
7	900	40	2.5	154.0	43.7504	154.0
8	900	45	2.0	162.0	44.1903	162.0
9	1000	30	2.0	134.0	42.5421	134.0
10	1000	35	2.5	141.0	42.9844	141.0
11	1000	40	1.0	152.0	43.6369	152.0
12	1000	45	1.5	138.0	42.7976	138.0

13	1100	30	2.5	145.0	43.2274	145.0
14	1100	35	2.0	135.0	42.6067	135.0
15	1100	40	1.5	138.0	42.7976	138.0
16	1100	45	1.0	150.0	43.5218	150.0

From Fig. 2 and 3, it is revealed that the tensile strength is maximum at the 2nd level of the parameters A and 4th level of the B, and C .Moreover, the S/N ratio analysis exposed in Figs. 3 also recommended that the parameter levels A2, B4 and C4 are the optimizing levels for reducing the variability of the Friction stir welding process of AA7075 alloy. It must be noted that the above combination of factorial levels (2, 4 and 4) was not one of the 16 combinations tested in our set of experiments. This was expected because of the small number of experiments conducted in the employed experimental design (16 from $3^4 = 81$ possible combinations).

Table. 5 Response Table for Means

Level	**Speed**	**Feed**	**Tilt Angle**
1	133.8	137.3	139.0
2	149.0	135.8	139.8
3	141.3	145.4	142.2
4	142.0	147.6	145.1
Delta	15.3	11.8	6.1
Rank	1	2	3

Table. 6 Response Table for Signal to Noise Ratios

Level	**Speed**	**Feed**	**Tilt Angle**
1	42.51	42.73	42.82
2	43.44	42.65	42.90
3	42.99	43.24	43.03
4	43.04	43.36	43.22
Delta	0.93	0.71	0.40
Rank	1	2	3

In order to study the significance of process parameters, ANOVA was performed in Table 7. From Table 7, it shows that the speed of the machine (parameter A) significantly affect the mean average of tensile strength of 18.9%. Confidence interval (CI) has been calculated for 95% consistency level and some conformational experiments have been conducted at optimum level of the process parameters for validation of the adequacy of the Taguchi method. Table 8 shows the confidential intervals at 95 percentages of parameter speed levels. From this it was observed that the Level 2 which shows 900 rpm, is the influencing level of speed for optimization of FSW process.

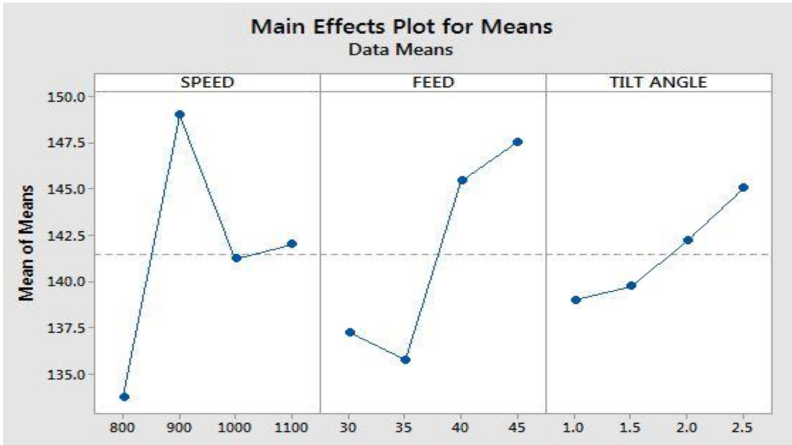

Fig 2 : Main Effects Plot for Means

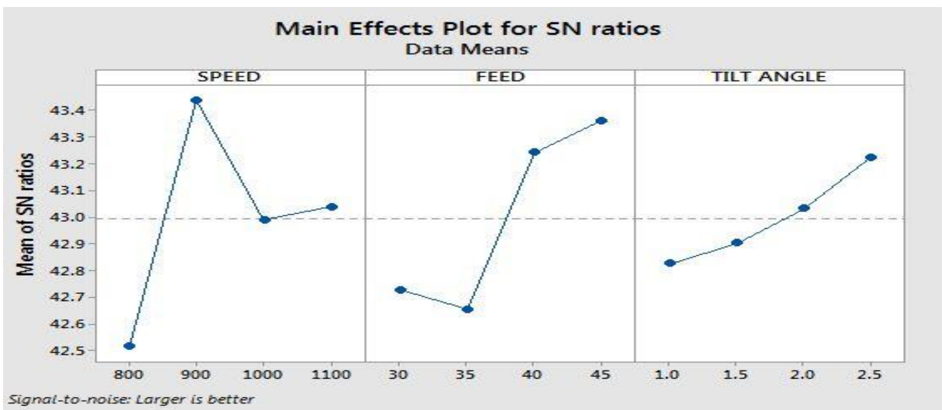

Fig 3: Main Effects Plot for SN ratios

Table 7: Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
SPEED	3	466.5	155.50	1.87	0.189
Error	12	998.4	83.20		
Total	15	1464.9			

Table 8: Standard deviation and confidential intervals speed

SPEED	N	Mean	StDev	95% CI
800	4	133.75	8.12	(123.81, 143.69)
900	4	149.00	12.70	(139.06, 158.94)
1000	4	141.25	7.72	(131.31, 151.19)

1100	4	142.00	6.78	(132.06, 151.94)

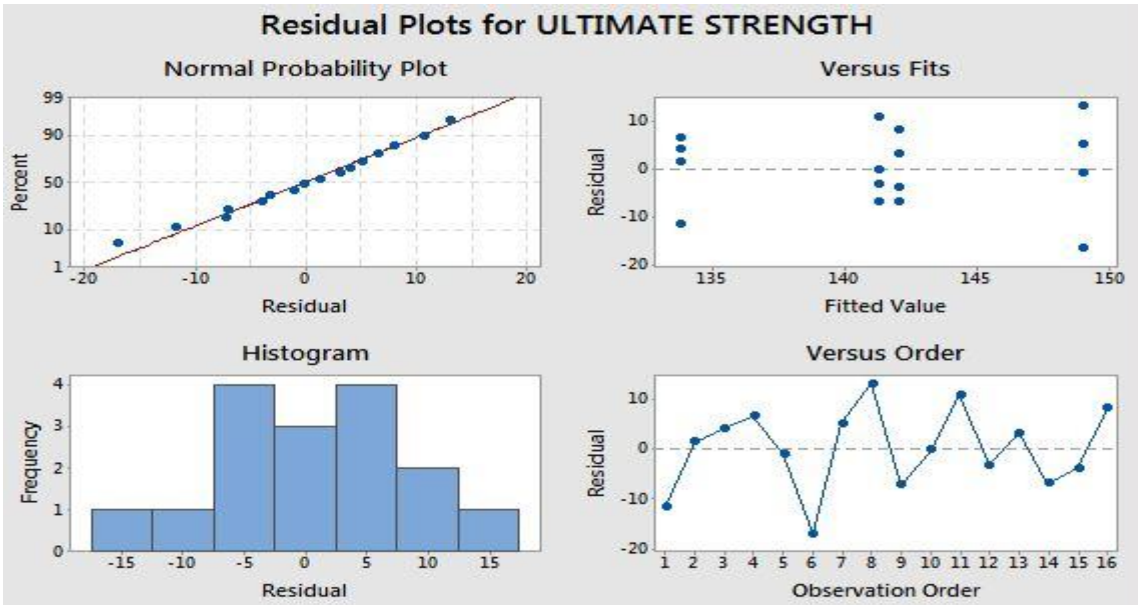

Fig 4: residual plots for ultimate strength

3.3 Microstructure of the Composite

The microstructure investigation was done using an optical microscope through inspecting electron Microscope (SEM) JEOL JCM-6000PLUS as shown in Fig 5 In order to understand the failure pattern, the scanning electron microscope was used to characterize the tensile fracture surface of friction stir processed composites of the tensile test specimens. As can be shown in Fig. 6 (a),(b) for , sample1 and sample 8, the fracture surface morphology of the samples comprises of dimples. Compared to sample8, where shallower and larger dimples were seen, which are indicative of increased UTS and low ductility, the deeper and lower dimples were detected for sample1.

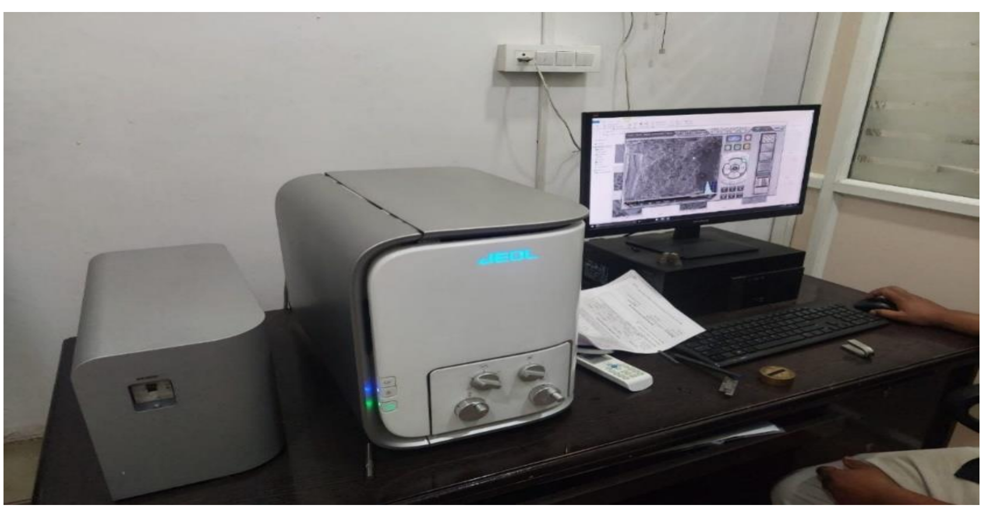

Fig 5: SEM equipment

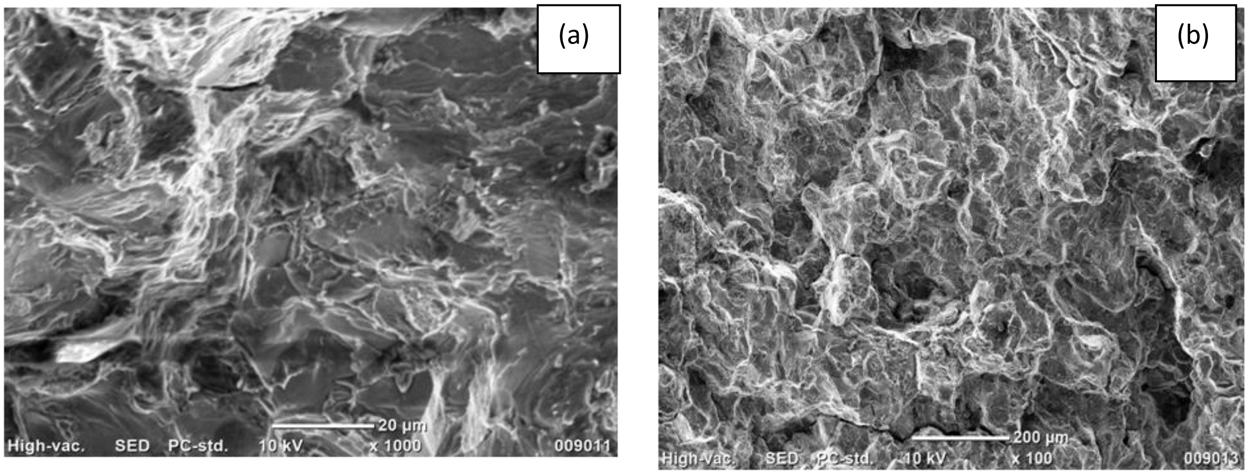

Fig 6:.Fractography of tensile specimens of (a) Sample1, (b) Sample 8

4. Conclusions

- After TiC, B_4C and Al_2O_3 reinforcement, the tensile properties of the friction stir welded Al-MMCs were enhanced. The dislocation density of TiC, B_4C and Al_2O_3 particles, plastic deformation during joining, and interactions between dislocations may all be responsible for the strengthened composite joints following the FSW process. The maximum ultimate tensile stress was found to be around 162 MPa for sample 8.
- The movement of plasticized metal from the advancing to the retreating metal is seen at the joints by Microstructural analysis**.**
- The fractured faces of the test specimens showed a large number of scattered shallow parts and dimples of various sizes within the composites, which is also consistent with the high ductility seen in the UTS investigations.
- By utilizing tapered conical threaded tool, microstructure studies demonstrate improved material mixing in the stir zone. Adding nanoparticles to the stir zone caused the grain size to be discovered to be fine.
- The optimal welding parameters were obtained for sample 8 the process at speed 900 rpm, feed 45 mm/min, and Tilt angle 2.5^0

Acknowledgement

Authors would like to acknowledge the MLR Institute of Technology is located at Dundigal, Hyderabad,Telangana, India and Venkateswara Welding works, Bala Nagar ,Hyderabad., For Support to carry out the experimental work of Mr. G. Sarat Raju, Research Scholar (Enrolment No.: 1203PH1517) under the guidance of Dr. D.V. Ravi Shankar, and B.Balu naik Jawaharlal Nehru Technological University, Hyderabad, India-500072.

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