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Experimental Investigation on Corrosion Behaviour of FSW Al6061 MMC Plates

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Abstract: Lightweight, flexible, stiff, and hard, metal matrix composites have numerous applications. In addition to its high strength and corrosion resistance, aluminium 6061 has a wide range of mechanical properties as well as good working ability. In addition to Marine equipment, trucks, buses, and transmission towers, these products are used because of their high corrosion resistance. Friction stir welding is being employed in various fields like automobile, aeronautical, shipbuilding, and food industries due to its robustness. In FSW, The rotating tool generates heat by friction with the workpiece material, which results in a softened region near the tool. Through mechanical pressure applied by the tool, the hot and softened metal is then forged by the tool as it traverses along the joint line. Compared to fusion stir welded joints, friction stir welded joints are 34% stronger. Among the most common alloys that FSW can join are aluminium, copper, titanium, mild steel, stainless steel, and magnesium metals. The present work is focused on the problems such as rust development and corrosion of aluminium MMC in automobile, aircraft, and marine applications. The corrosion test of FSW Aluminium MMC plates can be done by the following methods Immersion test, Salt spray test, and electrochemical test. Our study intends to investigate corrosion behaviour on FSW Aluminium Metal Matrix Composite (MMC) by performing an Immersion test in Acidified Sea water solution. The immersion samples were 1 cm2 in size. The pH of the seawater used was 7.71 and by the use of a mixture of acids, the pH of the seawater was reduced to 2 in which they were immersed. The zones involved in this study are the Nugget zone (NZ), Thermo-mechanically affected zone (TMAZ) and Base metal zone.

***Index Terms* - Al6061 MMC (Metal Matrix Composites), FSW (Friction Stir Welding), Corrosion, Immersion Test, Taguchi Method.**

I. INTRODUCTION

In the automotive and aerospace industries, aluminium alloys are used for a wide range of applications. In this way, their composition is determined by both their welding behaviour and the welding process that is employed. Aluminium alloys, especially aluminium 6xxx, have a high strength-to-weight ratio, is plastic, formable, and are highly corrosion resistant, as well as being used in armor structures, rockets, missile casings, lightweight defence vehicles, cars, and marine structures. Al6xxx alloy properties are affected by its chemical composition and processing conditions, such as hot, cold, annealing, and ageing. An alloy's properties are influenced by alloying elements like magnesium, silicon, copper, iron, and manganese. In alloys containing more copper and silicon, intergranular corrosion and stress corrosion cracking are more likely to occur. Also, with these primary elements, we have added E-glass fiber and Micro titanium to formulate Metal Matrix Composites which is our field of interest. Adding E-glass and micro- Titanium elements will result in better corrosion resistant properties, high specific strength and better mechanical properties.

Friction stir welding is a widely accepted technique in several manufacturing industries like automotive, aerospace, railway, marine, and food industries. Currently, this welding process is being used only for joining Al alloys, but it has a great potential for welding Mg-, Cu-, Ti-, Al- alloy metal matric composites and different material combinations particularly those with close melting temperature and similar behaviour such as hot workability. Heat Affected Zone (HAZ), Thermo-Mechanically Affected Zone (TMAZ), and Nugget Zone have changed microstructures in the weld due to plastic deformation caused to the alloy due to frictional interaction between the welding tool and the workpiece (NZ). The NZ receives severe deformation and high heat because it is the zone through which the tool pin passes. The metal is heated and plastically deformed in the TMAZ that is next to the nugget zone, but this is not enough to bring about recrystallization. Only a thermal effect, not mechanical deformation, occurs in the HAZ.

The material used in this study is a 6mm thick Al 6061 MMC plate having the chemical composition as shown in Table 1, the chemical composition of Al 6061 is shown in Table 2. The dimensions of base plates are 70mm in width and 65mm in length. These plates were welded using the friction stir welding practices with three different tools at three different weld speeds and feed rates which produced 27 samples. These 27 samples were optimized into 9 samples by the 'Taguchi method'.

For practical related applications, it is very significant to identify the corrosion behaviour of the FSW welds. It is also pertinent to explain the dominant corrosion mechanisms in the different FSW MMCs and various microstructural zones. The corrosion test procedure adopted in this study is the Immersion test. The samples were corroded by immersing them in a highly corrosive medium i.e., welded plates are tested for corrosion susceptibility by immersing them in acidified seawater solution at a pH value of 2. The acidified seawater solution was prepared in the laboratory by adding a mixture of acids (HNO3, H2SO4, HCl) in appropriate proportion. The pH value of the seawater was measured using a pH meter and electrodes used in the pH meter were standardized using buffers. The main function of the buffer is to produce an accurate pH value. The initial pH of seawater was 7.71 (Basic) and was later reduced to 2.0 (Highly acidic), which was our requirement for the study.

The test samples which were optimized by the Taguchi method were immersed in the highly corrosive medium (Acidified Sea water solution) and were left to corrode for 12 days under aerobic conditions. The weight of the test samples was measured at regular intervals of 96 hours. The corrosion rate (in mm/yr) was tabulated for each zone of the test samples and the analyzed reports and graphs were obtained from Minitab software.

Table 1. Chemical Combination of Al 6061 MMC

Elements	Micro titanium	E glass	Al 6061
Amount (wt. %)	1%	3%	96%

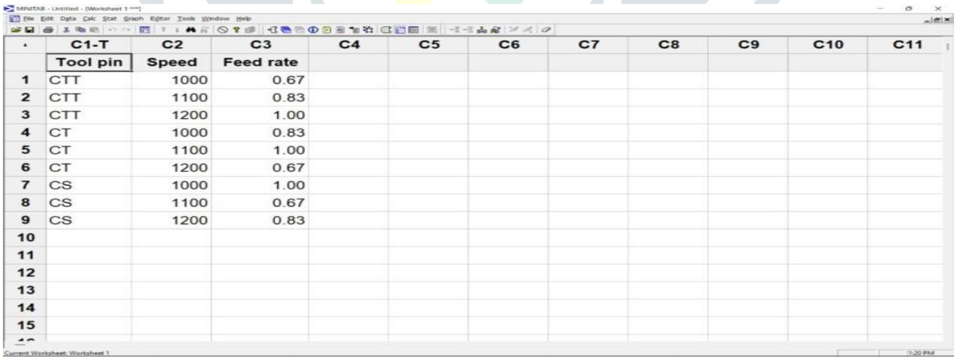
Table 2. Chemical Combination of Al 6061 Alloy

Elements	Al	Mg	Si	Fe	Cu	Cr	Zn	Ti	Mn	others
Amount (wt%)	96.85	0.9	0.7	0.6	0.30	0.25	.20	.10	.05	.05

II. TAGUCHI DESIGN OF EXPERIMENT

A Taguchi design is a planned experiment that enables you to select a good or procedure that performs more consistently in the real world. It is also a powerful technique to optimize the performance of products or processes. Taguchi's main purpose is to reduce the variability around the target value of product properties via a systematic application of statistical experimental design which is called robust design. Using mini tab software, we optimized the total 27 welded plates into 9 best-welded plates. We selected three factors, three-level. The three factors were Tool geometry, Tool Rotational Speed (in rpm), and Tool Traverse Speed (in mm/sec). And the three levels for Tool geometry are Cylindrical Tapered Threaded (CTT), Cylindrical Tapered (CT), and Cylindrical Straight (CS). The three levels for Tool Rotational Speed are 1000rpm, 1100rpm, and 1200rpm. The three-level for Feed rates are 0.67mm/sec, 0.83mm/sec, and 1.00mm/sec. The steps involved to optimize the samples are given below

- Open Minitab software, In the toolbar select, "Stat>DOE>Taguchi>Create Taguchi Design".
- Selecting the number of factors and levels:
- In the Taguchi design, the pop-up tab selects 3-level design under "Types of design" and selects the number of factors as 3.
- Then click on Display Available Design, now under the 3-level column select 2-4, press ok
- Now in the design option select L9 and press ok
- And finally, select the factors option and enter all the factors and levels, click Ok, this will provide us with nine samples out of twenty-seven samples (as shown in fig 1).



↓	C1-T	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
	Tool pin	Speed	Feed rate								
1	CTT	1000	0.67								
2	CTT	1100	0.83								
3	CTT	1200	1.00								
4	CT	1000	0.83								
5	CT	1100	1.00								
6	CT	1200	0.67								
7	CS	1000	1.00								
8	CS	1100	0.67								
9	CS	1200	0.83								
10											
11											
12											
13											
14											
15											

Fig 1 Optimized samples

III. EXPERIMENTAL PROCEDURE

3.1 Preparation of test Specimens:

After the welding process, the weld samples were cut using A500 – MARK 25 SODICK WIRE CUTTING EDM machine (as shown in fig 2). Compared to laser, flame cut, and plasma machining, wire EDM is more accurate. Since wire EDM machining imparts no force on the part, it can achieve very high tolerances for precise dimensions and accurate fitting. In this way, parts need not be further processed or finished after machining. The test specimens were 1cm^2 in the area and 6mm in thickness. From each plate, four cut samples were obtained, according to the zones i.e., base metal zone, weld nugget zone and attacking & retrieving of thermomechanical zones.

Fig 2 MARK-25 EDM Machine

After receiving the test specimens, they were polished using emery paper to remove the greasy layer that was deposited during the cutting process. The image of the cut samples is shown in Fig 3. The numbering of the samples is based on the zones of each combination that was obtained from the Taguchi method.

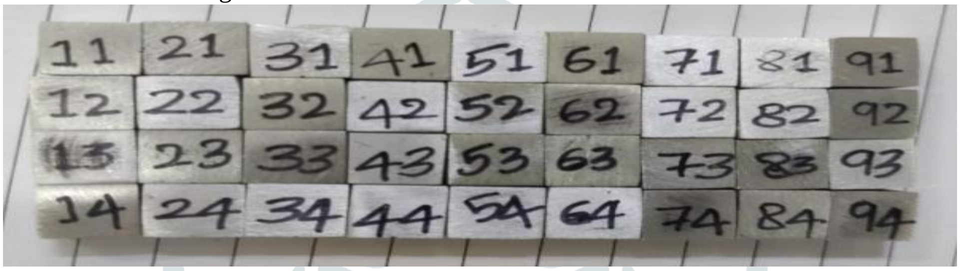


Fig 3 Cut Samples

3.2 Preparation of Acidified Sea Water

The acidified seawater is the testing medium used in our study. The pH value of the seawater was measured using a pH meter and it was found to be 7.71 (Basic), before acidifying the seawater the electrodes used in the pH meter were standardized using two buffers (4.01 and 9.18). The main function of a buffer is to produce an accurate pH value. By adding the mixture of acids (HNO_3, H_2SO_4, HCl) into seawater the pH was reduced to 2.0. The images of pH reading of seawater before and after adding acids & buffers are shown in fig 4, 5 and 6 respectively.

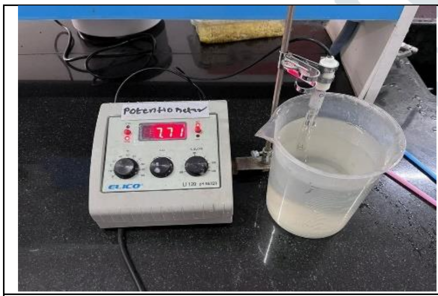


Fig 4 pH of sea water before acidifying

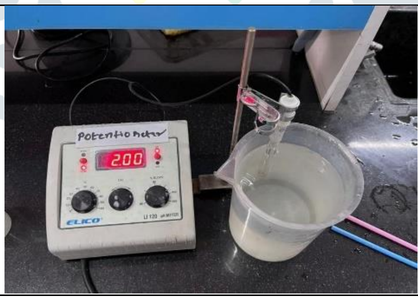


Fig 5 pH of sea water after acidifying

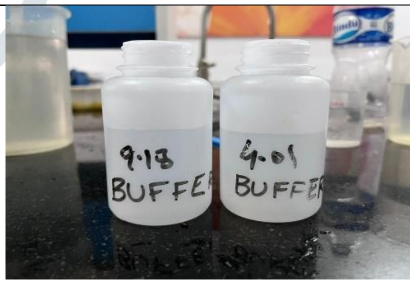


Fig 6 Buffers used to standardise the electrodes

3.3 Corrosion Rate Using Immersion Test:

Susceptibility to corrosion was determined by an immersion test. The test solution was prepared by adding the mixture of acids in the right proportion to the seawater. By using the Taguchi method, a total of 27 welded plates were optimized to 9 welded plates on which the corrosion behaviour was conducted. Test specimens of $1cm^2$ in the area were cut adjacent to the zones thereby producing four test specimens from each plate, resulting in a total of 36 cut test specimens from nine welded plates. The samples were polished with emery paper before the immersion. These samples were weighed and the values were noted down before immersing in the test solution. The prepared test solution was poured equally into 36 cups (as shown in fig 7) to which each cut specimen were immersed and left to corrode for 12 days under aerobic condition. The corrosion rate of the specimens was estimated by weight loss measurement. The weights of specimens were measured at regular intervals W_i at 0hr, W_1 at 96hr, W_2 at 192hr, and W_3 at 288hr. We cleaned and dried the corroded specimens at each interval, then weighed them before immersing them again. Fig 8 represents weight readings of the test samples at various intervals of time. The Readings at regular intervals were tabulated.

Fig 7 Test samples immersed in acidified sea water solution

Fig 8 (a) Weight reading at Interval 0 hr.

Fig 8 (b) Weight reading at Interval 192 hr.

There are 9 combinations in the table (as shown in Fig 1), each containing 4 test specimens based on the zones. For example, X1 represents the base metal zone, X2 represents the thermo-mechanically affected zone – advancing side, X3 represents – the Weld nugget Zone and X4 represent the thermo-mechanically affected zone – retreating side, where x represents the nine combinations and Weight readings were calculated at each interval (0hr-96hr-192hr-288hr) for each test specimen of the combination.

IV. CALCULATION AND TABULATION

This is the sample template that is used to calculate the corrosion rate for each test specimen according to the zones i.e., the base metal zone, the thermo-mechanically affected zone – advancing side, the weld nugget zone, and the thermo-mechanically affected zone – retreating side for each combination that was obtained from the

Example: Sample XY

W_i-W_1 = ________g

W_1-W_2 = ________g

W_2-W_3 = ________g

Average W (in gms) = $\frac{(W_i - W_1) + (W_1 - W_2) + (W_2 - W_3)}{3}$ = ________g

Taguchi design of experiment.

Corrosion rate = $\frac{876 \times 10^2 \times W}{A * D * T}$ = ______mm/year

Where W = average of Weight Loss in grams.
A = Surface Area of Test Specimens in cm^2.
D = Density of Aluminium 6061 MMC in g/cc.
T = Average Immersion time in hours.

Steps followed to calculate the corrosion rate:

- Calculate the weight loss at the interval 0-96 hr, 96-192 hr, and 192-288 hr.
- Take the average weight loss by substituting the weight loss values in the above average Weight 'W' formula.
- Finally substitute the average 'W' in grams, area 'A' as 1cm2, Density 'D' as 2.7g/cc, and Time 'T' in hrs.

Example of a calculation for sample 11:

Sample 11

W_i-W_1 = 1.5538 – 1.5510 = 2.8×10^{-3} g

W_1-W_2 = 1.5510 – 1.5507 = 3×10^{-4} g

W_2-W_3 = 1.5507 – 1.5506 = 1×10^{-4} g

Average W (in gms) = $\frac{2.8 \times 10^{-3} + 3 \times 10^{-4} + 1 \times 10^{-4}}{3}$ = 1.067×10^{-3} g

Corrosion rate (in mm/yr) = $\frac{8.76 \times 10^{4} \times 1.067 \times 10^{-3}}{1 \times 2.7 \times 96}$ = 0.3606 mm/yr

Similarly, the corrosion rate is calculated, for all the nine combinations, according to the zones. The different zones are the Base metal zone (X1), TMAZ at the advancing side (X2), weld nugget zone (X3) and TMAZ at the retreating side (X4).

The least corroded sample is 62, which is TMAZ-Advancing and the most corroded sample is 41, which is BMZ. It was observed that the corrosion rate of the weld decreases with an increase in the time of exposure.

V. RESULTS, CONCLUSION AND FUTURE SCOPE

5.1 Corrosion Behaviour

The corrosion rates of Test Samples for a pH value of 2, the three different times of exposure are (96, 192, and 288 h). The corrosion rate of the weld decreases with an increase in the time of exposure. It was found that the corrosion resistance of the base material is better than that of the weld. It has been found that the corrosion resistance decreases with a decrease in pH value. It was also found the corrosion resistance of the TMAZ is better than that of the weld zone. According to corrosion rates obtained from the experiment, it is very clear that the nugget zone is more susceptible to corrosion and the TMAZ-R is least susceptible to corrosion. Finally, we noticed that as time progressed salt deposition took place on the test samples. The images of corroded samples and salt deposition are shown in fig 9(a), 9(b) and fig 9(c) respectively.

From table 3, we can justify that:

- The average corrosion rate of the Base metal zone is 0.5658mm/year.
- The average corrosion rate of the Thermo-mechanically affected zone - Advancing side is 0.4672mm/year.
- The average corrosion rate of the Base metal zone is 0.5706mm/year.
- The average corrosion rate of theThermo-mechanically affected zone – Retreating side is 0.4642mm/year.

Table 3 Average Corrosion Rate(mm/year) of Zones

Zones	Calculation	Average
BMZ	(0.3606 + 0.5522 + 0.5971 + 1.5434 + 0.4846 + 0.3494 + 0.4281 + 0.3944 + 0.3832) / 9	0.5658
TMAZ-A	(0.6985 + 0.6083 + 0.5745 + 0.4281 + 0.4528 + 0.2142 + 0.2480 + 0.5860 + 0.3944) / 9	0.4672
NZ	(0.6647 + 0.6198 + 0.6536 + 0.5860 + 0.4170 + 0.6759 + 0.4713 + 0.5407 + 0.5069)/9	0.5706
TMAZ-R	(0.7908 + 0.3606 + 0.2703 + 0.2818 + 0.4731 + 0.5407 + 0.5745 + 0.5295 + 0.3569) / 9	0.4642

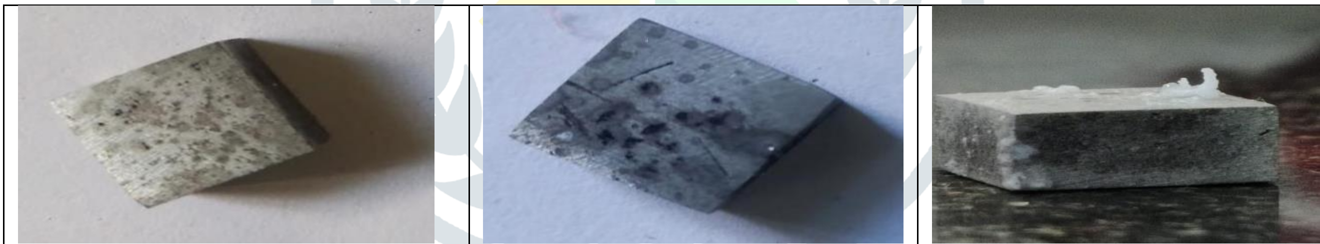


Fig 9 (a) Corroded sample after 96 hrs. | **Fig 9** (b) Corroded sample after 192 hrs. | **Fig 9** (c) Salt formation on Corroded Sample after 192 hrs.

5.2 Conclusion

- Al 6061 MMC plates of 6mm thickness were joined using FSW.
- A total of 27 samples were optimized into 9 samples using the Taguchi method.
- The corrosion behaviour of Al 6061 MMC was studied under Immersion Test in acidified seawater solution.
- Using Minitab software, the zone was analysed concerning corrosion rate and the best combination among the 27 samples was obtained.
- The Nugget zone was most susceptible to corrosion and the Thermo-mechanically affected zone was the least susceptible to corrosion.
- It was observed that the corrosion rate decreases with an increase in the time of exposure.
- As the time increased, the salt deposition took place on the sample.

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