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RECENT TRENDS IN CORROSION STUDIES OF FRICTION STIR WELDED JOINTS- A REVIEW

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Abstract

Friction Stir Welding (FSW) has numerous applications in the aviation, nautical sectors, automobile industries, railway industries, nautical industrial parts etc. and were where conventional welding is difficult and can't give the desired results. However, metals deteriorate due to corrosion because of chemical reactions with their immediate surroundings. Corrosion in metals happens primarily due to electrochemical interactions between the metal's outermost layer and the electrolyte. Incorporating an appropriate interlayer in between two FSW plates can help increase the corrosion resistance of the structure. The grain size has a substantial impact on the corrosion activity of the FSW joint, however the influence of IMCs is modest. Alterations in the tool's rotating speed and traverse speed both have a substantial impact on the corrosion resistance of FSW joints. In this paper, a study was done to understand and correlate the latest developments in the corrosional studies of FSW joints. An effort was made to summarize the significant effects of various hybrid FSW methods such as adding interlayer, backing plate, reinforcements, post welding heat treatments etc. to improve corrosion resistance. Also all the significant dynamics of corrosion such as tool rotational speed (TRS), traverse speed (TS), tilt angle, welding positions, tool profile etc. were summarized based on their impact on corrosion.

Keywords: Corrosion, Friction Stir.

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I. INTRODUCTION

FSW is a type of solid-state welding that was invented in the United Kingdom at a welding institute. In this type of welding, the welding joint is generated by friction between the rotating tool and the work piece. The temperature reached in order to create a welded joint is significantly lower than the point at which the material of the work piece would melt. In the FSW process, rather than using an electrode with a variety of forms to create a welded joint, a non-consumable tool is used instead. Application of FSW is widely in maritime industries, aerospace industries, automobile industries, railway industries, nautical industrial parts etc. and were where conventional welding is difficult and can't give the desired results [1-7]. Especially Aluminum alloys are widely used in the above mentioned fields because of their light weight and versatile nature. The microstructure of the welded joint, as well as its resistance to corrosion, is largely determined by the welding parameters, which include tool pin shape, tool rotational speed, traverse speed, and axial force, amongst others [35].

Shown in Figure 1, To friction stir weld, a non-consumable rotating tool with a pin that may take on a variety of forms is inserted into the inside edges of the joining plates and moved along the joint line specifications of the work piece to weld. Friction between the tool shoulder and the connecting plates causes mechanical deformation and frictional heating. The application of downward force drives the tool further into the base material. Friction stirring tools have pins or probes and shoulders. As the shoulder touches the work piece, the softer region extends and limits the distorted material. When pin touches the work samples, frictional and deformation heating softens it. Wear resistance, coefficient of thermal expansion, enhanced temperature strength, tool reactivity, fracture-resistant machinability, and microstructure homogeneity are necessary for friction stir applications [9-11].

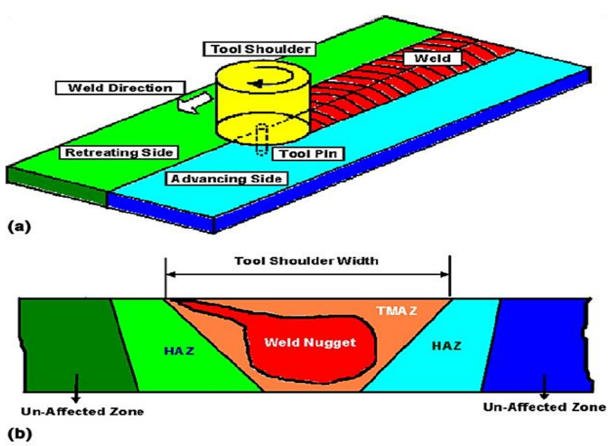

Fig. 1 a) FSW parameters b) Microstructural zones [8]

According to extensive literature, FSW produces high-quality aluminum and magnesium alloy welded joints [12]. Friction between a mixing tool and a work piece aids in the recrystallization and cooling of metal grains as a joint. Just heat cycle difference is applied to the base metal, creating the Heat Affected Zone (HAZ). Heat from the Stir Zone (SZ) through Thermo-Mechanical Affected Zone (TMAZ) heats HAZ, coarsening the grain. Tool pin shape is also an important affecting factor for quality of weld and plasticized material flow. Improving tool shoulder shape to produce more heat or stir better enhances oxide layer breakup, mixing, and heat generation [13-15]. The FSW technique is a revolutionary way to connect all of these alloys. In comparison to conventional welding techniques for non-ferrous alloys, FSW appears to be superior. There isn't any porosity, minimal residual strains, minimal deformation, and few weld faults as a result of this method [16-20]. A basic insight of the mechanics of welding formation, gained through material flow analysis, is vital for manipulating process parameters and generating defect-free welds. friction stir welded joints are used in many different industries nowadays, but they were not always so common [21-28].

Metals deteriorate due to corrosion because of chemical reactions with their immediate surroundings. Electrochemical reaction between the metal's outer layer and the electrolyte is the primary mechanism by which corrosion occurs in metals. Metals are susceptible to several types of corrosion as seen in the figure 2 [29]. It was also stated that corrosion in the industrial equipment tends to create downtime and expenses for the industries [30]. Corrosion has forced the oil and gas plants to opt for different material solutions for avoiding the shutdown period [31]. Numerous studies were done to solve and inspect corrosion before it made huge losses to the industries [32]. Hence, this study was done to widely cover and analyze the various FSW welding parameters and their relation with corrosion. It also covers the relation of corrosional behavior with FSW output parameters such as hardness, ultimate tensile strength (UTS), microstructure etc.

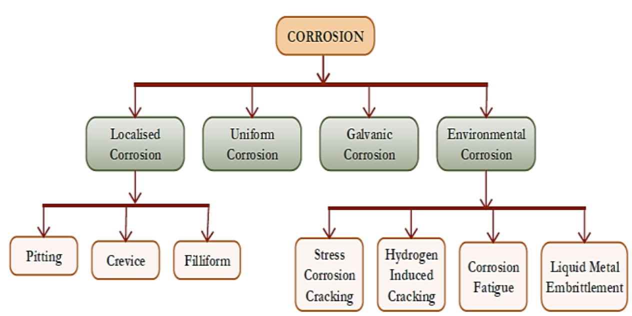

Fig. 2 Types of Corrosion forms [29]

II. Literature Review

Shyamlal et al. investigated corrosion analysis for aluminum alloy AA8090T87 which contains 2.3% lithium with different welding parameters such as traverse speed of 90 and 110mm/min and tool rotational speed of 900rpm. The study was done to analyze the effect of corrosion on the surface roughness, microstructure and hardness of the welded joints. Corrosion analysis was done for six hours at 32° C by solution which comprised of H_2O_2 (10ml/l) and NaCl (57g/l). The condition of the two types of FSW joints based on the welding parameters i.e. one with traverse speed of 90 and tool rotational speed equal to 900rpm and another with traverse speed of 110 and tool rotational speed of 900rpm were analyzed before and after corrosion test. It was observed that the traverse speed of 90mm/min lead to lower hardness values, corrosional mass loss and surface roughness values [33].

Laska et al. studied corrosion resistance for aluminum alloy AA6082 through potentiodynamic test, which helps in determining the properties of FSW welded joints and their resistance to corrosion. Corrosional studies were carried out by solution which consisted of 3.5 (wt) % NaCl at 20°C for 60 minutes as per ASTM G5-94. It is of most importance that even small corrosional losses caused by environment (especially marine vehicles) may be measured, as they play a significant role in decreasing the material strength. Also various important factors such as tool tilt angle with 0°and 2°, tool rotational speed of 1000 and 1250rpm and traverse speed of 200 and 250mm/min effecting the strength, microstructure and corrosion resistance were analyzed. Better corrosion resistance, small grain size of the welded region and higher hardness was found in the FSW welded joints with tool tilt angle of 2° [34].

Kumar et al. analyzed the corrosional behavior of two different aluminum alloys AA5083 and AA6061 welded by FSW at different rotational speed and traverse speed to study the effect on mechanical properties, material flow and corrosional behavior. FSW joints of thickness 6mm were analyzed by keeping the tool rotational speed constant at 800rpm and changing the traverse speed to 40, 60 and 80mm/min and also keeping the traverse speed constant at 60mm/min against tool rotational speeds of 1100, 1400 and 1700rpm. At higher tool rotational and lower traverse speeds, better intermixing of base materials was observed which lead to high tensile strength, higher grain size and more corrosion resistance. FSW welded joints had lesser corrosion resistance than the base metal itself and the increase in traverse speed from 40 to 80mm/min lead to decrease in corrosion resistance and also increase in tool rotational speed, increased corrosion resistance of the joints [35].

Haribalaji et al. investigated the corrosional behavior of aluminum alloys namely AA7075 and AA2014 welded with FSW. The impact of tool rotational and traverse speeds on corrosion rate and tensile strength was investigated using a full factorial design. Three rotational speeds (1000, 1200 and 1400rpm) and three different traverse speeds (35, 40 and 60 mm/min) were selected to study their significance. By using statistical analysis, a prediction of optimal tool rotational speed and traverse speed was made and validation was done by conformational experiment. The corrosion analysis was done by saltwater solution which was sprayed by a convergent nozzle over a period of time. The tool rotating speed of 1400rpm and traverse speed of 60mm/min resulted in the lowest corrosion rate, whereas the tool rotational speed of 1400rpm and traverse speed of 45mm/min resulted in the highest tensile strength [36].

Amara et al. assessed the influence of post welding heat treatment (PWHT) by joining AZ31 magnesium alloy, on corrosional behavior and microstructural change in the nugget zone (NZ) in FSW welded joints. The study was done by varying the PWHT temperature in three steps 200, 300 and 400°C keeping the time constant at 1 hour for corrosional behavior and changing the PWHT to 200 and 400°C against the time 1 and 4 hour for microstructural analysis. It was prominent that the grain-size started increasing in the NZ region from 300°C and the maximum corrosion resistance was noted at 300°C of PWHT and 1 hour of holding time. It was also witnessed that grain-size plays a significant role in corrosional behavior of the FSW joint [37].

Che Liu et al. did a thermal simulation of FSW samples of 7075-T6 aluminum alloy to study the effect on Heat Affected Zone (HAZ) and Thermo-Mechanical Affected Zone (TMAZ) simulation with significance to corrosional behavior and microstructural changes. The simulated temperature changes were from 378°C to 428°C for TMAZ and from 332°C to 372°C for HAZ. The FSW welding parameters were kept constant namely the tool rotational speed was kept at 600rpm, Traverse speed at 60mm/min, Tool sinking value of 0.05mm. It was discovered that when the maximum temperature for TMAZ was raised, so did the corrosion potential. The results for HAZ were inconsistent for both corrosion and hardness with regards to maximum temperature. However, the hardness in TMAZ was found to be interesting as it decreases first for maximum temperature of 378 and 388°C and then it starts increasing with increase in maximum temperature [38].

Nagu et al. investigated the corrosional behavior and microstructural changes in aluminum alloy (AA6061-T6) with inserting a brass as interlayer in between a FSW joint. The welding parameters such as TS kept at 25mm/min while the TRS changed from 600 to 1000rpm. A defect-free joint was achieved at tool rotational speed of 800rpm with the brass interlayer and was studied further. It was witnessed that corrosion rate decreased for samples with brass interlayer of 200µm and the ultimate tensile strength increased with average smaller grain-size compared to FSW welded samples without the interlayer [39].

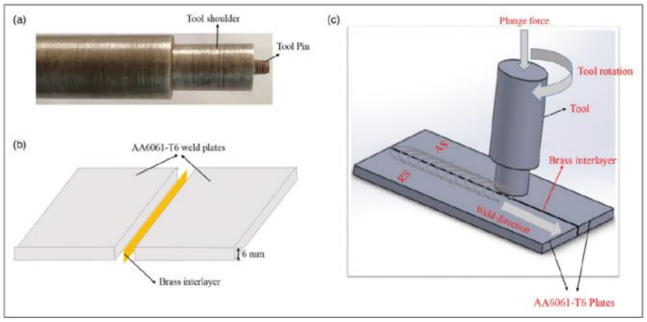

Fig. 3 Application of interlayer (Brass) in FSW [39]

Matlou et al. analyzed the effects of 45° rolling direction of FSW welding plates on corrosion resistance and mechanical properties. They kept the other welding parameters constant such as traverse speed of 300mm/min, tool pin plunge depth at 5mm and the tool rotational speed of 500rpm. They came to conclusion that rolling direction angle of 0° exhibited the highest UTS of 289MPa than rolling angle of 45° which showed the UTS of 282MPa. It was also noted that the base metal was more resistant to corrosion than the FSW welded region, Nonetheless, there was a little increase in toughness in the welded region's stir zone [40].

Kulkarni et al. considered the effect of temperature control through backing plate kept behind the FSW joint on corrosion and mechanical properties. The material used for FSW was aluminum alloy AA6061 and for the backing plates were aluminum, asbestos and composite material. After the experimentation, they optimized the significant parameters such as backing plate material, TS and the TRS to achieve maximum corrosion resistance and good mechanical properties. It was found that aluminum has the least corrosion rate of any backing plate material at 0.8174mm/year and maximum tensile strength while the FSW parameters (optimized) were 1200rpm and 60mm/min. And with composite material backing plate, it was noted that the corrosion rate was 1.559mm/year which was the highest. It was also noted that the FSW samples' corrosion resistance increased with post-weld machining [41].

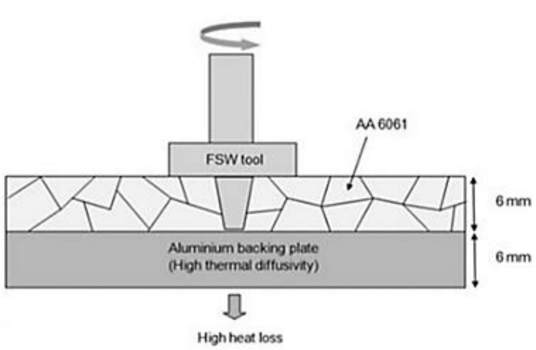

Fig. 4 Application of backing plate (Aluminum) in FSW [41]

The combined impact of corrosion and tensile stress under different aging circumstances was studied by Guo et al. in their research of Stress Corrosion Cracking (SCC) in aluminum alloy AA7075. They concentrated the study on TMAZ region as it is weakest in performance and established a relation between SSC and microstructure. The aging treatments done were double-aging treatment (DA) with 120℃ @ 4h plus 160℃ @ 7h and retrogression and re-aging treatment (RRA) with 120℃ @ 24h plus 190℃ @ 0.5h plus 120℃ @ 24 h. RRA alloy joints were shown to have greater SCC resilience than DA alloy joints due to their more coarse and discrete microstructure and higher copper content, both of which served to lower the potential difference between the junction and its surroundings [42].

Welding factors such TRS and TS were investigated by Yang et al. for their impact on corrosion resistance and mechanical properties. They took three set of readings for these parameters and drew the results. It was noted that the FSW sample with TS of 80mm/min and TRS of 600rpm had the highest value (38MPa) of UTS i.e. 95.7% of the base metal. The highest mass loss of 14.41mg/cm2 was noted for the FSW parameters with TS of 80mm/min and TRS of 600rpm. It was also concluded that welding parameters were less significant compared to grain structure state [43].

Anwar et al. conducted the study of effect of reinforcements in the FSW with aluminum alloy 5083 plates on corrosion behavior, mechanical properties and microstructure. The reinforcements consisted of various combinations which included addition of carbon nanotubes and boron carbide separately and as a combination of both (hybrid reinforcement). It was observed that there was a significant improvement in corrosion resistance and the UTS and hardness also improved almost equal to the base metal for both the reinforcements added individually. Grain size was found to be decreased as a result of recrystallization in the nugget zone. However, the hybrid reinforcement wasn't properly bonded [44].

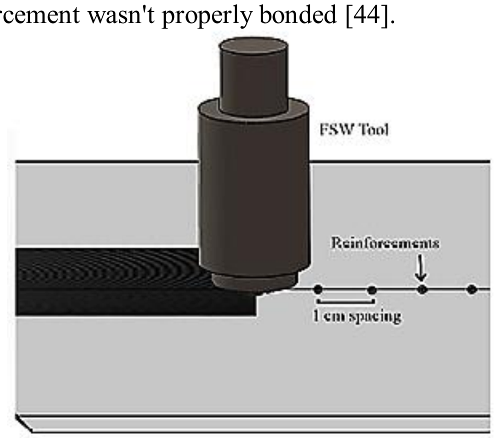

Fig. 5 Application of reinforcement in FSW [41]

Kumar et al. did a review on corrosional behavior of magnesium and its alloy, as they are highly reactive to corrosion than other materials. It was concluded from the studies that the FSW of magnesium and its alloy refines the grain structure and changes its corrosional behavior. The stir zone showed the highest corrosion resistance, and the insertion of inclusions into the zone further enhanced corrosion resistance. Also corrosion resistance was significantly affected by the by the formation of bimodal grains, intermetallic compound formation and orientation due to recrystallization. Also it was observed that corrosional behavior depended on heat and grain refinement [45].

Zheng et al. considered the influence on corrosion behavior and microstructure of two different alloys welded together through FSW, namely aluminum alloy (6061Al) and magnesium alloy (AZ31Mg). The FSW parameters were fixed such as TS of 100mm/min, TRS of 800rpm, tool pin plunge depth of 0.2mm, tilt angle of 3°. Also an interlayer of Zirconium (Zr) of 0.2 mm-thick foil was placed between the Al-Mg joint to make Al-Zr-Mg joint and study its effect as well. It was found that the joint with Zr interlayer reduced the Al-Mg intermetallic compounds due to the thermal barrier formed and chemical changes. The Al-Zr-Mg joint has better corrosion resistance than the Al-Mg joint because of the interlayer [46].

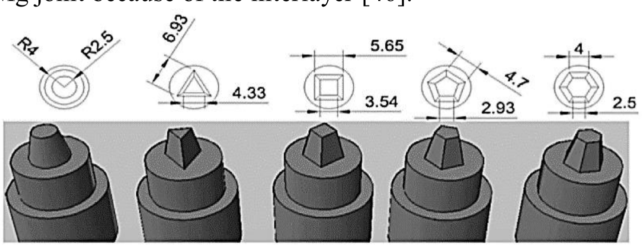

Fig. 6 Application of different tool pin profile in FSW [47]

Rambabu et al. investigated mathematical modelling to study the effect of welding parameters such as TRS, TS, tool pin profile and axial force on corrosional resistance of FSW joint. High corrosion resistance was achieved by optimizing the settings and tool profiles for FSW with an algorithm. We examined the influence of welding settings and tool profiles on the corrosion resistance of AA2219 aluminum alloy by producing reaction graphs and contour plots. The optimized FSW parameters through the simulation was then experimented to obtain conclusions. It was noted that the pin had significant influence on the corrosional properties of FSW joint especially with hexagonal tool pin which had the best quality. Joints produced at lower TRS of 1000 rpm and higher TRS of 1400 rpm have poorer corrosion characteristics [47].

Qian et al. analyzed the effect of Ultrasonic Impact Treatment (UIT) on FSW of 2219-T6 aluminum alloy with 6mm thick plates and its significance in corrosion resistance. The UIT method is used to improve the strength of the surface, mechanical properties and refine grain structure. By refining the grains on the joint's surface, UIT increased the corrosion resistance FSW joints. Moreover, UIT caused the precipitates to disintegrate, reduce in density and size, and become dispersed in grains. Hence, naturally, the propensity for intergranular corrosion was reduced. After receiving UIT, the stress sensitive index of FSW joints using a 3.5% NaCl solution decreases from 0.139 to 0.129. UIT reduced the propensity for intergranular corrosion under salt spray. Self-corrosion potential for HAZ was elevated from 0.653 to 0.628 V, and corrosion current density decreased from 7.48 to 6.18 mA/cm^2 [48].

Kumar et al. investigated the pitting corrosion after post welding treatments such peak aging (T6) and retrogression heat treatment and re-aging (RRA). They used friction stir welding to join sheets of AA7075 alloy that were 8 millimeters thick. The base metal and the welds have both passed a hardness and tensile testing. The dynamic polarization test was used to assess the material's resistance to pitting corrosion. In the ultimate aged (T6) condition, the welds discovered to have relatively good hardness and strength, but poor corrosion resistance. By using RRA, we were able to preserve the mechanical qualities while increasing the resistance to pitting corrosion. With only a slight decrease in weld strength, the RRA condition significantly increased resistance to pitting corrosion. RRA treated samples showed higher post-weld strength compared to PWHT-T6 samples via a combination of UTS and corrosion resistance. In the presence of widely distributed grain boundary precipitates, corrosion cannot proceed in a continuous chain. Hence, RRA samples are more resistant to pitting corrosion. T6 samples, because of the smaller grains and continuous precipitates along grain boundaries, pitting corrosion was severe [49].

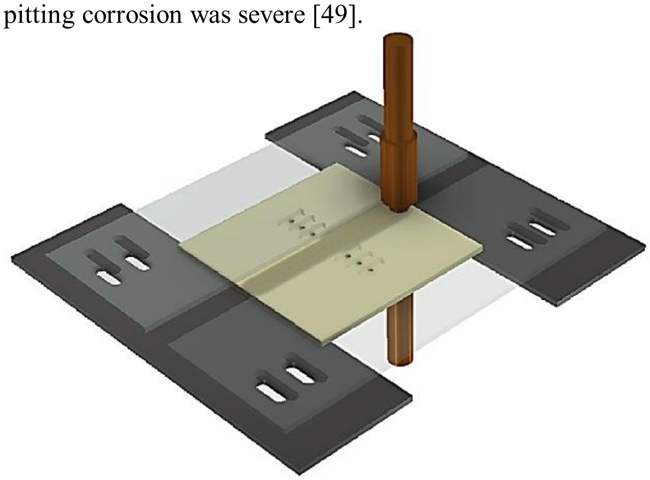
Fig. 6 Double sided friction stir welding [50]

Priyasudana et al. analyzed double sided friction stir welding (DS-FSW) of AA6061 with 6mm thick where two tools work on both the sides of the work piece. Effect on corrosion rate and mechanical properties was investigated by changing the axis of bottom and top tool and tool rotational speed. The result showed that the work sample with 1G welding position and TRS of 1500rpm had the maximum corrosion rate of 0.63856mm/year. However, the work sample with 1G welding position and tool rotational speed of 900rpm had the lowermost corrosion rate of 0.058567mm/year. It was found that the rate of corrosion increased with the intensity of the heat source. The corrosion rate is affected by the non-uniform cooling rate and occurrence of more heat owing to friction, which induces metallurgical changes in the areas of the HAZ and weld metal [50].

Gupta et al. conducted a study showing weld zones to be affected differently depending on the traverse speed, as demonstrated by mechanical and corrosion testing. Weld yield strength at greater traverse speeds (287MPa) and re-passivation corrosion resistance (0.958V) are superior to those at lower speeds. Microstructural examination with transmission electron microscope (TEM) and comprehensive DSC (differential scanning calorimetry) have confirmed that welding parameters have an influence on the disintegration, reprecipitation, development, and roughening of precipitates in the weld zones. Additionally, changes in precipitate structure in the weld zones confirmed that post-weld heat treatment enhanced the weld's mechanical and corrosion characteristics [51].

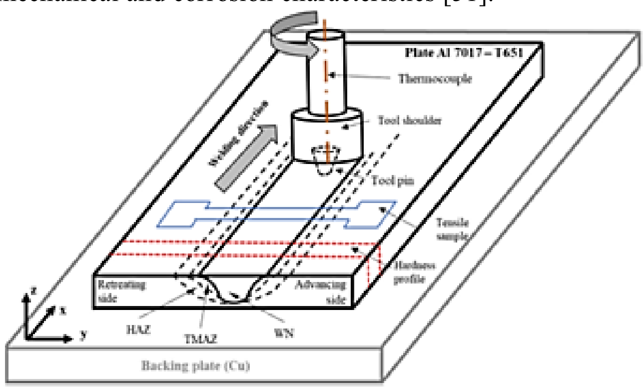

Fig. 7 FSW with thermocouple and locations for tests [51]

Kumar et al. did a study where they improved hardness and refined microstructure in the nugget zone by using boron carbide powder while welding AA7075 aluminum alloy. The inclusion of boron carbide powder to the friction-stirred weld nugget resulted in a considerable improvement in the nugget's resistance to pitting corrosion in the RRA state of the weld nugget [52].

Lemos et al. suggested FSW as a means of reducing the susceptibility of alloy 625 grade I to damage resulting from intergranular corrosion. Corrosion testing using ASTM G28 Method A for intergranular corrosion confirmed the Double-loop electrochemical potentiokinetic reactivation results, showing a mean corrosion rate of 0.4406 mm/year, indicating high weld quality [53].

Zamrudi et al. did a review for the corrosion resistance of friction stir welded aluminum alloys using electrochemical methods. The influence of corrosion mechanism and welding parameters, heat input formulations and welding temperature were discussed [54].

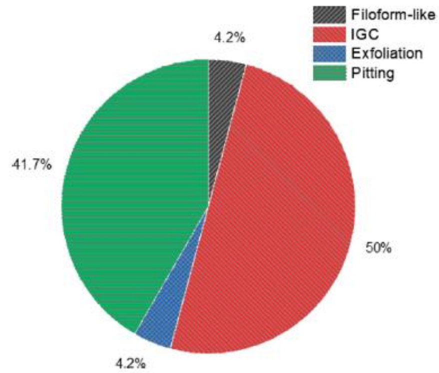

Fig. 8 Corrosion studies done (48 studies) [54]

Ding et al. conducted a study to analyze the FSW of aluminum and magnesum alloy on corrosion and mechanical properties. They found that the corrosion rate was shown to decrease with time as a result of the passivation effect and the generation of somewhat soluble products [55].

TABLE I

SUMMARY OF CORROSIONAL RELATION WITH FSW METHODS, TESTING PROCEDURES AND INFLUENCING PARAMETERS

AUTHORS	MATERIAL	CORROSION METHOD	PROCESS PARAMETERS			TESTS			
Shyamlal et al. [33]	AA8090T87 & 5 mm	H_2O_2 (10ml/l) + NaCl (57g/l) @ 6 Hours	Traverse speed TS (mm/min)	Tool Rotational Speed TRS (RPM)		Surface Roughness	Corrosion Analysis		Hardness
			90	900		24.5% increase	Mass loss of 0.2%		2.79% increase
			110	900		116% increase	Mass loss of 0.8%		27.3% increase
Laska et al. [34]	AA6082 & 3 mm	3.5 (wt) % NaCl at 20°C @ 60 mins	Traverse speed	Tool Rotational Speed	Tool Tilt Angle (°)	Potentiodynamic	Microstructure		Hardness
			1000	200	0	Lower corrosion resistance	Higher grain-size values were observed		lower values were observed
			1000	250	0				
			1250	200	0				
			1250	250	0				
			1000	200	2	Better corrosion resistance	Lower grain-size values were observed		Higher values were observed
			1000	250	2				
			1250	200	2				
			1250	250	2				
Kumar et al. [35]	AA5083-AA6061 & 6 mm	3.5% NaCl solution @ 30 mins	Traverse speed	TRS		Potentiodynamic	Tensile Strength	Microstructure	Hardness
			40	800		Lower corrosion resistance	Higher values of UTS	Lower grain-size values were observed	Higher values were observed
			60	800					
			80	800					
			60	1100		Better corrosion resistance	Superior UTS	Higher grain-size values were observed	Lower values were observed
			60	1400			Lower values of UTI		
			60	1700		Decreased Corrosion resistance			
Haribalaji et al. [36]	AA7075-AA2014& 10 mm	Salt spray corrosion testing method	Traverse speed	TRS		Corrosion rate		Tensile Strength	
			30	1000		Higher corrosion rate		Increasing values	
			45	1000					
			60	1000		Minimum corrosion rate			
			30	1200		Higher corrosion rate			
			45	1200				Maximum value	
			60	1200				Decreasing values	
			30	1400					
			45	1400					
			60	1400					
Amara et al. [37]	AZ31 magnesium alloy & 8.5 mm	3.5% wt NaCl solution	PWHT temperature (°C)	Time (Hour)		Electrochemical impedance spectroscopy (EIS)		Microstructure	
			200	1		Lower corrosion resistance		unchanged	
			300	1		Highest corrosion resistance		Increase in grain size	
			400	1		Lower corrosion resistance			
Liu et al. [38]	7075-T6 aluminum alloy & 12 mm	3.5% wt NaCl solution @ 4000 sec	Parameters	Max Temperature (TMAZ)		EIS		Hardness	
			TRS = 600rpm, Traverse speed = 60mm/min, Tool sinking value = 0.05mm	378		Lower corrosion potential		Decrease in hardness	
				388					
				398					
				408				Increase in hardness	
				418		Higher corrosion potential			
				428					
Nagu et al. [39]	AA6061-T6 & 6 mm	3.5% NaCl solution at room temperature @ 60 days	Parameters	Brass Interlayer of 200µm		Microstructure		Tensile Strength	Corrosion rate
			Traverse speed = 25mm/min, TRS = 800rpm (optimized)	Without interlayer		bigger grain size		Lower	Higher
				With interlayer		smaller grain size		Higher	lower
Matlou et al. [40]	AA5083 & 6 mm	0.6mol/L NaCl at 30°C @ 30 mins	Parameters	Rolling Direction Angle		Microstructure		Tensile Strength	Corrosion resistance
			Traverse speed = 300mm/min, TRS = 500rpm, Tool pin plunge depth = 5mm	0°		Higher volume of discontinuities (porosity)		Higher	low resistance than base metal
				45°				Lower	

Kulkarni et al. [41]	AA6061 & 6 mm	4M of NaCl, 0.5M of KNO3 and 0.1M HNO3 in 1L of distilled water @ 96h.	Optimized Parameters	Backing Plate	Exfoliation-Corrosion test	Tensile Strength		
			Traverse speed = 60mm/min, TRS = 1200rpm	Aluminum	Highest corrosion resistance	Highest value		
			Traverse speed = 60mm/min, TRS = 800rpm	Asbestos	Median corrosion resistance	Median values		
			Traverse speed = 30mm/min, TRS = 1200rpm	Composite	Lowest corrosion resistance	Lowest value		
Yang et al. [43]	Al-4.60Mg-0.60Mn-0.12Zr-0.28Er, wt.% & 5mm	3.5% wt NaCl solution	Welding Parameters		Intergranular Corrosion	Tensile Strength		
			TS = 100mm/min, TRS = 800rpm		Lowest mass loss	Median value		
			TS = 80mm/min, TRS= 800rpm		Median mass loss	Lowest value		
			TS = 80mm/min, TRS= 600rpm		Highest mass loss	Highest value		
Anwar et al. [44]	5083 aluminium alloy & 6 mm	1% HCl solution/1% HNO3 solution and 3.5 wt. % NaCl (3 methods)	Parameters	Reinforcement	Electrochemical Testing	Tensile Strength		
			Traverse speed = 40mm/min, TRS = 750rpm, Tool tilt angle = 2°	Carbon nanotubes	All the three methods gave decreased corrosion rate than the base metal	Highest value		
				Boron carbide		Higher value		
				Hybrid (both)		Very low		
Zheng et al. [46]	aluminum alloy (6061Al) to magnesium alloy (AZ31Mg) & 3 mm	3.5% NaCl solution for 60 h.	Parameters	FSW Joint	Microstructure	Corrosion resistance		
			Traverse speed = 100mm/min, TRS = 800rpm, Tool pin plunge depth = 0.2mm, tilt angle = 3°	Al-Mg	More Al-Mg IMCs	Higher corrosion rate		
				Al-Zr-Mg	Less Al-Mg IMCs	14% reduced corrosion rate		
Rambabu et al. [47]	AA2219 & 7 mm	Aerated 3.5% NaCl solution with pH10	Parameters	Tool Profile	Corrosion resistance			
			Traverse speed = 880.5mm/min, TRS = 1307rpm, Axial force = 12.20kN	Hexogonal tool pin	Highest corrosion resistance than other tool profiles			
Kumar et al. [49]	AA7075 & 8mm	Aerated 3.5% NaCl solution with pH10	Parameters	PWHT	Microstructure	Tensile Strength	Corrosion resistance	Hardness
			Solution heat treated at 515°C for 90 mins with cold water quench and heating at 120°C @ 1 day.	T6	Coarse grains	Higher	Less corrosion resistant	More hardness values
			Heat treated @ 220°C for 5 min & water quenched & aging @ T6 condition.	RRA	Fine grains	Lower	More corrosion resistant	Less hardness values
Priyasudana et al. [50]	AA6061 & 6 mm	sea salt mix as per ASTM D1141 standard	FSW Method	TRS	Welding Position	Corrosion resistance		
			Double sided friction stir welding (DS-FSW)	1500	1G	Highest corrosion rate		
				900	1G	Lowest corrosion rate		

III. Conclusion

After the study of the various recent methods and developments in corrosional studies, it can be concluded that:

1. The use of FSW is one method that has the potential to improve not only the grain structure of the welded joint but also its resistance to corrosion.

2.Corrosion behavior in the distinct FSW zones (stir zone, TMAZ and HAZ) varies depending on the amount of heat introduced and the degree to which the grains in each zone have been refined.

3.Corrosion resistance is shown to be affected by grain size, orientation, recrystallization, and the creation of intermetallic compounds (IMC). Inclusions added into the stir zone boost FSW joints' resistance to corrosion.

4. It was also found that the RRA alloy joints had stronger resistance to SCC than the DA alloy joints. Corrosion resistance in FSW samples of Aluminum Alloys is much improved after post-weld machining. Also, aluminum has the strongest corrosion resistance when used as a backing plate while welding.

5.For future recommendations, it can be concluded that there is research need to study the different materials as interlayer, reinforcement and backing plate to increase the corrosion resistance in FSW joints of similar or dissimilar materials.

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