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A Review on Corrosion Analysis of Friction Stir Welded Aluminium Alloy Plates

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***Abstract*—The following is a review paper on corrosion analysis of friction stir welded aluminium alloys. It is proven from several experiments and researches that friction stir welding is preferable to conventional arc welding processes when one wants to increase the corrosion resistance. But the effect of cryogenic treatment on the welds is yet to be studied. This review paper is a combination of the works done on corrosion analysis of aluminium alloys, preferably AA5083.**

Keywords—Friction stir welding, Corrosion, Aluminium alloys, AA5083, Cryogenic treatment

I. Introduction

The aluminium alloys are ductile with melting point lesser than steel and have considerably high strength to weight ratio. All these properties makes it a worthy replacement for steel in various applications. Hence, these alloys are being used for several transportation machines such as automobiles, aircrafts and including marine vessels. It is a known fact that aluminium possess higher corrosion resistance when compared to its counterparts. So nobody bothered to do its corrosion analysis in the initial days of its implementation. But in the later part of the twentieth century, dozens of marine vessels were sent to scrap and rework not because of any failure in mechanical properties, but because of corrosion. It was found that even aluminium is susceptible to corrosion in prolonged usage in severe environments. This started the corrosion analysis of aluminium alloys. One of the findings is that corrosion can be reduced if we use Friction Stir Processing (FSP) instead of conventional arc welding. One of the reason is in FSP there is no foreign particle inclusion in the weldment.

II. INFLUENCE OF GRAIN SIZE

R. Zhang [1] et al has shown that the susceptibility to intergranular corrosion for sensitized AA5083 is significantly influenced by both grain size and the grain boundary misorientation, which are both heavily dependenton specific processing methods. Based onthe results herein, it is concluded that:

i. Various processing methods including ECAP, HPT,rolling, and cryo-rolling were able to impart significantlyimproved hardness, and distinct grain size and grainboundary structure in AA5083.

ii. For ECAP processed AA5083 specimens, EBSDmapping suggests that the fraction of high-angle grainboundaries (HAGBs) was continually increased as thenumber of ECAP passes increased. In contrast, coldrolled samples possess a lower fraction of HAGBs, with afurther reduction in HAGBs via cryo-rolling. HAGBsare postulated to contribute to the nucleation andgrowth of thick β phase, and hence increased DoS. Incontrast, LAGBs can hinder the DoS in 5xxx series.

iii.Not just grain size, but grain boundry disorientation also affects the grain boundary precipitation. Similar grain sizes can give a large variation in DoS depending on distribution of grain boundary misorientations if the grain size is bigger(above 1 micrometre) . With significant grain refinement to a lower grain size (sub-micrometer), the regime is no longer dictated by grain disorientation but by the much larger grain boundary length and finer grain core only.

III. CORROSION INHIBITORS

JinwookSeong et al [4] has studied the Integranular corrosion on sensitised AA5083. Intergranular corrosion (IGC) attack and intergranular stress corrosion cracking (IGSCC) because of sensitization involves the formation of the anodic β phase (Mg_2Al_3) along the grain boundary. This study is focused on the inhibition of the SCC of sensitized AA5083 in 3.5 wt% NaCl solution by the addition of potassium chromate [K_2CrO_4], sodium silicate [Na_2SiO_3], and sodium vanadate [$NaVO_3$]. Their findings are:

1. Solutionised samples are immune to IGSCC whereas sensitised samples are not.
2. Addition of chromate and vanadate improved corrosion resistance and prevented low ductility fracture, but K_2CrO_4 showed better inhibition than $NaVO_3$.
3. Addition of silicate doesn't improve corrosion resistance , it doesn't prevent IGSCC and low ductility fracture

Ajit [3] et al has studied the effect of rare earth chlorides on corrosion. Their findings are:

The inhibitive effect of lanthanum and cerium chloride addition (at four different concentrations of 250, 500, 750, 1000 ppm) in NaCl solution on the corrosion of pure aluminium has been studied by electrochemical techniques. Corrosion resistance increased with increasing inhibitor concentration, with anomalous behavior observed at 750 ppm inhibitor addition. Polarization resistance and electrochemical impedance spectroscopy confirmed that $LaCl_3$ additions resulted in enhanced increase in polarization resistance compared to $CeCl_3$ additions, with maximum increase observed for 1000 ppm addition in both cases. The improved resistance offered by $LaCl_3$ addition has been related to the morphology of the precipitated oxide/hydroxide. Agglomerated faceted precipitates were

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noted in case of $CeCl_3$ addition and uniformly distributed fine globular precipitates with $LaCl_3$ addition. The formation of precipitates of oxides/hydroxides of lanthanum and cerium occurred on cathodic intermetallic sites at low inhibitor concentration and the surface in general at high inhibitor concentration resulted in improved corrosion resistance.

IV. EFFECT OF CRYO ROLLING

K.S.V.B.R. Krishna [7] et al has studied the effect of cryo rolling on the mechanical properties of AA5083 alloy. The effect of rolling strain and temperature on the Portevin–Le Chatelier effect experienced by aluminium alloys with magnesium as a major constituent was also studied in this research. Their findings are

1. Strain hardening due to rolling reductions was responsible forimproved hardness values. Room Temperature Rolling(RTR) samples exhibited high hardnessvalues, possibly due to the effect of second-phase strengtheningof the grain boundary regions compared to Cryo rolling(LNR) samples.
2. As the rolling reduction levels were increased, the strength levels were also increased, as expected. However, reducing therolling temperature of the AA5083 alloy did not show any improvement in strength. This result is most likely due to the strengthening from Al_4Mn or $Al_{12}(Mn, Cr)$ dispersoids that formed during RTR samples, in addition to strain hardening evidencedby X-ray results.
3. The PLC effect was clearly visible in the stress–strain plot. Theeffect of increasing the rolling strain was to lower the criticalstrain required for the onset of the PLC effect. In contrast, loweringthe deformation temperature was not equally effective inlowering the critical strain.
4. RTR samples were more effective than LN rolling in reducing thecritical strain for the onset of PLC. In addition, RTR samples caused a low magnitude of stress drop due to the large solutecluster concentration that it can cause.
5. The necking percentage is higher for 75% reduction comparedwith 50% reduction.

V. EFFECT OF PROCESS PARAMETERS OF FRICTION STIR WELDING

R. Palanivel [8] et al has studied the Effect of tool rotational speed and pin profile on microstructure and tensile strength of dissimilar friction stir welded AA5083-H111 and AA6351-T6 aluminum alloys. Their research has given these results:
The joints fabricated using straighttool profiles had no defects while tapered tool profiles caused atunnel defect at the bottom of the joints under the experimentalconditions considered. Three different regions namely unmixedregion, mechanically mixed region and mixed flow region were observed in the weld zone. The tool rotational speed and pin profileinfluenced the formation of mixed flow region. The joints fabricatedusing tapered tool profiles and tool rotational speed of600 rpm showed absence of mixed flow region. The joint fabricatedusing tool rotational speed of 950 rpm and straight square pin profileyielded highest strength of 273 MPa. The variation in tensilestrength of the dissimilar joints was attributed to material flowbehavior, loss of cold work in the HAZ of AA5083, dissolutionand over aging of precipitates of AA6351 and formation of macroscopicdefects in the weld zone.

H. Bisadi [13] et al has studied the influence of welding speed and tool rotational speed on mechanical properties of AA5083 and commercially pure copper sheets lap joints. Their studies have given these results:

1. Very low welding temperature leads to some defects like channels that show up at a region near the sheets interface especially in the Cu sheet. Also extremely high process temperature leads to some cavities appearance at the interface of the defused aluminum particles and the copper sheet material.
2. The maximum hardness of the copper side of the joint was observed at the weld SZ because of its fine grain size. Also albeit the grain size reductions, the hardness values of the joint aluminium side SZ were considerably lower than the aluminum base material. Production of micro voids at this area (Fig. 7b) might be the reason.
3. The hardness values of different weld areas are affected by firstly the welding temperature and secondly the amounts of the strain and material flow.
4. In all the tensile shear tested specimens, the fracture regions were AS of the joints beside the weld SZ. The aluminum sheet thinning caused by the shoulder depth and the hooking defect and also the brittle Al/Cu compositions are the main reasons of that. Also intermetallic compounds were detected mostly at the brittle fracture areas
5. Almost all of the ultimate tensile stresses decreased by increasing the process temperature. Increasing of the process temperature reportedly leads to higher amounts of copper particles diffusion to the aluminum sheet, intermetallic compositions and numbers of micro cracks.
6. The highest value of the ultimate tensile stresses was about 78% of the Cu and also about 74% of the aluminum sheets parent materials.

Gianluca [11] et al has studied the influence of process parameters on corrosion behaviour of friction stir welded aluminium joints (alloy 7075 and 2024). Their analysis has shown these results:

The best conditions in terms of mechanical strength were obtained using the “intermediate” values of rotational speed, and, in general, when the process parameters result in low values feed rate per unit revolution (F/S), that corresponds to the higher thermal contribution to the joint region. Free corrosion potential measurements and four oint bending tests were performed to evaluate -p the corrosion behaviour and stress corrosion cracking susceptibility of FSW Joints. No SCC occurrence was evidenced. A good correlation between microhardness and free corrosion potentials was noticed. The lower the hardness, the more anodic the corrosion potential. Severe localized attack occurs in the heat affected zones owing to the presence of sub micrometric precipitates. No systematic relationship between the process parameters and the corrosion behaviour

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can be observed. The presence of preferential corrosion sites was confirmed also by means of long time immersion tests.

VI. OPTIMIZATION OF PROCESS PARAMETERS

R. Vaira Ganesh [5] et al has studied the intergranular corrosion susceptibility of friction stir processed AA583 alloy. The study has shown these results:

The friction stir processed specimens were subjected to intergranular corrosion susceptibility test and a mathematical model was built to study the effect of process parameters on the intergranular corrosion susceptibility. The model was used to optimize the FSP process parameters for minimizing the intergranular corrosion susceptibility. The results of the test are summarized below.

1.The β phase of the alloy is deposited along the grain boundaries of α phase. Aggressive HNO3 dissolved β phase and it shredded off α phase grains, which resulted in huge mass loss in the base specimen.

2.Friction stir processing resulted in disintegration and dispersion of the secondary β phase, which reduced the intergranular corrosion susceptibility of the FSPed specimens.

3. The amount of heat generated at the interface of the workpiece and the tool greatly influenced the induction of dynamic recrystallization and grain refinement in the matrix.

4. Specimens processed at SD of 18 mm, TRS of 1000 rpm and TTS of 45 mm/min was less susceptible to intergranular corrosion, because of optimum heat generation to disperse the secondary phase in the matrix.

VII. FACTORS AFFECTING INTERGRANULAR CORROSION

Mary [2] et al has given an overview of intergranular corrosion mechanisms, phenomenological observation and modelling of AA5083. Their study shows IGC can lead to mass loss through grain fall-out and transition to intergranular stress corrosion cracking (IGSCC), as well as corrosion fatigue in the presence of stress. Factors affecting IGC and a review of IGC in Al-Mg alloy immersed in aqueous solutions (NaCl) is studied in this paper. The dependence of IGC susceptibility on important variables such as Mg content, temperature, exposure time, and grain boundary characteristics is explained. IGC initiation stage and spreading stage is studied by varying the breakdown potentials of the Al-Mg solid solution and the β phase (Mg_2 Al_3) grain size, and electrolyte concentration effects. In NaCl solution, the spreading/initiation of IGC occurs for a highly sensitized alloy as a result of the amount of high β-phase coverage grain boundaries. IGC propagation depends on DoS, but more directly on grain orientation, temper, and critically on electrochemical potential. For IGC susceptible DoS levels, there appears to be an IGC propagation threshold potential. Some of the factors affecting IGC and its effects are:

A. Alloy Metallurgy and Microstructure

DoS is linked to the distribution and morphology of β phase Average nearest neighbor distance (NND) divided by equivalent diameter and NAMLT are inversely proportional.

B. Solution Chemistry and pH

IGC formation is more in acidic environment (corrosion involves more uniform matrix dissolution) followed by basic (corrosion is limited to grain boundary attack) and neutral environment.

C. Applied Potential

Applied potential influences localized corrosion morphology in a wide range of aluminum alloys. It was observed that the sensitized alloy has a lower breakdown potential than the unsensitizedalloy(spreading of IGC on surface). A linear potential dependence was also observed for IGC propagation into the depth from the surface.

D. Electrochemical Factor

To establish a range of potential over which AA5083 is susceptible to IGC in NaCl as a function of chloride ion concentration, an electrochemical framework was developed.The framework suggests that IGC spreading is expected at the range of potential between the breakdown potential of sensitized AA5083 or the spreading potential and the breakdown potential of the β phase.

VII. COATINGS FOR CORROSION PROTEECTION

Hamed [11] et al has studied the sol-gel coating on AA5083 to improve corrosion resistance. Chromium based-pretreatments are among the mostefficient and successful system for aluminum and its alloys. Furthermore,the use of chromate will be totally banded in coatingmaterials in the near feature because of their extremely toxic effect. In last decade an intensive research is ongoing to develop environmentallyfriendly alternatives to chromate based-pretreatmentprocesses. The hybrid sol–gel coatings were reported as promisingenvironmentally friendly alternatives for anti-corrosion pretreatments on different substrates. Hybrid coatings combineboth the advantages of inorganic polymers (flexibility, lightweight,reduces defects, good impact resistance and process ability, etc.)and inorganic components (high mechanical strength, good chemicalresistance, high ductility and superior adhesion to the metal surface, etc.). Good adhesion of sol–gel films to aluminum derives from the formation of strong covalent Si-O-Al bands corrosion performance of sol–gelorganic–inorganic hybrid system depends upon a number of compositionaland processing factors. Their results show that-

The sol–gel coatings provided a physicalbarrier on AA5083 substrate for blocking the electrochemicalprocess.

1. DoE methodology based on Taguchi method has beenfound to be a very effective tool in the optimization of key processparameters.
2. The results show that hydrolysis water contentamong other factors is the most significant one.
3. Minimum corrosioncurrent density was obtained by using optimum parametersinclude organic/inorganic molar ratio (GPTMS/TEOS = 3/7), hydrolysiswater content (x

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=12), drying temperature (D = 90 ◦C), andcuring temperature (C = 130 ◦C).

4. Electrochemical impedance spectroscopyapplied in this work allowed estimation of corrosionprotection properties of optimum hybrid sol–gel films

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