Galvanic corrosion study of aluminium alloy plates mounted to stainless and mild steel bolts by accelerated exposure test

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Despite the fact that aluminium alloy members have a proven durability over stainless steel members, their joint fasteners like bolts, nuts and washers are drawn from steel material due to aluminium alloy inferior mechanical properties. Bare contact between aluminium alloy members and stainless steel fasteners results to galvanic corrosion of aluminium alloy members. A corrosion behaviour study was carried out on different aluminium alloy types with different surface treatments mounted to stainless and mild steel fasteners with different surface treatments and subjected to a 1000 hours salt water spray test. It was found that fasteners treated with zinc flake coating exhibited strongest resistance against galvanic corrosion. Among untreated specimens, aluminium alloy type A5083P-O was found to be the most durable.

Keywords: aluminium alloy, salt water spray test, galvanic corrosion, surface treatment

1. INTRODUCTION

Steel has been a traditional material for more than 150 years in construction of bridges, railways, and manufacturing of vehicles and hand tools because of its excellent mechanical properties and low manufacturing cost[1]. It is evident that success of industrial revolution of many countries relied on utilization of steel. There has been an increasing demand to construct massive steel structures which are durable but corrosion of steel has been the most challenging aspect. Although painting coating systems are widely used to prevent corrosion damages on steel structures, but the anti-corrosion performance of coating films decreases gradually[2]. In the recent years, researchers and designers assessed the possibility of using aluminium alloy in place of steel due to its considerable light weight and high corrosion resistance compared to steel[1]. Currently innovation in aluminium alloy has offered a paramount advantage in manufacturing of energy efficient and durable transportation vessels due to light weight and corrosion resistance of aluminium alloy[3]. Aluminium alloy is used only for light duty components of structures due to limited mechanical strength, low Young's modulus and high cost.

Due to limited strength of aluminium alloy, fastening of aluminium alloy members requires fasteners which are made up of other strong materials different from aluminium alloy. However, the different material of fasteners such as stainless steel bolts causes galvanic corrosion of aluminium alloy members. In order to prevent galvanic corrosion, several kinds of surface treatment have been proposed but their quantitative effectiveness is still unknown.

(a) 21 Years of service (b) 18 Years of service

Fig. 1 Typical galvanic corrosion on guiderails in Okinawa 2013

Severity of galvanic corrosion depends on geographical location and climate condition. This can be verified on a research carried out by Japan Aluminium Association in 2006 in Tokyo, Tsukuba and Okinawa[4]. Three types of field test specimens were used to investigate the durability of aluminium alloy A5051 by 10 years field exposure test. One of three specimens was to investigate galvanic corrosion between aluminium alloy plates and steel bolts. Stainless and mild steel bolts treated with various types of coating were bolted on specimens.

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After 10 years, almost no harmful damages were observed in Tokyo and Tsukuba except on specimens with untreated mild steel bolts. However, due to dissimilar metal contact, severe corrosion was observed in Okinawa on some specimens with treated and untreated stainless and mild steel bolts. But there was no corrosion observed at stainless steel bolt with zinc flake coating[4]. Long service life of aluminium alloy members is mainly hindered by galvanic corrosion. This can be observed on a field survey which was done by Durability Research Committee (Chairman: Y. Itoh) of Japan Aluminium Association in 2013 where by 22 guiderails of 14 bridges were surveyed in Okinawa. On 6 guiderails served for 21 and 18 years, galvanic corrosion was observed between aluminium alloy and stainless steel bolts as shown in Fig. 1[5].

The main objective of this research is to investigate the galvanic corrosion behavior of selected aluminium alloy types with different surface treatments attached to stainless and mild steel fasteners with different surface treatments. The study is geared at improving and extending service life of bridge guiderails by identifying appropriate material and anti-corrosion systems[6, 7].

2. EXPERIMENT

2.1 Specimen description

The study was conducted on eleven specimens named SP01, SP02, SP03, SP04, SP05, SP06, SP07, SP08, SP11, SP12 and SP13 which are drawn from aluminium alloy plates of different thickness and different alloy types. They are also treated with various anti-corrosion treatments. Each specimen is fastened to treated or untreated stainless or mild steel fasteners as illustrated in Table 1. The study involved combination of different alloy types with different thickness and surface conditions because bridge guiderails are made up of aluminium alloy components with different alloy types and thickness for optimum material utilization. Specimens' appearance after salt spray test is shown in Table 2.

(1) Specimen alloy types and surface treatment

SP01, 02 and 03 are drawn from aluminium alloy type A6061S-T6 with chemical composition by weight of 0.40 to 0.8Si, 0.7Fe max, 0.15 to 0.4 Cu, 0.15Mn max, 0.8 to 1.2Mg, 0.25Zn max, 0.15Ti max and 0.04 to 0.35Cr[8]. This alloy type is formed by cooling from elevated temperature shaping process and artificially aged[9]. It is used in fabrication of guardrails beams where high strength, corrosion resistance and weldability are needed[10]. The specimens are treated by combined coating of anodic oxide and silver color organic film through electrolysis process, where the surface is coated with a film of aluminium. SP01 is treated on both sides but SP02 and SP03 are not treated on bottom and top side respectively. The untreated sides are covered with splice plates of same material and similarly treated but with exception of nuts and washers on those sides.

SP04 is drawn from aluminium alloy type A6N01S-T5 which is a special alloy type originated from Japan but are internationally similar to A6005A-T5. It has chemical composition by weight of 0.9 to 0.40Si, 0.35Fe max, 0.35Cu max, 0.50Mn max, 0.40 to 0.80Mg, 0.35Cr max, 0.25Zn max and 0.10Ti max[11]. It is formed by cooling from an elevated temperature shaping process and then artificially aged[12]. It is typically used for structural angles of inspection walkways deck plates in bridges. This specimen is not treated on both sides.

SP05 is drawn from aluminium alloy type A5083P-O with chemical composition by weight of 0.08Si, 0.26Fe, 0.10Cu, 0.25Zn max, 0.45 to 1.0Mn, 4.0 to 4.9Mg, 0.05 to 0.25Cr and 0.15Ti max[8]. It is formed by annealed process to obtain lowest strength temper but with improved ductility and dimension stability[13]. It is also used for structural angles of inspection walkways deck plates in bridges. This specimen is not treated on both sides.

SP06 is drawn from aluminium alloy type A3004P-H32 with chemical composition by weight of 0.30Si, 0.70Fe, 0.25Cu, 0.25Zn, 1.0 to 1.5Mn, 0.80 to 1.3Mg, and 0.05Ti. It is formed by strain hardening process whereby strength is increased and ductility is decreased. It is mainly used for industrial roofing[10]. This specimen is not treated on both sides.

SP07 and 08 are drawn from aluminium alloy type AC7A-F with chemical composition by weight of 0.20Si, 0.30Fe, 0.10Cu, 0.15Zn, 3.50 to 5.5Mg, 0.6Mn, 0.05Ni and 0.20Ti. It is formed by sand or steel mold casting process and offers excellent corrosion resistance, high strength and elongation. It is mainly used for posts of guardrails[14]. These specimens are both treated with 35μm silver colored baked acrylic resin. Mild steel splice plates similarly treated are attached on bottom side of SP07 and SP08 by similarly treated mild steel bolts, but with addition of sandwiched insulation sheet and insulation bushes on SP08.

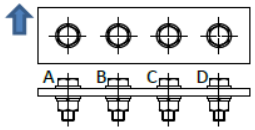
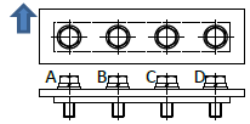
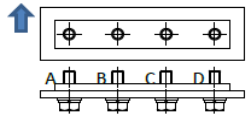
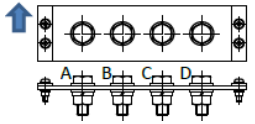
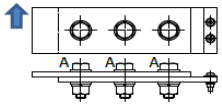
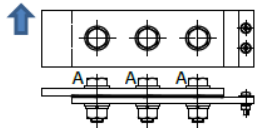
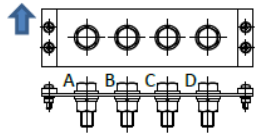
SP11, 12 and 13 are drawn from aluminium alloy type A6063S-T5 with chemical composition by weight of 0.20 to 0.0.60Si, 0.35Fe max, 0.15 to 0.10Cu, 0.10Zn, 0.10Mn, 0.45 to 0.9Mg, 0.10Cr max and 0.10Ti[8]. It is formed by cooling from an elevated temperature shaping process and then artificially aged[12]. The specimens are treated by combined coating of anodic oxide and organic film on both sides through electrolysis process, where the surfaces are coated with film of aluminium with different colours.

(2) Fastener types and surface treatment

SP01, SP02, SP03, SP04, SP05, SP06, SP11, SP12 and SP13 have bolt holes named with letters; 'A' for untreated stainless steel bolts, nuts and washers. 'B' for zinc flake coated stainless steel bolts, nuts and washers. The generic term used for zinc flake coating is GEOMET treatment which is a patented trademark. GEOMET treatment is a shot blasting and dip spinning of fasteners in an aqueous base solution containing zinc and aluminium flakes in an inorganic binder[15]. Letter 'C' is for untreated stainless steel bolts and nuts but with painted washers and letter 'D' is for untreated stainless steel bolts, nuts and washers but with insulation bush (vinyl chloride).

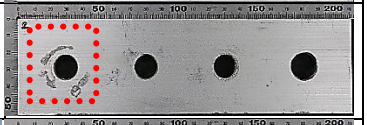
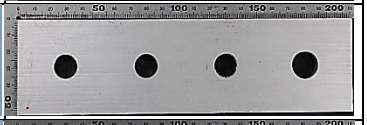
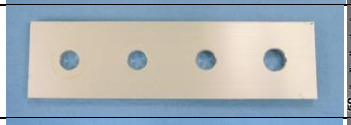
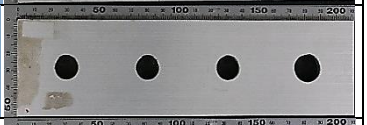
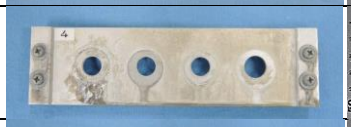
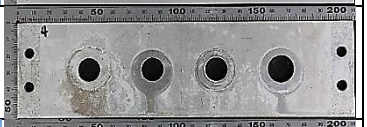
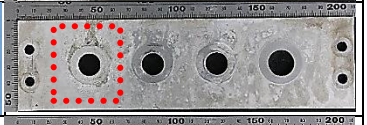
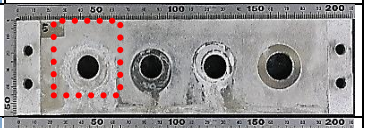
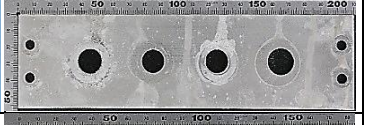
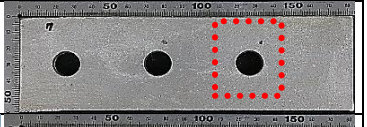
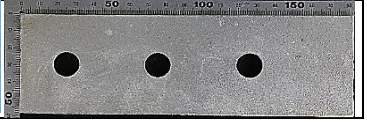
SP07 and SP08 bolt holes are all named with letter 'A'. Both bolt holes are for hot-dip zinc coated mild steel bolts, nuts and washers but with addition of sandwiched insulation sheet and bolts' insulation bush on SP08.

Table 1 Configuration and description aluminium alloy specimen for1000 hour salt water spray test

Specimen	Specimen configuration	Material type	Thickness (mm)	Specimen surface treatment	Fastening bolts, etc.				
					Material specifica-ions	A	B	C	D
SP01		A6061S-T6	t7.0	Both sides with A2 silver color	M12×35 N1,W2, SW1 SUS304	Without treatment	Geomet treatment	Washer only both sides painted other not treated	Without treatment/ electric insulation by bush (vinyl chloride)
SP02		A6061S-T6	t7.5	Top side: A2 silver color Bottom side: untreated	M12×35 W1,SW1 SUS304				
SP03		A6061S-T6	t7.5	Top side: untreated Bottom side: A2 silver color					
SP04		A6N01S-T5	t4.0	Both sides untreated	M12×35 N1,W2, SW1 SUS304				
SP05		A5083P-O	t6.0	Both sides untreated					
SP06		A3004P-H32	t2.0	Both sides untreated					
SP07		AC7A-F	t7.0	35μm or more baked acrylic resin silver color	M12×35 N1,W2, SW1 SS400	Hot-dip zinc coated (HDZ35)			
		SS400 (Mild Steel)	t6.0	Hot-dip zinc coated (HDZ55)					
SP08		AC7A-F	t7.0	35μm or more baked acrylic resin silver color and insulation sheet sticker on bottom side only		Hot-dip zinc coated (HDZ35) and insulating bush			
		SS400 (Mild Steel)	t6.0	Hot-dip zinc coated (HDZ55)					
SP11		A6063S-T5	t3.0	Double-sided A2 sutenkara color (KCS)	M12×35 N1,W2, SW1 SUS304	Without treatment	Geomet treatment	Washer only both sides painted other not treated	Without treatment/ electric insulation by bush (vinyl chloride)
SP12				Double-sided A2 brown color (KOB)					
SP13				Double-sided A2 dark brown color (KSB)					

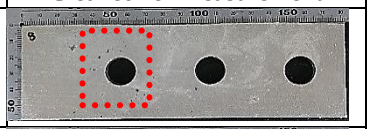
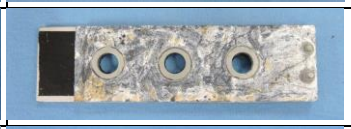
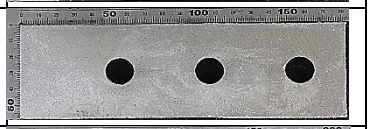
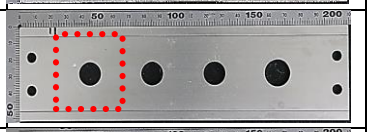
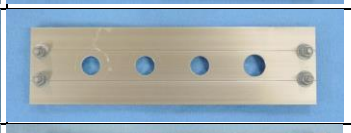
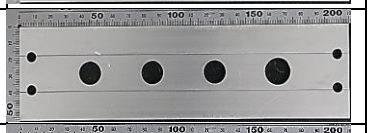
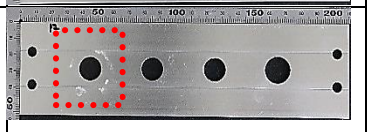
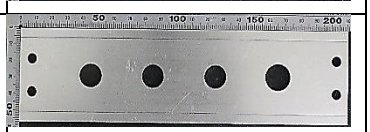
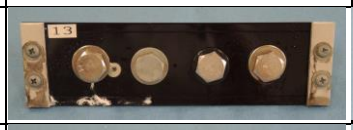
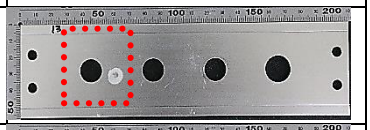
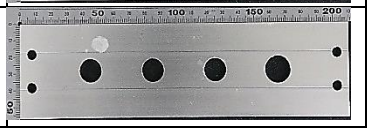
Blue arrow: Installation direction at the time of the salt water spray test
A2: The type of combined coating of anodic oxide and organic film (JIS H 8602)

Table 2 Appearance of specimens after 1000 hours salt water spray test

Specimens		After the test	Fasteners removed	Cleaned for measurement
SP 01	Top side			
	Bottom side			
SP 02	Top side			
	Bottom side			
SP 03	Top side			
	Bottom side			
SP 04	Top side			
	Bottom side			
SP 05	Top side			
	Bottom side			
SP 06	Top side			
	Bottom side			
SP 07	Top side			
	Bottom side			

: Areas with maximum corrosion depth (refer details in Table 3)

Table 2 Appearance of specimens after 1000 hours salt water spray test (continuing)

Specimens		After the test	Fasteners removed	Cleaned for measurement
SP 08	Top side			
	Bottom side			
SP 11	Top side			
	Bottom side			
SP 12	Top side			
	Bottom side			
SP 13	Top side			
	Bottom side			

: Areas with maximum corrosion depth (refer details in Table 3)

Salt
The salt is of sodium chloride (NaCl) of special grade specified in JIS K 8150 or equal to or higher grade.

Water
The water is deionised or distilled water with not more than 20μS/cm in electric conductivity at 25°C±2°C. It is recommended that the electric conductivity ought to be not more than1μS/cm.

Mixing
Salt is dissolved in water and salt concentration is adjusted to 50g/l±5g/l. As salt concentration is adjusted, density is measured by hydrometer to be confirmed if it is within the range of 1.029 to 1.036 at 20°C. If it is found to be outside the range, adjustment of solution is considered.

Fig. 2 Preparation of salt solution

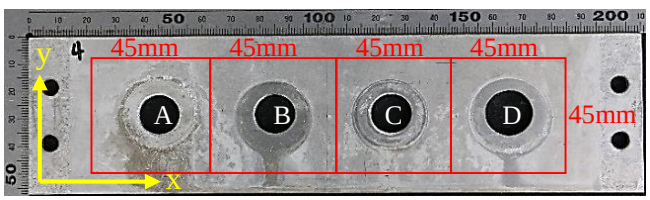


Fig. 3 Example of corrosion measurement areas on specimens

2.2 Salt water spray test

The salt water spray test was carried out according to Japanese Industrial Standard (JIS Z 2371). The experiment was done by simulating the corrosive environment that aluminium alloy members encounter during their service life. The exposure environment was accelerated in order to realize the effect of corrosion faster than in the real world.

Preparation of salt solution for salt water spray test is illustrated in Fig. 2. Salt water spraying was automatically done by a special spraying apparatus. In this experiment, aluminium alloy specimens were exposed to 1000 hours salt water spray test condition. Placement of specimens inside the apparatus was at an angle of 20°±5° to vertical and orientation is as described in Table 1[16].

2.3 Corrosion measurement

After salt water spray test, fasteners were removed and the specimens were thoroughly cleaned by chemical method to remove organic film (immersed in concentrated H_2SO_4 solution at 23°C for 30 minutes and then washed with water: except SP04, SP05, and SP06), anodic oxide film and corrosive products (immersed in 2% CrO_3 and 5% H_3PO_4 mixed solution at 100°C for 10 minutes and then washed with water and dried). Corrosion

measurement was done by laser displacement meter (KEYENCE, LE-4010) with vertical measuring range of ±5mm, diameter of laser-spot of 30µm and accuracy of 0.1µm. The measurement was carried out to determine the magnitude of corrosion depth, area and volume. Each specimen at a time was set on a laser displacement meter for measurement. Corrosion data were picked on both top and bottom sides of specimens surface at an interval of 200µm in both x and y direction on independent areas of 45x45mm around each bolt hole as shown in Fig. 3. Then, the data were retrieved from laser displacement meter for further analysis.

3. DATA ANALYSIS

3.1 Corrosion depth and 2D maps

Corrosion data were converted form comma-separated-values (CSV) format to a usable excel workbook format and re-arranged in a spot height grids by using Microsoft excel 2013 and plot 2D maps of each area around the bolt holes on both sides of specimen as shown in Fig. 4. The purpose of 2D maps is to reveal the most corroded points which cannot be observed by naked eyes on the specimens. From the 2D maps, several sections were taken at an interval of 200µm in y-direction to plot multi section corrosion profile. By using spot height data, multi section profiles were plotted on the same x and y plane for every specimen as shown in Fig. 5. On multi section profile, each section displayed a profile with unique color which could be traced easily. Profiles which had an outstanding trough depth with reference to base line (CD=0µm) were selected for further detailed plotting to identify the most outstanding profile among them. Then the most outstanding profile was plotted alone for presentation as shown in Table 3 and from it, maximum corrosion depth (CDmax) was calculated. The profiles with maximum corrosion depth were approved by cross checking with the location of the most corroded points on 2D maps. In case of any contradiction, re- measurement and data analysis were considered.

3.2 Corrosion area and volume

The magnitudes of corrosion area (CA) and corrosion volume (CV) were calculated automatically from the measurement results by laser displacement meter. The first step was to identify un-corroded area on the 2D map with its corresponding scale, and then carefully eliminate un-corroded areas by trimming the scale from 19µm to -128µm as shown in Fig. 6. The magnitude of area and volume of corroded portion remain after trimming are displayed automatically on laser displacement meter computer screen. This operation was repeated on each independent areas for all specimens.

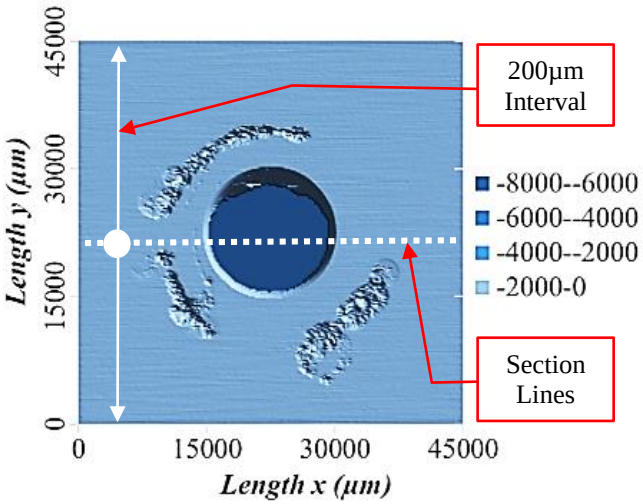


Fig. 4 Example of 2D map around bolt holes and sections lines

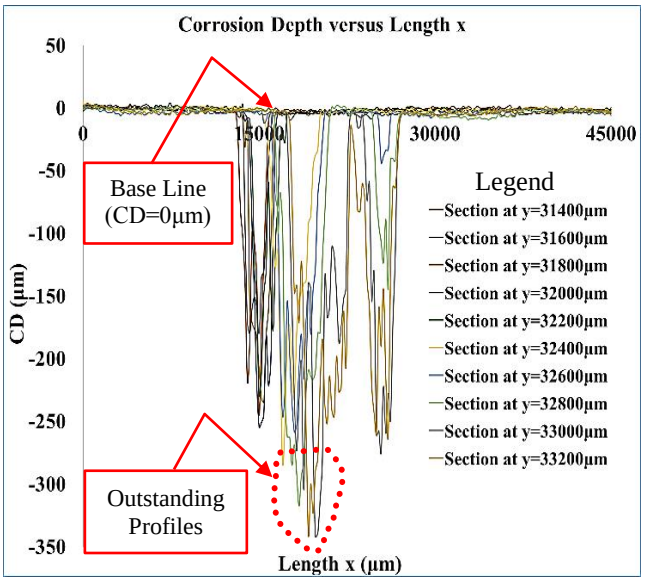
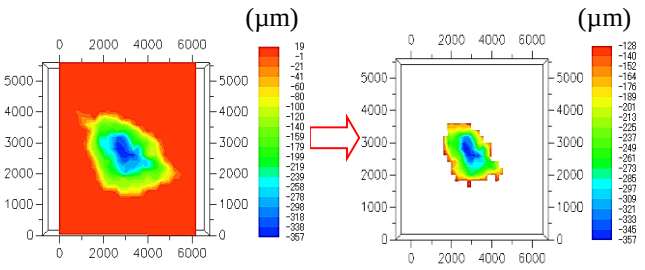


Fig. 5 Multi section profile



(a) Before trimming (b) After trimming

Fig. 6 Corrosion area and volume calculation

Table 3 2D Maps and corrosion profiles of areas pertaining maximum corrosion depth

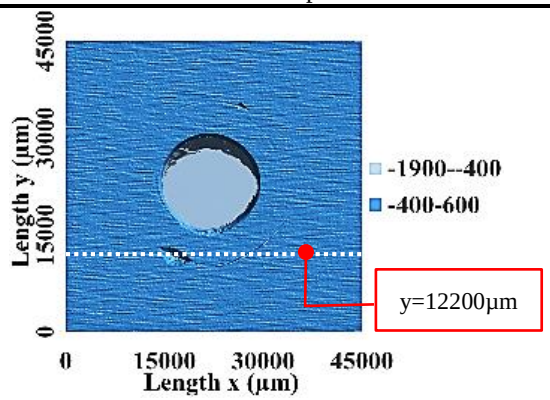
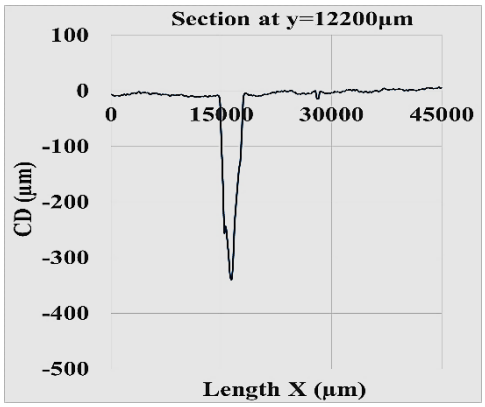
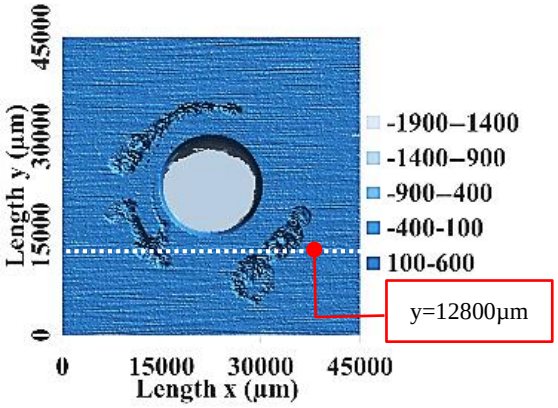
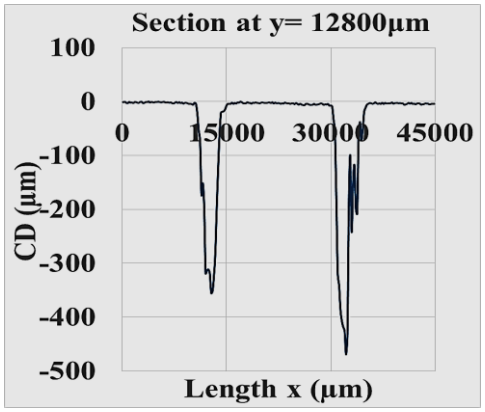
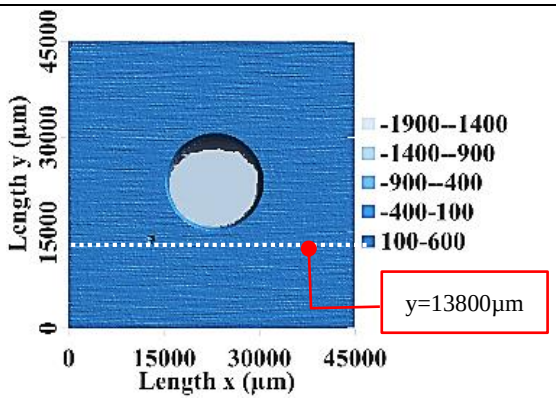
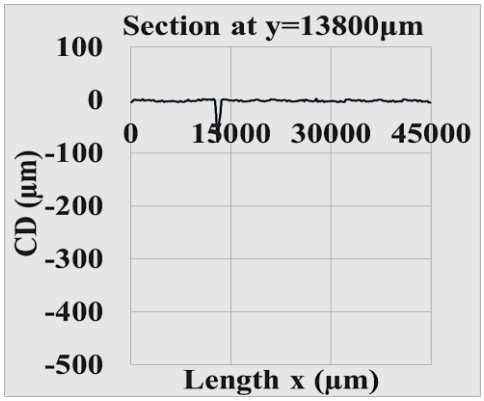
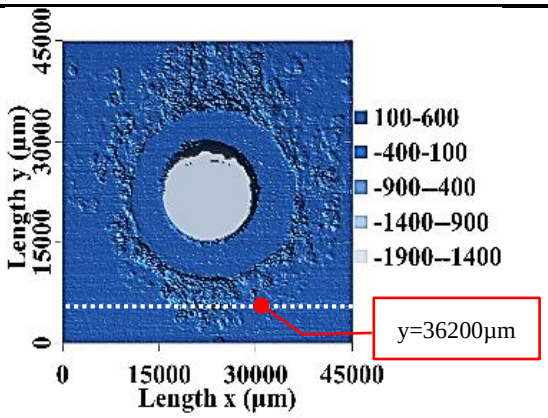
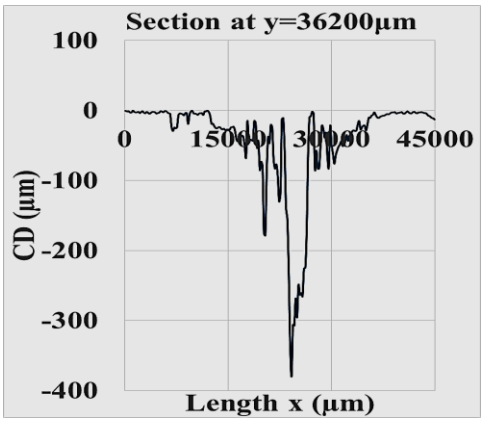
	2D Maps	Corrosion profiles
SP01 (Hole A – Top Side)		
SP02 (Hole A – Top Side)		
SP03 (Hole A – Top Side)		
SP04 (Hole A – Bottom Side)		

Table 3 2D Maps and corrosion profiles of areas pertaining maximum corrosion depth (continued)

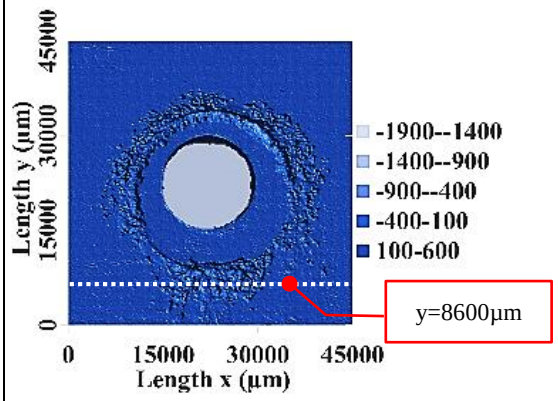
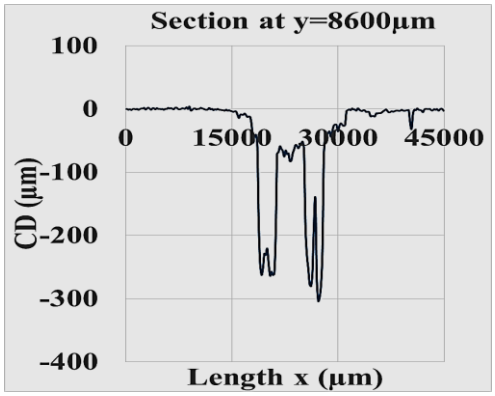
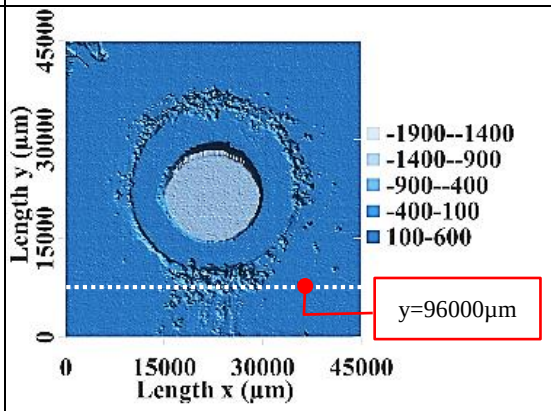
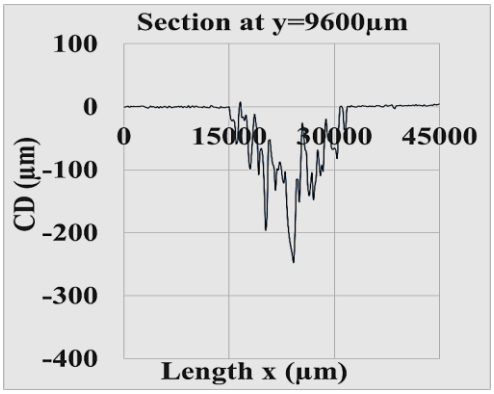
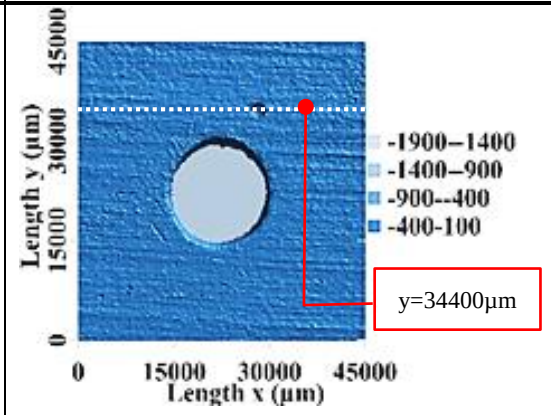
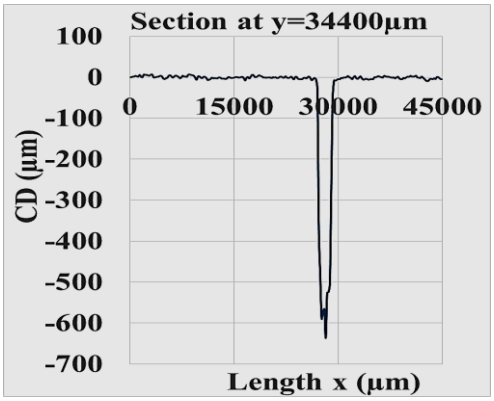
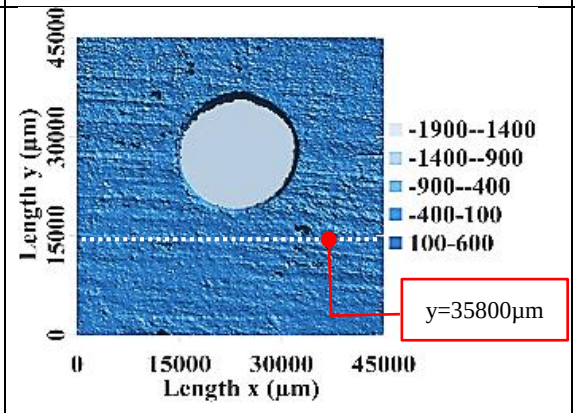
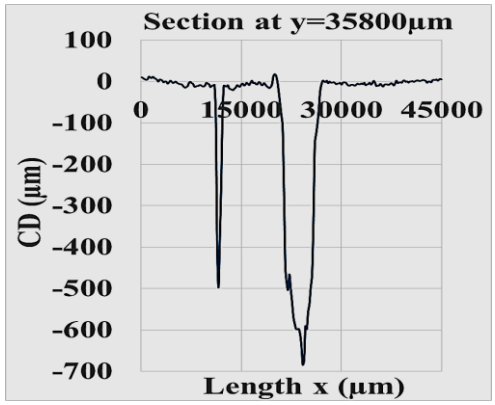
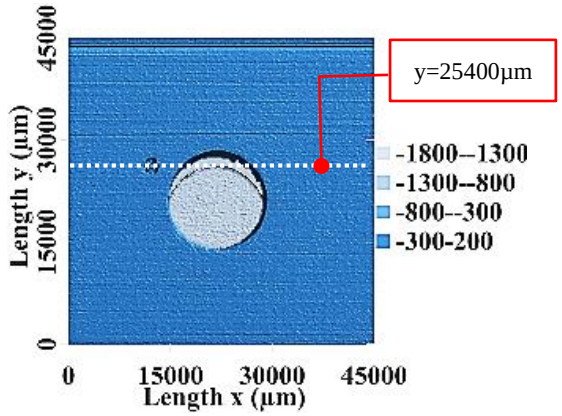
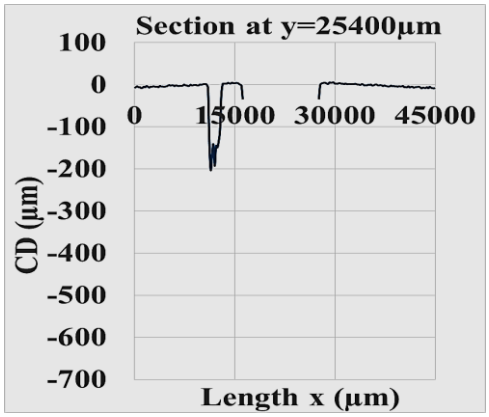
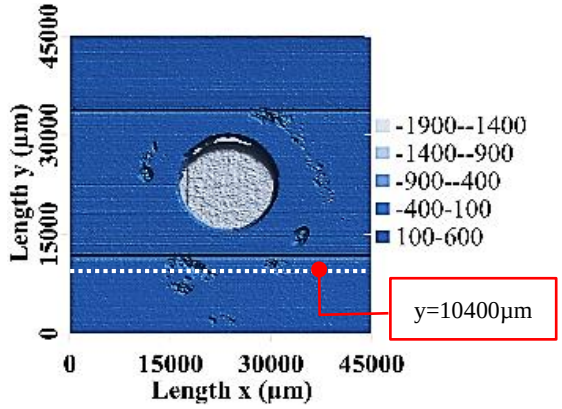
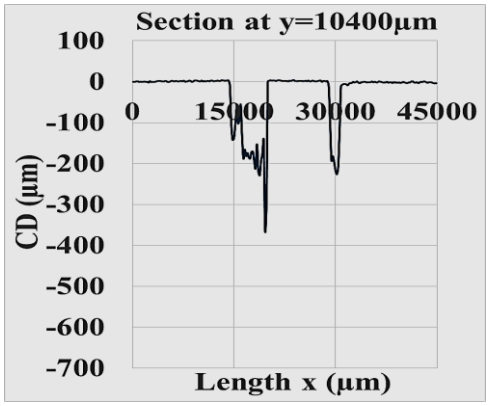
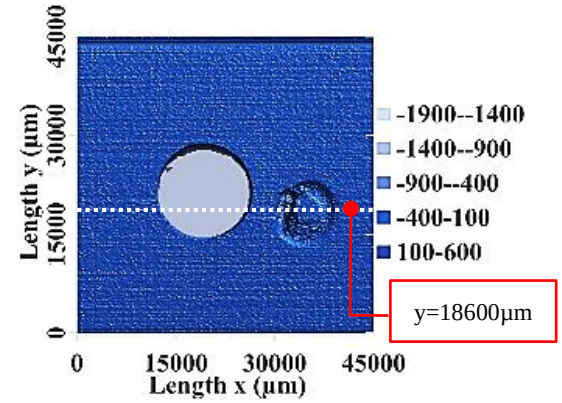
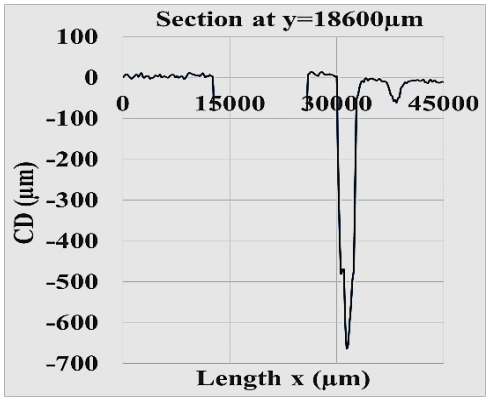
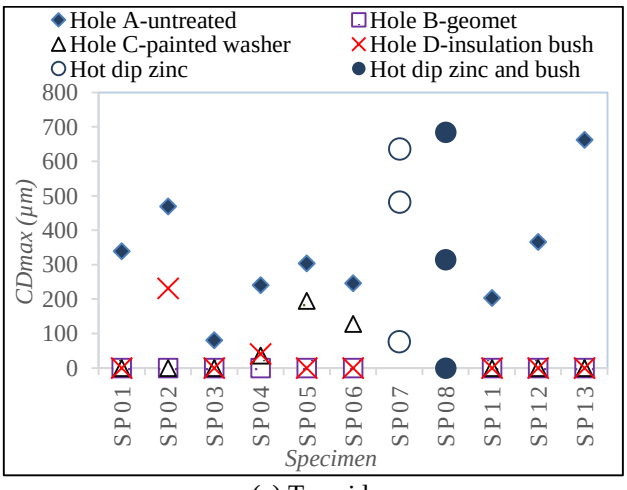
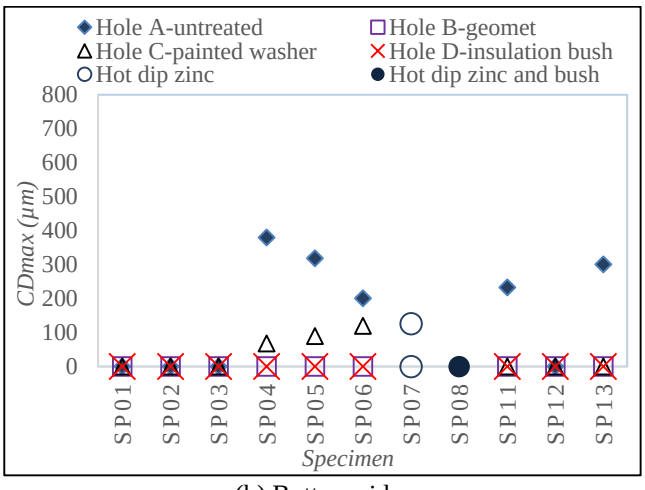
	2D Maps	Corrosion profiles
SP05 (Hole A – Top Side)		
SP06 (Hole A – Top Side)		
SP07 (Hole A – Top Side)		
SP08 (Hole A – Top Side)		

Table 3 2D Maps and corrosion profiles of areas pertaining maximum corrosion depth (continued)

	2D Maps	Corrosion profiles
SP11 (Hole A – Top Side)		
SP12 (Hole A – Top Side)		
SP13 (Hole A – Top Side)		

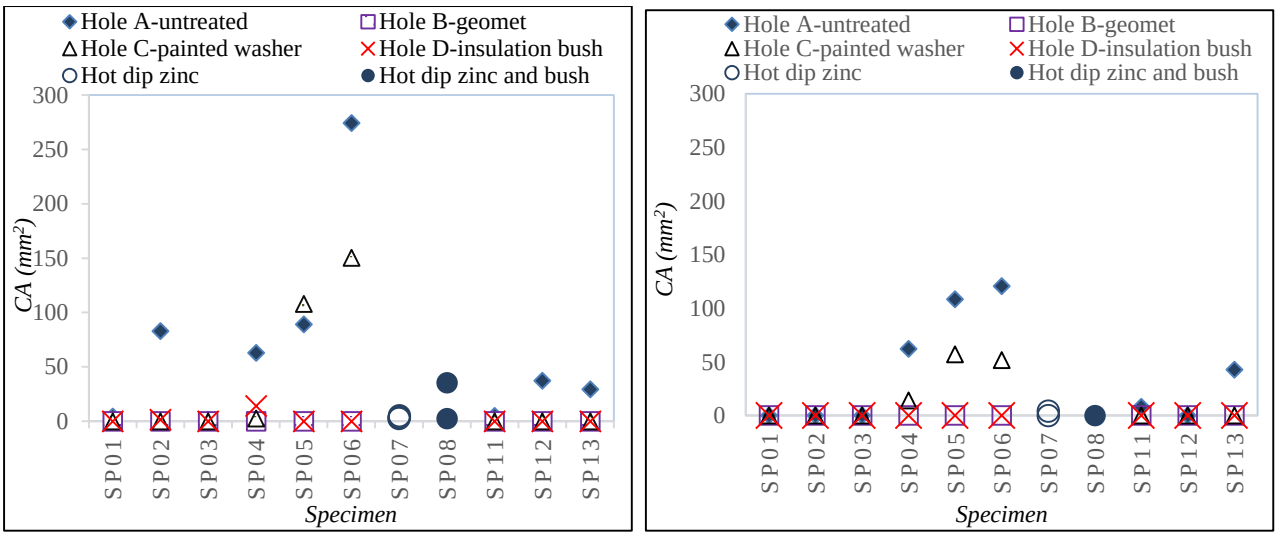


(a) Top side



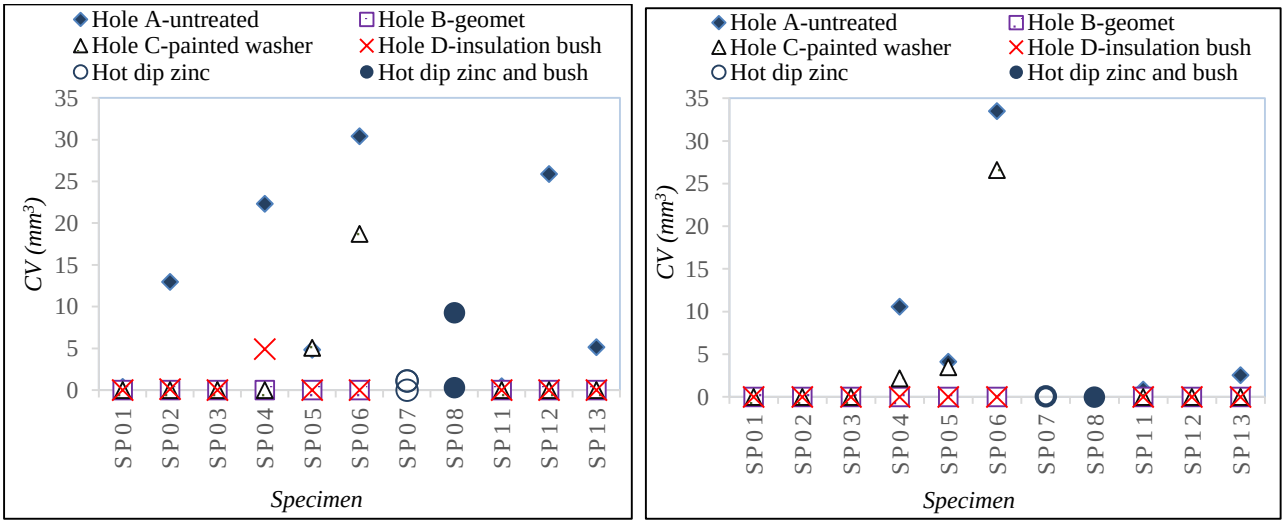
(b) Bottom side

Fig. 7 Relationship between fasteners' condition and Specimens' maximum corrosion depth



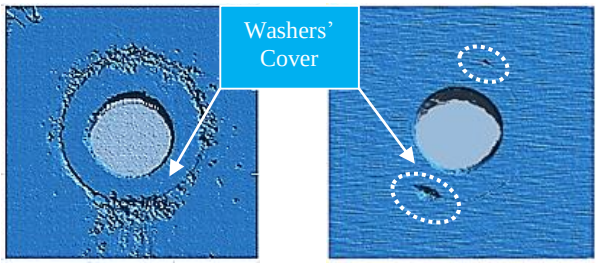
(a)Top side (b) Bottom side

Fig. 8 Relationship between fasteners' condition and specimens' corrosion areas



(a)Top side (b) Bottom side

Fig. 9 Relationship between fasteners' condition and specimens' corrosion volume



(a) Circular pattern (b) Spot pattern

Fig. 10 Galvanic corrosion patterns

4. EXPERIMENTAL RESULTS

4.1 Discussion

Corrosion on specimens showed two different appearance patterns. However, they are all attributed by galvanic effect and corrosive environment. The dominant pattern is a circular pattern which is mostly vivid on specimens SP04, SP05 and SP06. In this pattern, the areas covered by washers are sound even though they are dissimilar metal contact areas as shown in Fig.10 (a). This is because washers did not allow ingress of salt water in the areas. The areas outside washer's outer ring and vicinity are literally corroded due to combination of galvanic effect and corrosive environment.

Another pattern is of few and spaced spots of corrosion, localized outside washer's outer ring as shown in Fig. 10 (b). Since protection film has no uniform cover, galvanic effect and corrosive environment attacks more severely on the weakest and injured spots on the specimen. The exceptional corrosion appeared on SP13 is assumed to be located on the weakest or injured spot.

Galvanic effect on specimens is investigated with respect to three parameters; the maximum corrosion depth achieved on each specimen (CDmax), the area of corrosion covered by each fastener (CA) and volume of material corroded on each specimen (CV) as the result of galvanic effect rendered by fasteners. However, fasteners and specimens surface condition and alloy type have influence to galvanic corrosion. Hence, their influence is investigated with respect to each parameter but the ultimate judgement is made with respect to corrosion volume because it includes corrosion depth and area.

4.2 Influence of fasteners' surface condition

As shown in Figs. 8, 9 and 10, on all specimens except on SP07 and SP08, untreated fasteners at hole 'A' caused the highest effects of galvanic corrosion on both sides of specimens. Zinc flake (GEOMET) treated fasteners at hole 'B' did not show any signs of causing galvanic corrosion on both sides of specimens. Untreated fasteners with only painted washers at hole 'C' caused less severe galvanic corrosion on both sides of specimens compared to untreated fasteners. Untreated fasteners with insulation bush at hole 'D' caused much less galvanic corrosion only on top side of specimens compared to untreated and painted washer only fasteners.

On SP07 and SP08, hot-dip zinc coated mild steel fasteners at all holes caused considerable galvanic corrosion on top sides of both specimens. Despite the insulation bush on SP08, both specimens are almost equally corroded on top sides. The effectiveness of insulation bush on SP08 will be judged much clearer in other subsequent experiments. However, SP08 was not corroded on bottom side.

Generally, it is observed that despite the steel type of fasteners, both stainless and mild steel fasteners render galvanic corrosion on aluminium alloy members. The severity of galvanic corrosion can only be inhibited by appropriate surface treatment of fasteners.

4.3 Influence of specimens' surface condition

The influence of specimen surface condition to galvanic corrosion is compared between specimens of same alloy types and a holistic assessment is made by studying Figs. 7, 8 and 9.

It is obvious that, untreated SP04, SP05 and SP06 suffered severe galvanic corrosion due to bare contact with dissimilar metal.

Alternating surface condition and orientation of fasteners does not inhibit galvanic corrosion as was expected on SP02 and SP03 configuration. Untreated top side of SP03 which was covered by treated splice plate was not protected from galvanic corrosion.

SP07 and SP08 which were both attached to similarly treated mild steel splice plates but with addition of sandwiched insulation sheet on SP08 demonstrated the effectiveness of insulation to inhibit galvanic corrosion. The bottom side of SP08 in contact with insulation sheet did not shown any traces of galvanic corrosion.

The colour of surface treatment has no significant influence to galvanic corrosion. SP11, SP12 and SP13 whose surfaces were treated with different colours of combined anodic oxide and organic film coating did not show any potential resistance to galvanic corrosion.

However, the deep corrosion observed on the surfaces of SP07 and SP08 might be caused by corrosion of blow hole. In order to investigate the clearer reason of this corrosion, the same salt water spray experiment and the exposure experiment on site are going to be performed.

4.4 Influence of alloy type

The influence of aluminium alloy type to galvanic corrosion is assessed with respect to specimens with different alloy types but with same surface condition which are SP04, SP05 and SP06. The corrosion resistance of SP05 drawn from alloy type A5083P-O is observed to be the best as shown in Figs.9 (a) and (b). This is because generally aluminium alloy series 5000 have the best inherent corrosion resistance due to high content of magnesium[17]. It also have lower copper content which makes it less corrosive. SP04 of alloy type A6N01S-T5 and SP06 of alloy type A3004P-H32 exhibited relatively high corrosion due to lower contents of magnesium and higher contents of copper compared to A5083P-O.

5. CONCLUSION AND RECOMMENDATIONS

From the experimental results and discussion, the following conclusion remarks and recommendations are drawn with focus on corrosion resistance performed by surface treatments of specimens and fasteners, influence of specimen configuration to corrosion and corrosion resistance performed by aluminium alloy types.

1) Zinc flake coating treatment for stainless steel bolts is effective treatment to prevent galvanic corrosion of aluminium alloy even in a severe corrosive environment.
2) Vinyl chloride insulation bush is also found to be the effective treatment for untreated stainless steel bolts to prevent galvanic corrosion.
3) Aluminium alloy specimens which were treated by the type of combined coating of anodic oxide and organic film exhibited vast corrosion resistance than other specimens. The difference of corrosion between the coating colours might be within the variation of experimental results.
4) In areas where surface treatment is not a priority, application of aluminium alloy type A5083P-O is recommended due to its best chemical composition to resist general corrosion compared to types A3004P-H32 and A6N01S-T5.
5) Covering untreated surface with treated cover plate does not prevent galvanic corrosion as observed on SP02 and SP03. However sandwiching insulation sheets between two dissimilar metal plates guaranties prevention of galvanic corrosion as observed on SP08.
6) Circular corrosion pertains appeared on untreated and painted washers indicate that tighten washers may have caused injuries to the surface treatment of specimens which can accelerated galvanic corrosion. Diligent fastening process is necessary to avoid injuries.
7) Untreated Specimens SP04, SP05 and SP06 which are of different alloy types are found to be the most corroded specimens in this study. This is because they displayed the highest values of total corrosion area and volume. From this remarks, it is evident that aluminium alloy members need treatment regardless of their alloy type.

Further research should be carried out to investigate the durability of insulation bushes since their premature deterioration can accelerate galvanic corrosion when untreated fasteners contact aluminium alloy members. However it is also recommended to carry out further experiment on these alloy types but with similar surface treatment for fair comparison.

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