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Characterization and Corrosion Study of Friction Stir Welded Titanium Alloy-A Review

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Abstract: ***Friction stir welding is a solid-state welding process used since 1990s. It was originally adopted for welding of Aluminium & for other materials like copper, steel, magnesium, titanium etc. Titanium has its wide range of applications due to its high strength to weight ratio along with good corrosion resistance and low thermal conductivity. This review is based on the friction stir welded joints of Titanium alloys and its characterization in the form of microstructure, macrostructure, non-destructive testing, hardness, corrosion testing etc. Microstructural changes can be easily evident by changes in parameters & changes in hardness profile of the weld and base metal. Problems associated with friction stir-welded joints will be understood to improve the properties of weld. It will result in significant technical and economic advantages because of its applications in critical aerospace industries.***

Keywords: Friction stir Welding, Titanium, Aerospace, Solid state process, Corrosion

1. Introduction

Titanium alloys are widely used in aerospace, biomedical, and chemical industries owing to their exceptional corrosion resistance, high strength-to-weight ratio, and biocompatibility. However, their welding via traditional fusion methods like gas tungsten arc welding, plasma arc welding, gas metal arc welding etc. often leads to defects such as porosity, grain coarsening, and oxidation due to the reactive nature of titanium at high temperatures. This necessitates the use of solid-state joining processes like diffusion bonding, friction welding, explosive welding among which Friction Stir Welding (FSW) has emerged as a promising solution. [1,2]

This review paper is focused on the problems and the characterization of the welded Titanium alloys in the ways to understand its behavior and working in different environments during its practical exposure. Friction stir welding developed in 1990s is such method that can be taking care of problems associated with arc welding processes and other such processes where melting of the base material takes place. This process is performed at relatively low temperature leading to plasticization of the material. It makes use of a rotating tool which is then utilized to create a mechanical mixture of elements near recrystallization temperature. This novel method stirs the weld zone mechanically and provides a sound weld of superior quality.[3,16,17]

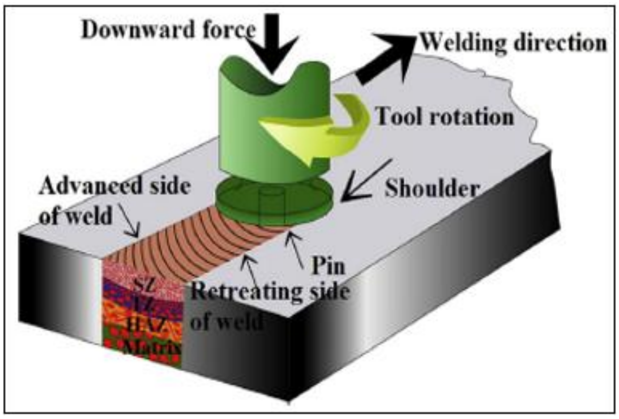

Figure 1: Schematic of FSW process [4]

After the welding is done, the weld is tested with different characterization techniques for the study of microstructure[5], hardness, tensile strength and corrosion behavior in different environments catering the need for high strength material used exclusively for aerospace and critical applications. This review paper undergoes deep study of corrosion of Titanium alloys in saline and acidic solutions which will resemble the conditions during service of the component.[6]

2. Research Progress in Titanium Alloys

Tool Materials and Designs

Friction stir welding was performed with different tools at different parameters and its effect on other properties were studied thoroughly. [7] studied different tools made up of W-Mo, W-Re, W-1% La_2O_3 with different shapes and were used for various joint thickness. Due to hardness of Titanium and its alloys tool pin undergoes massive wear even if it is made up of cemented carbide.

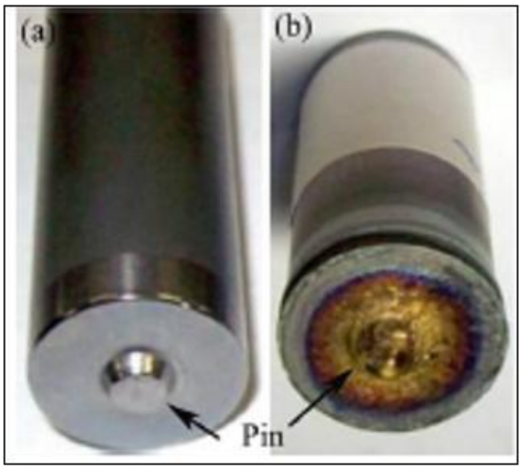

Figure 2: Cemented carbide tool a) Before welding b) After welding[7]

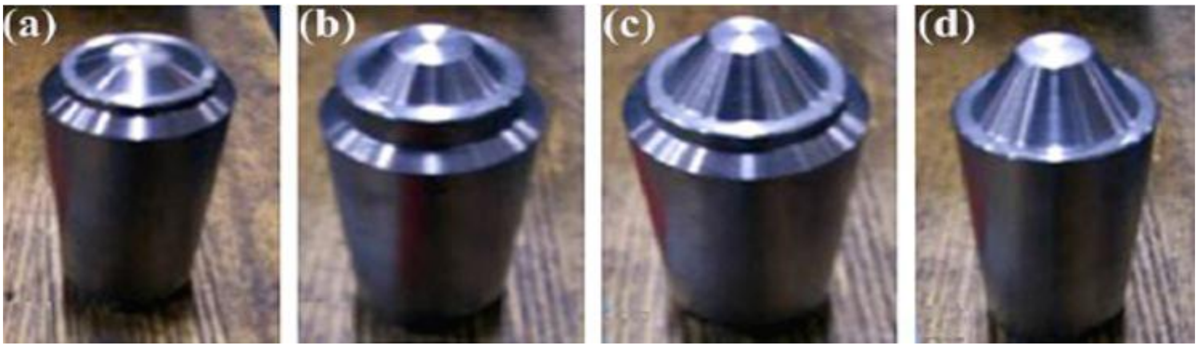

Figure 3: Various tools for various joint thickness[7]

In this work, different tools were studied with 400 rpm tool rotation speed and welding speeds of 25-100mm/min. The stir zone produced by controlling heat input of FSW joint had bimodal microstructure, whereas 500 or 600 rpm speed weld zone as lamellar structure. Also different zones were studied keeping in mind the temperature changes measured by thermocouple. It was observed that lamellar structure started to decrease with increase in the transition temperature. At this temperature, lamellar structure was converted to equiaxed grains.

[5] also studied about the influence of temperature on the stir zone microstructure. Figure clearly shows the micro and macrostructure of the joints. Its effect shows the presence of alpha grains. It is clear from the figure that it consists of bimodal structure of lamellar and elongated alpha grains in the base metal. This microstructure formation also affects the fatigue crack paths to higher level compared to conventional welding processes leading to a smaller number of defects due to fatigue mechanism.

[3] studied three different FSW weld joints in titanium grade 1 by keeping the tool rotation speed as 250 rpm and changing the welding speeds as 75, 100 and 200 mm/min respectively. Plate with 250 x 1000 x 3.2 mm were taken with W25Re tool with pin diameter of 5-6 mm and 3 mm length along with plunge depth of 3 mm and 20 kN axial force. Argon gas was also used for shielding against high solubility of hot Titanium for hydrogen, oxygen and nitrogen leading to brittleness. The samples obtained were sectioned perpendicular and were studied after metallography practice to reveal the microstructure.

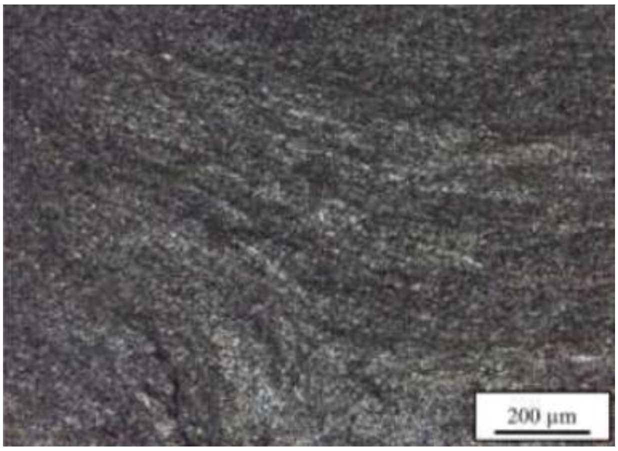

Figure 4: Microstructure of Stir zone Ti-200

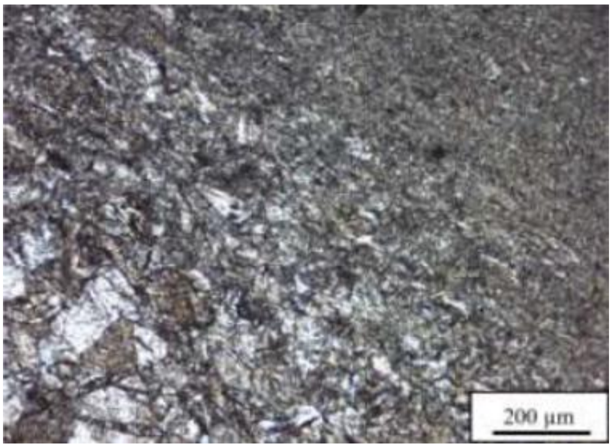

Figure 5: Microstructure of Thermo mechanically affected zone Ti-200

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It was clear from the observation that the width of thermo mechanically affected zone decreased along with increase in the welding speed from 75,100 and 200 respectively. Thermo mechanically affected zone is characterized by thinner grains than the base metal with visible deformation texture. Tunneling defect as well as kissing bond was observed during the investigation as shown in the figure. Also when the hardness profile was properly investigated, it was found that significant grain refinement in the stir zone increased the microhardness value upto 180-200 HV. There is increase in the microhardness value of stir zone from base metal value but it decreases with increasing the welding velocities as shown in the microhardness analysis graph. It is clear that even if there is presence of some defects, a good joint efficiency is observed above 90 % due to presence of recrystallized ultrafine grain microstructure.

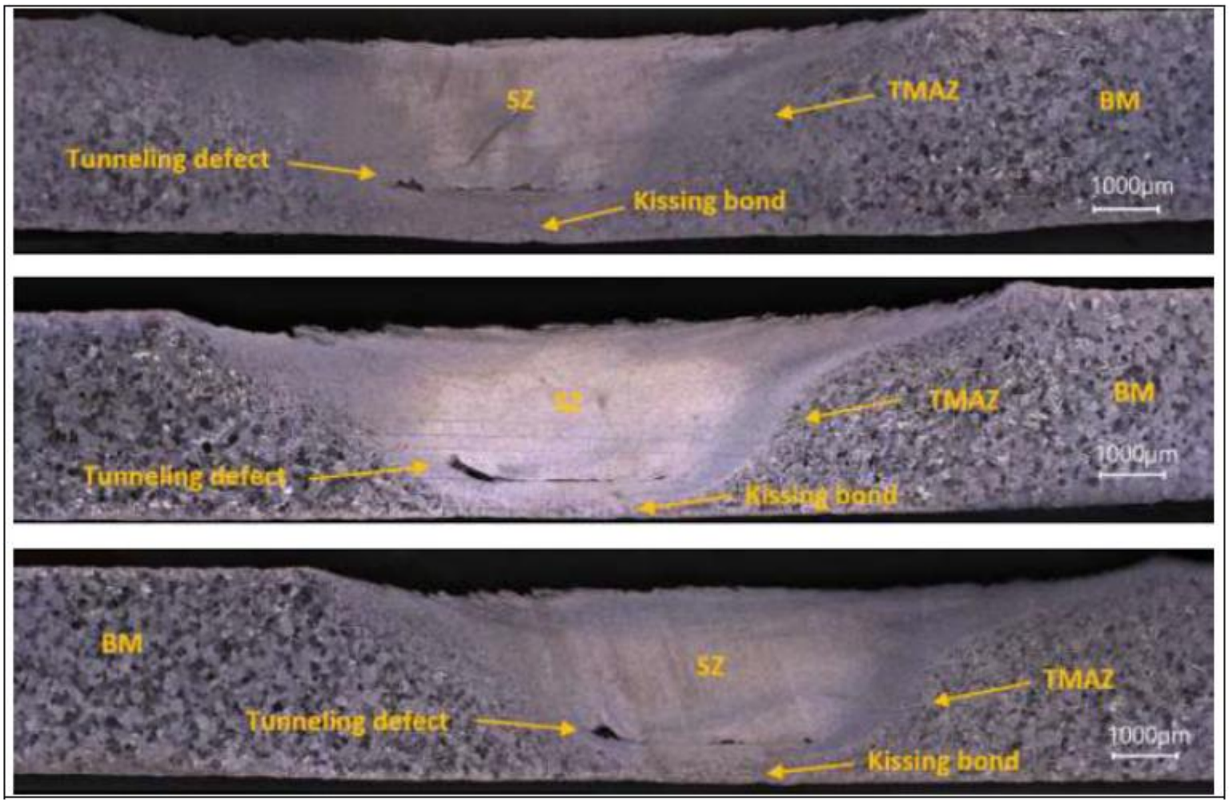

Figure 6: Microstructures of the welds of a) Ti 75 b) Ti 100 c) Ti 200 [3]

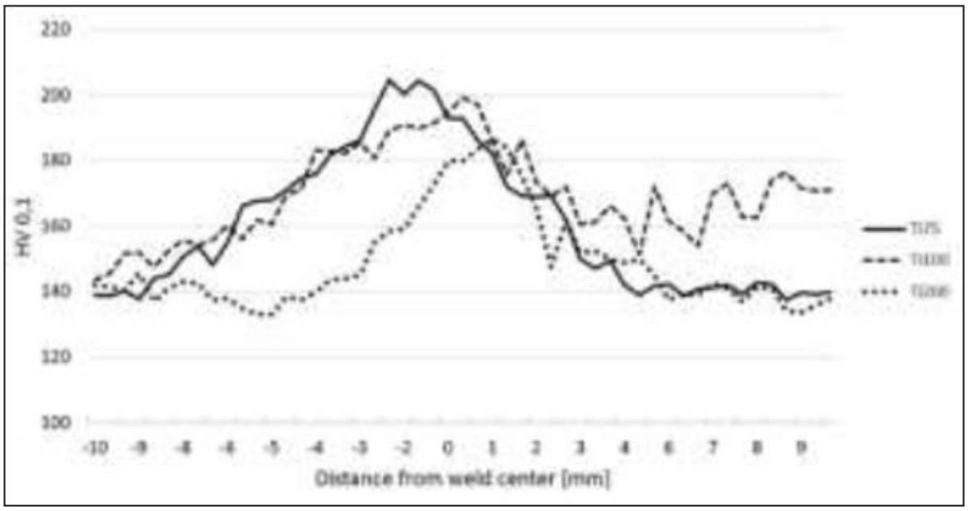

Figure 7: Microhardness analysis [3]

Macrostructure, microstructure and hardness profile of the welds gave a good idea about the properties and applications on the improvement side.

[6] studied about the corrosion behavior of titanium alloys in acidic and saline solutions. Titanium is known for its good corrosion resistance, but this study shows its behavior in strong reducing acids and fluorides that corrode titanium. Titanium alloys were regarded as most biocompatible material showing best combination of mechanical properties than stainless steel and cobalt based alloys.

Titanium has its higher corrosion resistance because of the presence of oxide film on the surface (passive layer). Some elements like Mn, V and Al may reduce the effectiveness of the film to some extent but noble metals like Pa and Ru significantly improve the corrosion resistance. Apart from alloying elements, Titanium alloys may be prone to corrosion attack in strong reducing acids such as HCl (hydrochloric acid) and sulfuric acid (H_2SO_4). If the concentration is high enough, it forms Ti hydride film on the surface which does not form readily as the oxide layer. Figure shows the superior corrosion resistance of Ti-6Al-4V to stainless steel in terms of pitting resistance.

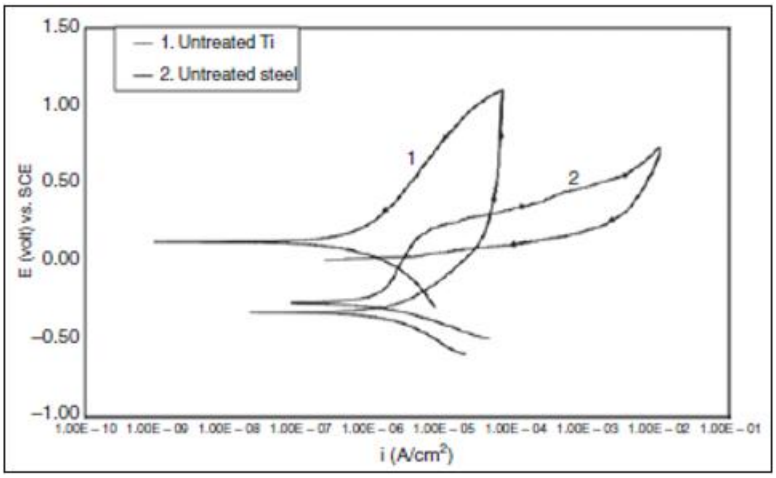

Figure 8: Comparison of cyclic polarization curves of stainless steel and Ti alloy[6]

Corrosion behavior was studied through open circuit potential, potentiodynamic polarization and electrochemical impedance spectroscopy. Mainly two solutions of HCl (hydrochloric acid) and sulfuric acid (H_2SO_4) were most common in the Ti alloys.[18] It was evident that corrosion performance of Ti alloys is reduced with increasing concentration and increasing temperature of the solutions and the corrosion behavior of alloys is dependent on the alloy compositions, phase compositions and surface properties. As Ti alloys are more corrosion resistant in non-acidic environment, its effect was observed in SEM analysis with neutral electrolyte. It showed from figure that anodic oxide layer formed in neutral electrolyte is nonporous and it protected the microstructure of the substrate. SEM analysis also showed that thickness of the anodic oxide film formed in neutral solutions is higher than that of the acidic solutions. It is very important that Ti oxide layer structure and thickness of the film should be considered when looking for prevention or control of corrosion.[15]

[8]studied about the key issues occurring during welding of titanium alloy Ti-6Al-4V. Improvements in different tool systems were developed by liquid cooling system, shielding gas and W-Re pin tool. Hydrogen was added to improve thermo-plasticity of alloy and thermo-hydrogen processed titanium alloy by designing a new tool system and to evaluate the tool wear. Tool developed using W-Re alloy with nickel alloy shank and gas inlet was also developed for cooling as well as shielding of the weld structure. The coolant used was ethylene glycol plus distilled water and was flowed circularly through chiller. Pure argon was used as shielding gas to prevent oxidization of the weld zone and the pin tool.

Figure 9: FSW tool design (a)[8]

Figure 10: Tool holder with gas inlet (b)

Table 1: Different welding tool parameters used are shown in Table:[8]

Pin Tool	Tilt Angle	Plunge Speed (mm/min)	Rotation speed(rpm)	Travel speed (mm/min)
W-Re	2.5°	0.5	300-600	25-125

It was reported that the greatest changes in tool dimensions occurred during initial plunging stage. Plunge test was designed to evaluate tool wear during FSW. The plunge test was performed at a rotation speed of 400rpm and a plunge

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speed of 0.5 mm/min. Welds observed did not show macro defects & with increase in hydrogen content weld showed full penetration which is solely due to improvement of thermos plasticity of titanium alloy. Microstructure of the weld only consists of stir zone instead of stir zone and thermo mechanically affected zone, heat affected zone obtained is extremely narrow and is characterized by highly deformed grains.

This lack of TMAZ is due to accommodation and distribution of sizeable strains associated with stir zone. Also tensile strength of base material decreases with increasing hydrogen content, elongation of all joints significantly decreases ac compared to base metal.

[1] studied about the benefits of FSW in different ways as it was a process not involving melting of the material as well as problems associated with arc welding were reduced owing to metallurgical and environmental benefits as shown in Table.[9]

Table 2: Key benefits of FSW welding

Metallurgical Benefits	Environmental benefits	Energy benefits
Solid phase process	No shielding gas required	Improved material use & allows reduction in weight
Low distortion of workpiece	No surface cleaning required	Decreased fuel consumption in light weight automotive and aerospace applications.
Good dimensional stability and repeatability	Eliminate solvents & grinding wastes	
No loss of alloying elements	Saving consumable materials such as rugs, wire or any other gases	
Fine microstructure & Absence of cracking		

Effect of tool geometry is studied on thorough basis because of its influence on process development. Different tool shoulder geometry was made and studied for deep understanding of its effect on mechanical properties. The main welding parameters under consideration here are tool rotation speed and tool traverse speed which helps in stirring and mixing of the material. It is also noted that higher tool rotation speed will lead to higher temperatures because of higher friction heating. Materials with higher melting points like Titanium or steel may be required for preheating because the tool rotation may not be sufficient to soften the zone and create mechanical stirring in the weld zone. Also, the most conventional design is butt or lap joint for FSW welds because of its superior control. [19]

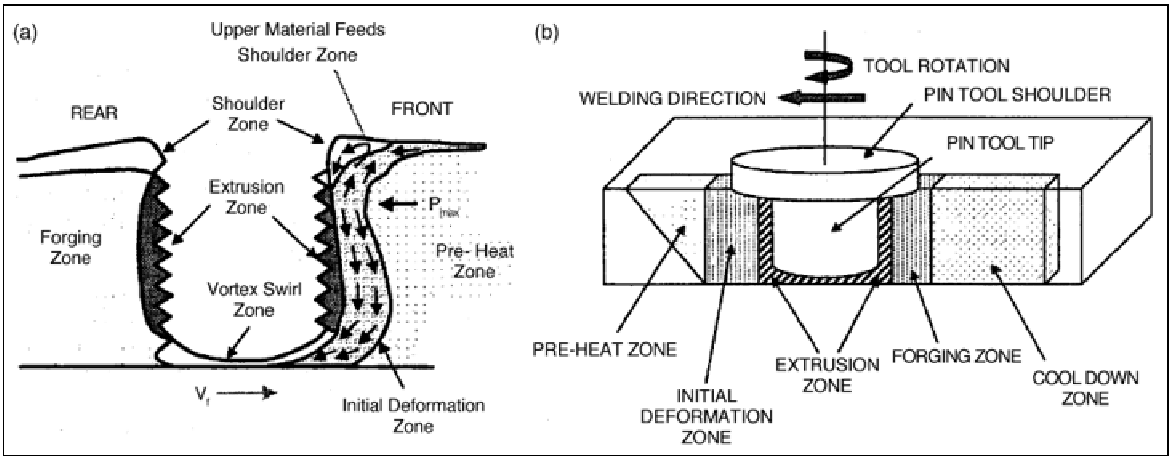

Figure 11 (a) & (b): Metal flow patterns and metallurgical zones produced [1]

[10] introduced the recent developments by showing the work of invention in the form of SSFSW (Stationary shoulder FSW) which consists of rotating pin located in non-rotating shoulder component which slides over the surface of the material during welding. A very smooth weld was observed creating consistent and almost linear input through the weld cross section. Its main advantages include uniform heat profile generation making it suitable for low thermal conductivity materials. The thermal cycle observed is also reduced compared to conventional FSW. Smooth surface along with precise control and management gave more stable welding technique by reducing tool wear. Hence the quality welds obtained in Titanium welding can be a great breakthrough for understanding this process.

[11] presents findings on stress corrosion cracking (SCC) of titanium alloys, particularly Ti 6Al 4V. It includes effect of chloride, iodide and fluoride solutions on SCC. Different experimental methods were adopted by NASA like rotating disk experiments and rapid fracture tests in which rotating disk method used to scrap the titanium surface to study electrochemical behavior and rapid fracture tests involved current density changes in different electrolytes. The electrochemistry of freshly generated titanium surfaces was analyzed, focusing on the formation of soluble titanium ions. Current density measurements indicated that a significant fraction of current contributes to the formation of Ti^{3+} ions. The presence of hydride and oxide layers affects the electrochemical reactions occurring on titanium surfaces. It was found that titanium surfaces rapidly passivate in acidic solution. It also suggests that titanium alloys exhibit complex electrochemical behavior under stress, influenced by environmental factor. Hence to improve performance and

safety of the titanium components in aerospace applications stress corrosion cracking test is much more needed.

[12] introduces the FSW welding as green welding process, energy efficient and ecofriendly technology. FSW is highlighted as a significant green technology due to its low energy consumption and lack of harmful emissions. Conventional welding methods produce harmful gases and consume substantial electrical energy, contributing to global pollution. FSW shows potential for significant energy savings, with studies indicating up to 90% reduction in energy consumption compared to traditional methods. The ability to acquire a wide range of materials, including advanced alloys, is crucial for future applications in engineering. There is a strong relationship between the microstructural characteristics and the mechanical properties of FSW joints. Fine equiaxed grains in the nugget zone led to increased strength and joint efficiency. Hardness profiles are influenced by precipitate distributions, with maximum hardness observed in the base metal. The tensile strength of FSW joints can reach up to 370 MPa, with joint efficiency at 91%.

[13] discussed about influence of oxygen in titanium alloys leading to stress corrosion cracking at elevated temperatures in jet engines. It was evident that combined effects of Oxygen and Hydrogen lead to cracking and causing embrittlement. Sometimes H may drain away due to its high solubility by forming hydrides and mechanism of SCC may take place in titanium alloys. It was due to dislocation pile up at the microstructure grain boundary observed in TEM leading to embrittlement. Presence of hydrogen in small amounts may have influence on plasticity while oxygen had effect on microstructural evolution and compositional variation. This may also lead to stress concentration and accelerate crack propagation. [14] studied the influence of sulfides on the passivation behavior of titanium alloy in seawater environments by electrochemical methods. It showed that the passivation process was irreversible as well as it composed of thickness less than 2nm and Tio sub oxide layer upto 13nm.

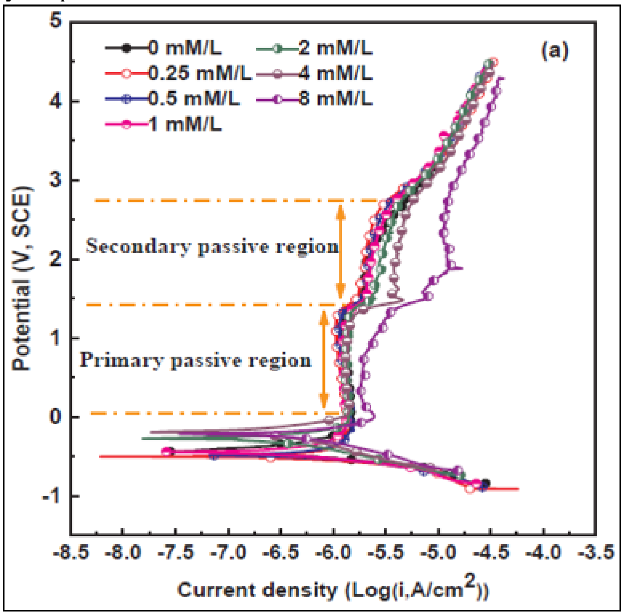

Figure 12: Potentiodynamic polarization curve for TA2 in sea water environments

Figure shows primary and secondary passive region at different potential values in different concentrations. If the sulfide concentration increases there is increase in the formation of titanium dioxide layer, it also increases the corrosion resistance of the TA2 material.

3. Conclusions

This paper involves understanding the research work in progress of FSW weld joints and invention in this field by applications in aerospace industries. Its effect on different mechanical as well as hardness properties were based on changes in tool pin profile and tool geometry. After that, corrosion in different environments like acidic media, saline media were understood to know its effect on corrosion rate. Corrosion rate is affected due to changes in different concentrations of environments, Stress corrosion cracking is as important as any other process because of its critical practical applications. Effect of sulfides concentration also shows the increase in corrosion resistance due to the formation of titanium dioxide layer.

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