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Studies of corrosion on AA 6061 and AZ 61 friction stir welded plates

Raguraman, D.[a,*], Muruganandam, D.[a], Kumaraswami Dhas, L.A.[b]

[a]Department of Production Engineering, Sri Sairam Engineering College, Chennai, India
[b]Department of Mining Machinery and Engineering, Indian Institute of Technology Dhanbad (ISM), Dhanbad, India

A B S T R A C T

A remarkably new welding process, namely friction stir welding (FSW) has reached a tremendous research interest on the present decade due to bonding of similar or dissimilar materials at solidus state. This welding technique is environment friendly and versatile. In specific, FSW can be used to join the high strength aluminium alloys and other dissimilar alloys that are difficult to weld by conventional fusion welding. The process parameters have a major role in changing the characterisation of the joint. In this work, three parameters of the weld, namely rotational speed (rpm), axial load (kN), and weld speed (mm/min) are considered. Three pairs of AA 6061 and AZ 61 plates were welded with three different sets of these parameters. The welded zone was immersed in corrosive solution of NaOH for six months period. Corrosion behaviour was studied with the help of SEM and EDAX. Through this investigation, the importance of weld parameters control for the study of effects on the susceptibility for corrosion on the welded region can be sought.

A R T I C L E I N F O

Keywords:
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**Corresponding author:*
raguraman150807@gmail.com
(Raguraman, D.)

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1. Introduction

The corrosion is caused by the chemical and/or electro chemical reaction of metals with environment. Due to the conservation and safety requirements of alloys the need of investigation on corrosion arises. To reduce the impact of corrosion, corrosion engineers and scientists made a major investigation on the corrosion of piping, bridges, marine structures, ships, metal components of machines and so on to reduce material losses and to utilize the conservation metal usage. Corrosion study is vast important in the safety point of operating equipment. Loss of metal by corrosion is not only affecting the physical strength but also raising the cost consumption for the replacement of the corroded metal structures within its useful life. In addition, rebuilding of corroded components involves further investment of all the men, materials and machines resources.

It is well known that aluminium is one among the most abundant metals in nature. It is ductile in mechanical characterization and can be easily cast and machined. Adequate properties kept aluminium as a different alloy from other alloys. First, it is lighter compared to all other engineering alloys except magnesium and beryllium. It has a density value of about 2990 kg/m^3. A second noted property of aluminium is its electrical and thermal conductivity. The third property which is made the most responsible for the selection of aluminium alloys is their corrosion resistance. Resistance welding can be preferred on some aluminium alloys but the surface preparation is expensive and the formation of surface oxide being a major problem.

The magnesium series alloys are often used in automobile applications, marine and aviation due to their high strength to density ratio. The challenge on making fatigue and fracture resistant welds in aluminium alloys have been found wider use for joining aerospace structures. In the case of magnesium alloy, if the aluminium content is a dominant alloying element then it is characterized as magnesium alloy AZ61.

Aluminium and magnesium are found as one of the lightweight alloys with noted corrosion resistance with good thermal and electrical conductivity. The remarked corrosion behaviour of aluminium is effected by the small amounts of impurities present in the metal; all these impurities, with the exception of magnesium which tends to be cathodic to aluminium.

The distinct applications of aluminium alloys in aerospace and automobile industries directs the choice on welding behaviour and selection of most appropriate welding method. Aluminium alloys of 2xxx, 6xxx and 7xxx series have been adopted for remarkable usage in these industries [1]. This transpires the desirable strength to weight ratio, good form ability, appropriate weld ability and acceptable corrosion resistance [2]. According to the particular application, corrosion behaviour have a major role on the strength of welded joint [3].

Magnesium (Mg) alloys are considered to be one of the light weight metallic alloys due to its higher mechanical stiffness and lower density which is around 1.74 g/cm^3 [4]. In the presence of seawater, the benefits of magnesium are distinctive by high corrosion rate compared to aluminium or Steel [5]. The areas unexposed to the atmosphere such as electronic boxes and car seats have been regulated its usage of alloy by high corrosion resistance of magnesium [6, 7].

Earlier investigations on the tool geometry design were aimed on optimization of the tool pin with respect to mechanical properties and micro structure [8-11]. Recent investigation on corrosion behaviour on aluminium alloy 6061 reveals that control of grain size enhances the susceptibility to corrosion and intermetallics dominates the role on formation of galvanic corrosion couples [12]. Also as per microstructure analysis on corroded surfaces of Al-Zn-Mg aluminium alloy 7039 FSW joints, the different weld zones like HAZ, TMAZ and NZ are compared for corrosion behaviour. By comparison the Heat Affected Zone (HAZ) was more susceptible to corrosion [13]. The studies focused to the effect of tool pin profile and change of weld parameter on the corrosion behaviour and micro structure on corroded surface are less [14]. The current investigation is with corrosion behaviour of FSW joints with different weld parameter for threaded pin profile.

2. Friction stir welding

2.1 Process

The basic principle of FSW is concerned with a metal flow of metal/alloy to be welded by a combination of axial load and rotational as well as transverse feed by a rotating tool which is having a specifically designed probe (pin) and shoulder profiles. The tool preserves two primary functions such as heat input on the metal to be welded and metal flow mechanism in the joint. The heat input is generated by friction on the tool and the metal/alloy interface. The localized heat generation softens the metal/alloy which is welded closer to the probe and combination of tool rotation speed and transverse speed plays major role in the metal flow. Because of different geometrical features of the tool profiles and the metal flow intense plastic deformation set up. Due to the efficient utilization of energy, environment friendly feature and versatility the FSW is considered to be the most effective metal joining method in the recent decade.

2.2 Tool geometry

The design/selection of tool geometry is the influential aspect of heat input in FSW process. Since tool geometry have a critical role in material flow and in turn it governs the heat generation rate at which FSW is processes [15]. An FSW tool consists of a shoulder and a probe (pin) as shown schematically in Fig. 1.

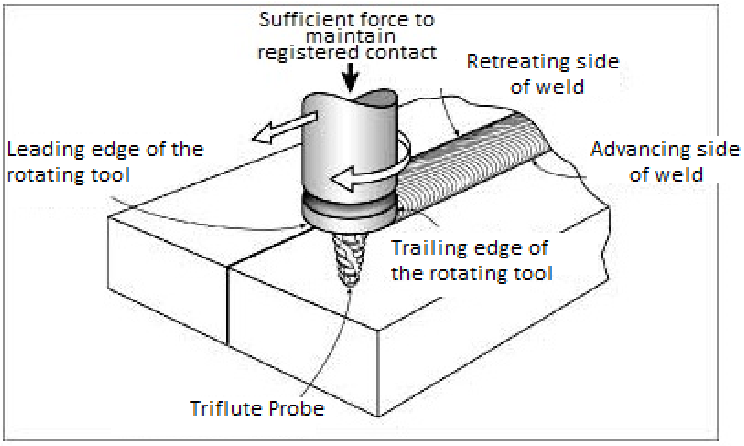


Fig. 1 A schematic view of friction stir welding [16]

As per literature, the tool has two primary functions one is a mechanism of material flow, and the other one is localized heating. In tool plunging, the heat generation is primarily due to the friction on the interface of tool and base metal/alloy. Later additional heat results from plastic deformation of material. From the heat generation point of view, the relative size of tool probe and shoulder is significant. According to the recent numerical evaluation the weld nugget zone experiences a serious compression and shear [17]. The uniformity of micro structure and physical properties are affected by the tool design. Generally a threaded cylindrical pins and concave shoulder are used. Complex features on tool profile have been added to improve material flow and reduction of process loads. Fig. 2 shows the tool geometries tested for the corrosion behaviour.

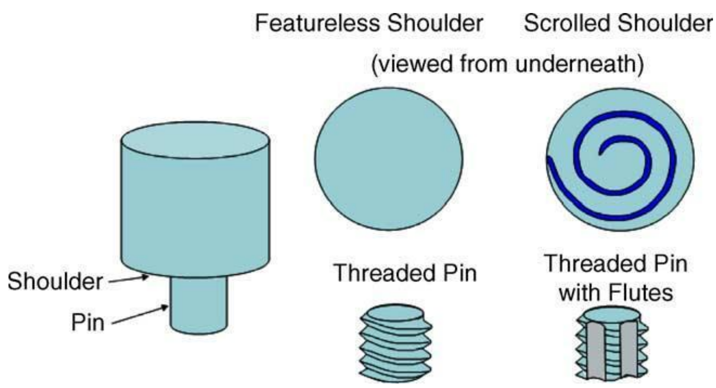


Fig. 2 Line sketch of friction stir welding tool used for the butt joints of AA 6061-AZ 61 alloys for corrosion behaviour study [15]

2.3 Welding parameters

As per the trend on weld parameters of FSW for investigation tool rotation rate (*v*, rpm) and tool traverse speed (*n*, mm/min) are the most involved along the line of joint. The rotation of tool with some axial load results in stirring and mixing of base metal/alloy to be welded and the translation of tool pushes the stirred material from the advancing side to the retreating side. Higher tool rotation rates set up a higher temperature because of higher friction and results in more influences on stirring and mixing of material. However, the friction of tool with weld metal is responsible for the heating [18].

3. Experimental work

The corrosion behaviour was tested experimentally for the components which are joined with different weld parameters using friction stir welding.

3.1 Welding

Two alloys were chosen for the current corrosion investigation of FSW butt joint. One is from the AA 6XXX series – AA 6061. The other one is from the magnesium alloy series – AZ 61. Three plates each of 5 mm thickness of these alloys were taken. The dimensions of the plates are 100 mm × 100 mm. The friction stir welding of these plates was carried on these plates using three different weld parameters listed as in Table 1.

Table 1 Weld parameters of the three samples

Weld parameters	Samples		
	A	B	C
Load (kN)	10	12	16
Rotational speed (rpm)	400	600	1200
Transverse speed (mm/min)	30	40	50

Thus, three different samples were prepared. These samples were left as such for six months. During this aging period, the atmospheric corrosive agents will affects the defective surfaces on the welded region, if any. The aged plate is then taken for further analysis.

3.2 Corrosion testing

To examine the effect of corrosion on the weld it was decided to immerse the welded region in strong alkaline solution for specific time periods. Then NaOH solution of pH 8 was prepared. The welded portion of each sample was cut into five pieces of 10 mm width, Fig. 3. These were separately immersed in 100 ml of the NaOH solution prepared. They were immersed for six month time periods. After removing the samples from the solution, they were washed in distilled water. Then they were washed with acetone to prevent further corrosion of the samples. These samples were concealed in airtight covers and labelled. A few photographs of the samples tested are shown in the Fig. 4.

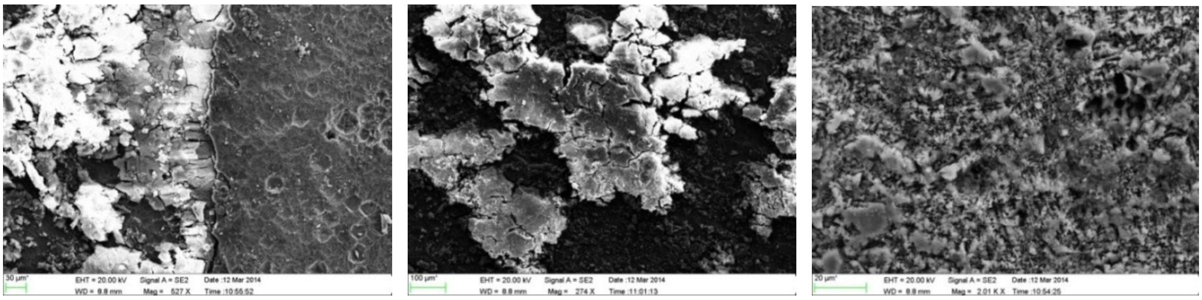
Fig. 3 Welded sample: A cut into pieces for corrosion testing

(a) (b) (c)

Fig. 4 Welded samples dipped in NaOH: (a) sample A (FSW joint with parameters axial load 10 kN, rotational speed 400 rpm and transverse speed 30 mm/min); (b) sample B (FSW joint with parameters axial load 12 kN, rotational speed 600 rpm and transverse speed 40 mm/min); (c) sample C (FSW joint with parameters axial load 16 kN, rotational speed 1200 rpm and transverse speed 50 mm/min) [19]

3.3 Microscopic examination

Each specimen was examined under metallurgical microscope. The effects of corrosion were hard to find under it. So the samples were examined with a Scanning Electron Microscope (SEM). The images were taken at the portion where the welded region met with the parent metal and at the centre of the welded region. The Energy Dispersive X-Ray Analysis (EDAX) was also carried out for the welded and corroded region.



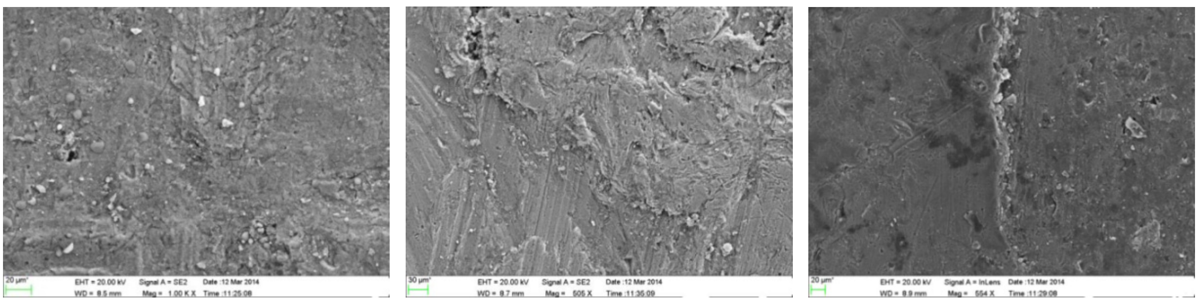
(a) (b) (c)

Fig. 5 SEM images of sample A with FSW joint with parameters axial load 10 kN, rotational speed 400 rpm and transverse speed 30 mm/min: (a) left side of nugget zone; (b) nugget zone; (c) right side of nugget zone

Fig. 5 shows the scanning electron microscopic images of sample A. It has three parts: (a) showing the left side of the weld zone, (b) showing the right side of the weld zone and (c) showing the centre of the weld zone. The sample A shows severe attack of the alkaline solution on the surface of the welded plate. The corrosion of the metal is found to have occurred in the welded zone. The oxides of metal are formed on the surface. Pitting corrosion is found to take place in the welded zone.

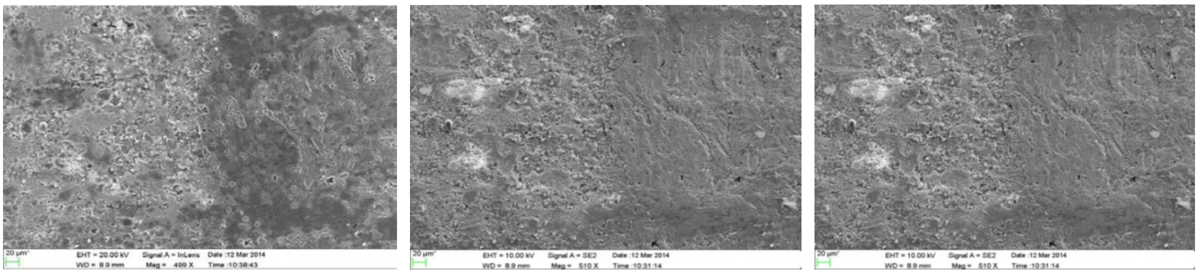
Fig. 6 shows the scanning electron microscopic images of sample B. It has three parts: (a) showing the left side of the weld zone, (b) showing the right side of the weld zone and (c) showing the centre of the weld zone. The alkaline solution, in which the welded plate was immersed, is found to have caused some effect on the surface. There are no severe traces of corrosion in sample B. The sample B shows considerable corrosion resistance.

Fig. 7 shows the scanning electron microscopic images of sample C. It has three parts: (a) showing the left side of the weld zone, (b) showing the right side of the weld zone and (c) showing the centre of the weld zone. The welded surface is found to be least attacked by the alkaline solution in sample C. There are traces of oxides present on the surface. It is not as severe in sample A.



(a) (b) (c)

Fig. 6 SEM images of sample B with FSW joint with parameters axial load 12 kN, rotational speed 600 rpm and transverse speed 40 mm/min: (a) left side of nugget zone; (b) nugget zone; (c) right side of nugget zone



(a) (b) (c)

Fig. 7 SEM images of sample C with FSW joint with parameters axial load 16 kN, rotational speed 1200 rpm and transverse speed 50 mm/min: (a) left side of nugget zone; (b) nugget zone; (c) right side of nugget zone

4. Result and discussion

4.1 EDAX analysis of sample A

The EDAX image of sample A is shown in the Fig. 8. This shows the presence of oxides of aluminium alone. The spectrum shows that 23.56% of O and remaining Al are present. Thus, the welded zone is severely corroded. The pitting corrosion has occurred on the surface due to the effect of the alkaline solution.

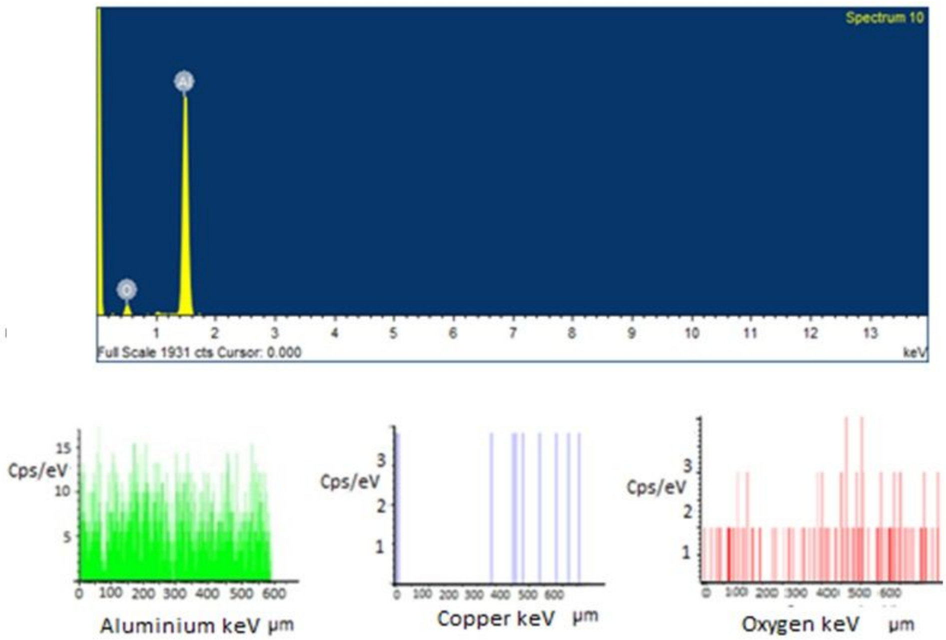


Fig. 8 EDAX images of sample A (FSW joint with parameters axial load 10 kN, rotational speed 400 rpm and transverse speed 30 mm/min)

4.2 EDAX analysis of sample B

The EDAX image of the sample B (Fig. 9) shows the presence of 28.34 % of O, 18.75 % of C, 5.20 % of Cu, 1.29 % of Mg, 1.21 % of Si, 1.12 % of Na, 0.86 % of Fe, 0.71 % of Mn, 0.50 % of Cl, 0.42 % of Ca and remaining Al by weight. This shows that the percentage composition by weight of sample B shows small deviation from that before corrosion.

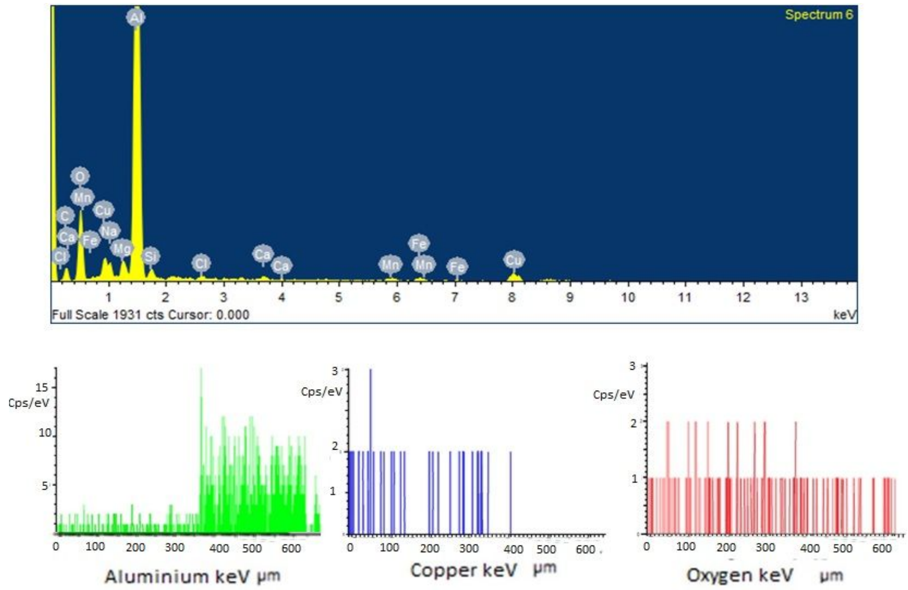


Fig. 9 EDAX images of sample B (FSW joint with parameters axial load 12 kN, rotational speed 600 rpm and transverse speed 40 mm/min)

4.3 EDAX analysis of sample C

The EDAX of sample C (Figure 10) shows the presence of 28.92 % of O, 16.52 % of C, 3.51 % of C, 0.96 % of Fe, 0.82 % of Si, 0.74 % of Mg, 0.42 % of Ca and remaining Al by weight. This shows that the composition percentage by weight of the corroded region shows slight variation from parent metal composition.

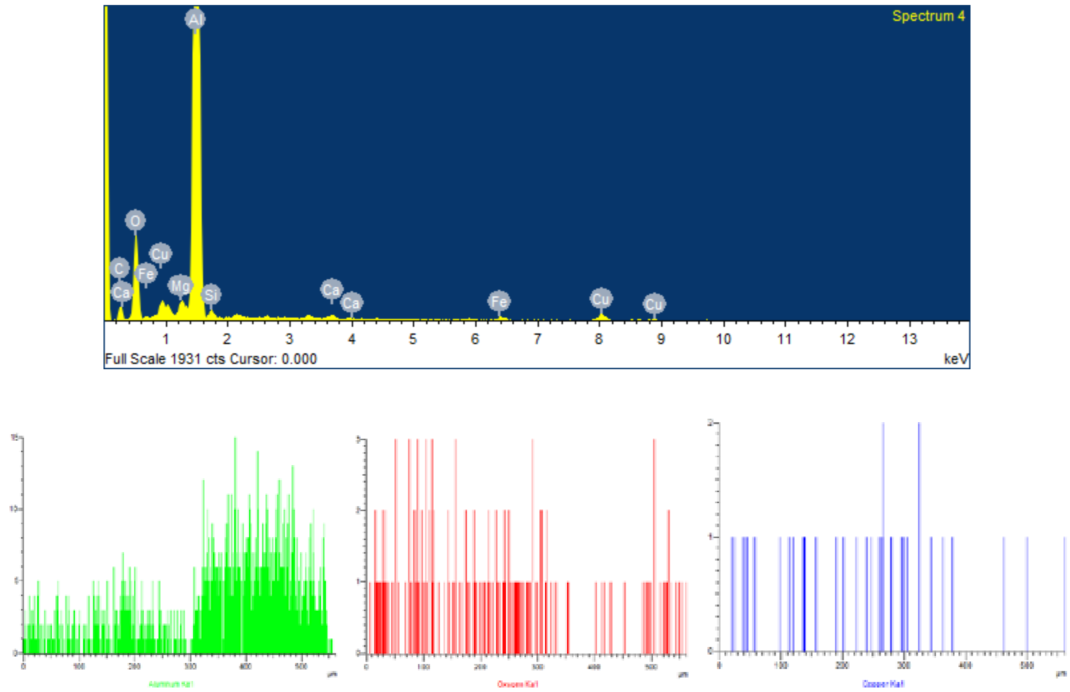


Fig. 10 EDAX images of sample C (FSW joint with parameters axial load 16 kN, rotational speed 1200 rpm and transverse speed 50 mm/min)

Thus upon experimental analysis, followed by imaging of the specimen with Scanning Electron Microscope, to study the microstructure, and the Energy Dispersive X-ray Analysis of the specimen, to study the composition, showed that two out of three specimen were much resistant to corrosion than the third specimen. The specimen B with weld parameters 12 kN, 600 rpm and

40 mm/min and the specimen C with weld parameters 16 kN, 1200 rpm and 40 mm/min are suitable for application. The specimen A with weld parameters 10 kN, 400 rpm and 30 mm/min is susceptible to corrosion. So it is not suitable for application in highly corrosive environments such as seawater.

5. Conclusion

The aluminium and magnesium alloys have a wide range of application such household utensils, construction equipment, packaging, vessels used in industries, pipes, aircrafts, ships, marine equipment, weapons, etc. They are mainly used for their corrosion resistance property. High strength alloys of aluminium and magnesium alloys are used in aircrafts and ships. They can be welded easily only by using friction stir welding technique. Therefore, care has to be taken that there is no probability of corrosion in the welded region. This work reveals that the so called non-corrosive alloys of aluminium and magnesium are also affected by the universal process of corrosion. But it can be reduced by using the optimum parameters of the weld. Welding can take place at any set of parameters, but a safe set of parameters to weld, which will prevent the welded zone from corrosion should be chosen. According to this investigation, it is concluded that welded region is susceptible for corrosion when the axial load and the rotational speed are kept low. As the value of these parameters increased the welding is done more and more perfectly. Out of the three sets of parameters the welded sample C shows more corrosion resistance than the other two sets of parameters. So we conclude that welding the alloy plates of AA 6061 and AZ 61 at 16 kN axial load, 1600 rpm rotational speed and 50 mm/min weld speed is most suitable.

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