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Effects of the Surface Preparation on the Life of Epoxy Coating in Steel Ship Plates: An Experimental Study

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Abstract

The durability of coating is considerably affected by the quality of surface preparation. The aim of the present paper is to experimentally examine the effects of the surface preparation on the life of epoxy coating in steel ship plates associated with the surface roughness. A total of three test specimens are considered with varying the roughness of the surface on mild steel plates. The test plates have been under submerged seawater condition in the laboratory. The surface profile of the test plates was examined by the technique of Optical Microscopy. It is found that the performance of epoxy coating is significantly influenced by the surface roughness of the steel plates under submerged seawater conditions. Details of test database are documented.

Keywords: Corrosion; steel ship plates; life of coating; surface preparation; epoxy coating; coating breakdown

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1. Introduction

While various methods are available to control corrosion (Paik and Thayamballi 2007), protection of metal surfaces by coating, e.g., painting is the most common option for corrosion control used for ships and offshore structures (Davis 2000; Koch 2004; Winston and Uhlig 2008; Salas and Schorr 2012, Gao et al. 2017). The life of coating in places governs the progress of corrosion. Protective coatings can be categorized into two types: inorganic coatings and organic ones. Various types of organic paints are being used on the surface of ship steel plates to protect the corrosion and extending the lifetime of metal and metal alloy objects. Melchers and Jiang (2006) estimated the durability of protective organic coatings in water ballast tanks. They concluded that the developed mathematical models of coating deterioration are not sufficient to predict the actual data in comparison to the actual field condition experience for well-defined vessel areas like ballast tanks, which is known to be particularly prone to coating breakdown and poor inspection. It is also recognized that the surface treatment plays an important role to prevent corrosion and enhance coating life before application of anti-corrosive painting on ship steel plates (Flores and Morcillo 1999; Staff 1996). Johnson (1999) reported that approximately 90% of surface coating fails due to inadequate surface preparation and application faults. The local environment is governed by structural detail and may in turn have an effect on such details, for example, with horizontal stiffeners which are more often exposed to the environment and hence more prone to corrosion than vertical surfaces. With passing age, the performance of steel structures is heavily affected due to corrosion process (Shifler 2004; Little and Lee 2007; Paik and Melchers 2008; Paik et al. 2004), specifically in the coastal and marine environment which is further directly associated to the numerous surrounding environmental factors such as oxygen content, carbon dioxide, salinity, pH value of water, carbonate solubility, temperature, atmospheric pressure, suspended solids, velocity of water waves, and the various physical and chemical factors of material including the chemical composition, surface roughness and method of preparation of the steel structures. In accordance with ISO 12944, a long-term corrosion protection, firstly, to be ensured that the correct surface preparation has been carried out before any paint is applied on steel. Studies on the assessment of the durability of single layer epoxy coating plates under natural sea water condition are very lacking in the literature.

The aim of the present study is, firstly, to analyze the deterioration process of single layer epoxy coating on different surface profiles of ship mild steel plates immersed in natural seawater. Secondly, the investigation leads to identify the pattern of coating breakdown such as blistering, paint creep, etc. The progress of the corrosion and erosion of epoxy coating from the local area of epoxy painted ship mild steel plates such as on the edges, front and rear surface of plates was studied by the means of careful monitoring of the specimens under sea submerged condition in the laboratory.

2. Test Specimens and Procedure

A total of three test specimens of mild steel plates (Grade A) with a size of 150mm x 150mm x 10mm were considered to experimentally obtain the effects of the surface preparation on the life of epoxy coating in sea submerged environment. The specimens were made of ASTM Grade A mild steel plates. The chemical composition of the test steel was obtained from a direct testing and is indicated in Table 1.

Table 1 Chemical composition of the material

Chemical composition of mild steel (Grade A)					
Elements	Carbon (C)	Manganese (Mn)	Silicon (Si)	Sulphur (S)	Phosphorus (P)
Percentage (%)	0.21	0.525	0.50	0.035	0.035

2.1 Surface preparation

The surface preparation is extremely important and desirable process before painting of structural steel. Surface profile represents roughness of the surface that results from abrasive blast cleaning. The profile roughness height is dependent on various number of factors such as; size, shape, type, and hardness of the abrasive, particle velocity and angle of impact, hardness of the surface, amount of abrasive recycling, and the proper maintenance of working mixtures of grit and/or shot.

A total of three square shaped mild steel test specimens were blasted to achieve different surface roughness according to ISO 8501-1(Sa2.5). The type and size of the abrasive used in grinding and polishing have a significant effect on the profile preparation. In addition to the degree of cleanliness, surface preparation specifications need to consider ‘roughness’ relative to the coating to be applied on the blasted surface. To prepare the test specimens, compressed air abrasive sand blasting machine was used with abrasive of 2 mm grain size angular shapes G-25 Steel Grit media. Chemical composition of G25 steel grit is noted as 0.9 % Carbon, 0.4% Silicon, 0.8% Manganese, 0.045% Phosphorus, 0.04% Sulfur. The blast cleaning operation was carried out according to field experience, blaster arranged effective blast angles by keeping the nozzle at approximately an angle of between 40 to 70 degrees and to reach the target profile depth abrasive velocity was adjusted during blasting. After sufficent blasting, all sharp edges were rounded by grinding. The theoretical surface roughness could be well-defined by the tip radius of the cutting tool using well known geometrical relation (Lukianowiz and Karpinski 2001). A principle of the surface generation of the specimen is schematically presented in Figure 1(a) and typical blasted surface of specimen in Figure 1(b), respectively.

Prior to blast cleaning, it made sure that the blasted surface shall be free from visible oil, grease and dirt, and from mill scale, rust, and any foreign matters. Salt contamination is a phenomenon that often happens on the blasted surface and could be responsible for adhesion and corrosion problems beneath a paint coating layer on steel surface due its to the hygroscopic nature. Its tendency to attract water through a permeable coating creates a build-up of water molecules between substrate and coating. The salt content could significantly reduce the durability of the coating layer and therefore, salt test has also been carried out before blast cleaning and painting on the blasted surface. Water soluble salts were measured with the help of bresle kit according to ISO 8502-9 and found to be 30.6 50mg/m^2 equivalent to NaCl. The variation in the surface microstructure could not be noticed through naked eyes, therefore, the surface microstructures of the test plates were examined by the technique of Optical Microscopy. The visible difference could be easily noticed in the high magnification pictures taken through the Hirox KH-8700 optical microscope, see Figure 2. It could be visually noticed that specimen A (Back), C (Front) have almost the same roughness profile and B (Front) has the uniformly high surface roughness.

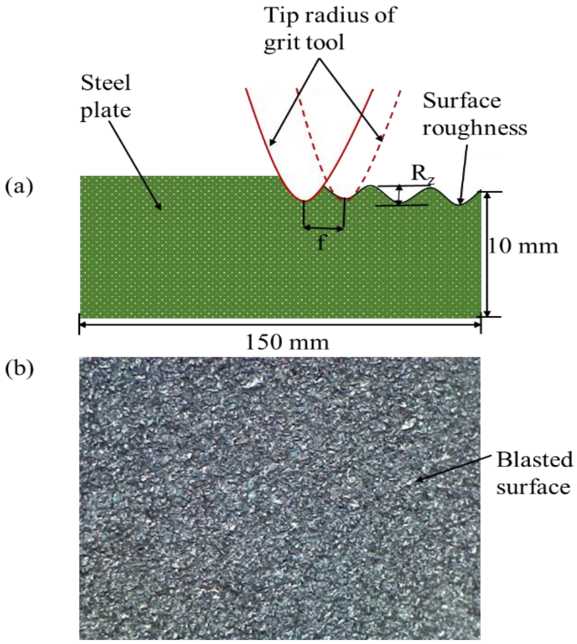

Figure 1 (a) Schematic of surface preparation by grit tool, (b) Typical surface prepared through abrasive blasting (Sa2.5)

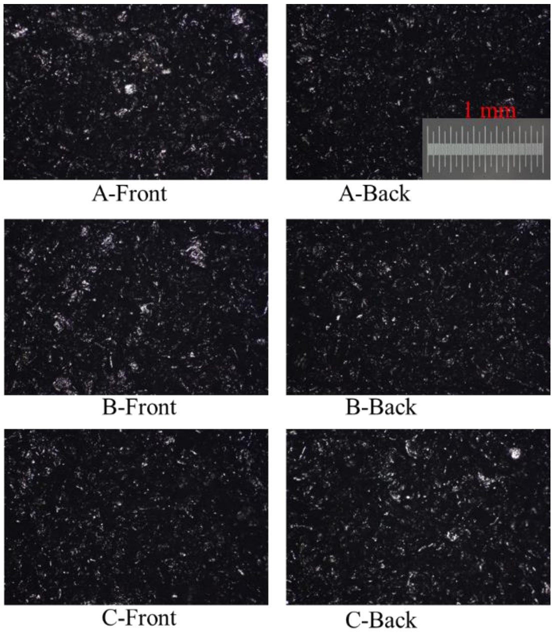

Figure 2 Optical microscope pictures of the specimens at 50 times magnification after surface preparation but before painting

2.2 Surface roughness measurement

Surface profile of the front and rear surface of each mild steel specimen A, B and C were measured by three different experimental methods namely replica tape, contact and contactless method. Firstly, a very common known replica tape method which is drafted in compliance according to international standard ISO 8503-5. Replica tape method comprises the use of a two-layer plastic film, one compressible, one 50 μm thick incompressible layer and a specially adapted flat anvil dial gauge.

In the present study, X Coarse grade Testex Press O-Film is chosen according to expected surface profile of our specimen. The backing is removed from the tape which is compressible layer and placed on clean and blasted surface. Tape is pressed firmly, and it is started to rub the circular cut out which moderate pressure by using burnishing tool. The rubbing continues until to get uniform dark color appear on the burnished area as a grey circle. Tape is removed from surface and placed inside the anvils of Testex dial gauge. The compressible layer is placed on the surface of the blast cleaned steel and is rubbed with a circular ended tool until the surface has conformed to that of the steel, indicated by a uniform dark coloration. The tape is then removed and measured with the dial gauge. The maximum profile can then be calculated by subtracting the thickness of the non-compressible backing, i.e. 50 μm from the dial reading. The replica tape method is relatively easy to use especially on difficult to access surfaces of fabricated components. This method also provides a permanent record of the surface roughness, see Figure 3.

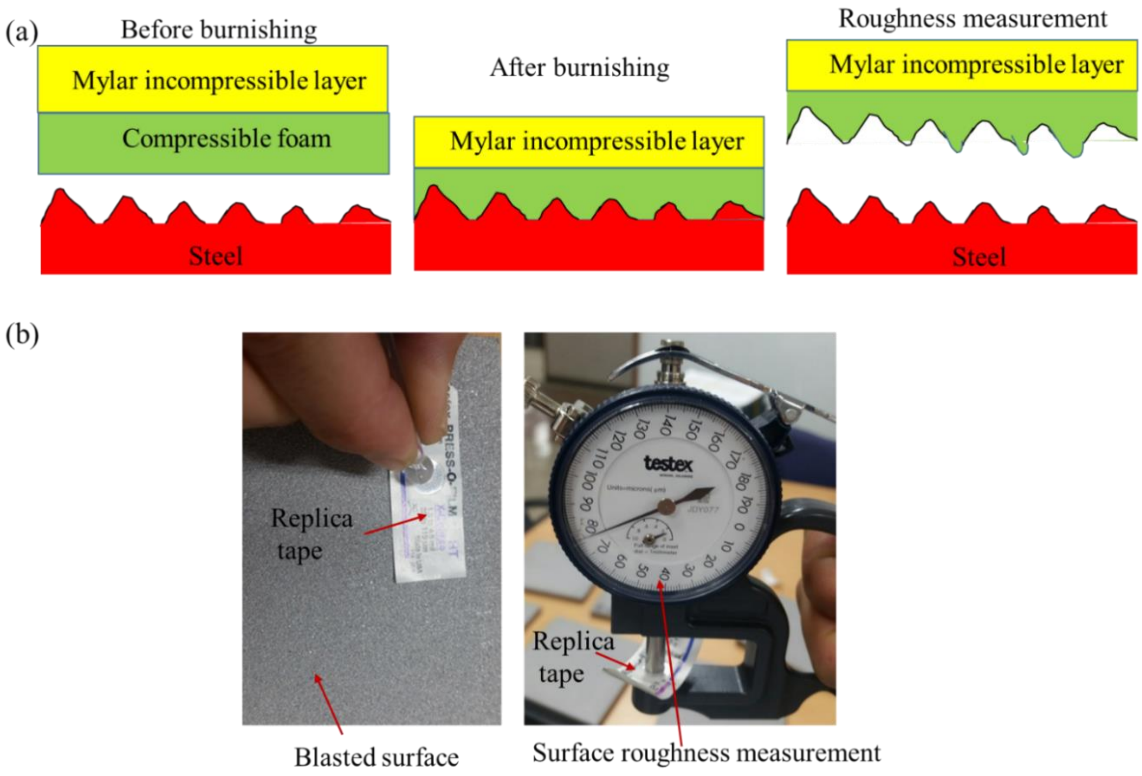

Figure 3 (a) Schematic of roughness appeariance on the film foam, (b) typical surface profile measurement through replica tape method.

Secondly, the surface roughness was measured at five and twenty times magnification of the specimen by Zygo Newview 8000 Scanning White Light Interferometers (optical surface profilers) generally used for fast non-contact 3D measurement of surface roughness of ultrafine surfaces. The center line average roughness (R_a) and maximum roughness (R_{max}) value of the specimens were obtained by measuring the roughness at three different positions on the front and back surface of each specimen, see Figure 4**.** The obtained data has also been presented in Table 2.

According to ISO 8503-3:2012, the optical surface profiler simply works with zoom optical sensor, microscope, objective lens, mirror and scanning optical system. The test surface is observed over a specified field of view using a specified microscope. The microscope is adjusted, by movement of the objective lens, to focus on the highest peak within the field of view. The distance is adjusted by the objective lens in order to focus on the lowest valley within the same field of view. The procedure is repeated to obtain the average distance between the highest peak and lowest valley in each field of view.

In the present study, the square area of 1600μm x 1600μm and 400μm x 400μm was measured corresponding to 5x and 20x magnification at three different points. The roughness was measured at various scales 5x, 20x, and 50x and 100x and then the best results were chosen that are corresponding to 5x and 20x magnification.

Lastly, the surface profile was measured by contact method with the help of Mitutoyo SJ-310 equipment. The centerline average roughness (R_a), and maximum roughness (R_{max}) were obtained at the identical positions similar to that were considered in the case of contactless method. The value of average surface roughness and maximum roughness are illustrated in Table 3.

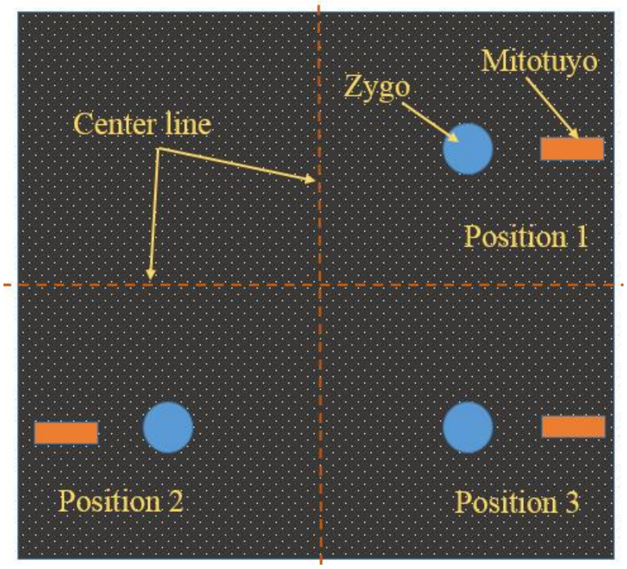

Figure 4 Schematic diagram of considered positions to measure the surface profile through contact method (Mitutoyo) and contactless method (Zygo).

Table 2 Surface roughness measurement by non-contact method through Zygo Newview 8000 instrument

Specimen	Surface	Scale	Position	Centerline average roughness (Ra in μm)	Average of average roughness	Maximum roughness (R_{max} in μm)	Average of maximum roughness
A (F)	Front	5X	1	14.495	14.42	71.137	63.903
			2	13.818		63.050	
			3	14.947		57.523	
		20X	1	11.333	11.118	42.330	43.983
			2	11.030		41.120	
			3	10.991		48.500	
A (B)	Back	5X	1	12.616	12.460	78.943	65.462
			2	10.268		51.507	
			3	14.498		65.937	
		20X	1	11.251		37.530	

			2	11.318	11.472	45.534	41.072
			3	11.849		40.152	
B (F)	Front	5X	1	10.837	12.369	52.814	66.173
			2	9.713		57.883	
			3	16.559		87.824	
		20X	1	12.059	10.648	42.559	39.839
			2	8.516		32.811	
			3	11.369		44.147	
B (B)	Back	5X	1	17.101	14.856	74.065	74.624
			2	10.908		61.984	
			3	16.559		87.824	
		20X	1	14.037	13.783	59.696	49.571
			2	15.805		50.366	
			3	11.509		38.653	
C (F)	Front	5X	1	17.612	15.555	78.603	72.720
			2	14.527		71.946	
			3	14.527		67.611	
		20X	1	19.851	15.235	68.680	51.781
			2	9.747		27.338	
			3	16.108		59.327	
C (B)	Back	5X	1	15.048	12.379	60.457	62.310
			2	8.496		47.328	
			3	13.594		79.146	
		20X	1	10.711	10.616	37.659	42.326
			2	11.157		40.136	
			3	9.981		49.183	

Table 3 Surface roughness measurement by contact method through Mitutoyo SJ-310 instrument

Specimen	Surface	Position	Centerline average roughness (R_a in μm)	Average of average roughness	Maximum roughness (R_{max} in μm)	Average maximum roughness
A (F)	Front	1	10.171	10.424	57.042	53.650
		2	10.985		53.109	
		3	10.117		50.801	
A (B)	Back	1	10.822	10.160	59.771	55.266
		2	9.380		51.299	
		3	10.278		54.728	
B (F)	Front	1	8.783	10.447	56.850	56.608
		2	11.906		54.543	
		3	10.654		58.431	
B (B)	Back	1	10.245		57.153	

		2	10.034	9.633	51.220	53.250
		3	8.620		51.378	
C (F)	Front	1	9.132	10.066	51.525	54.557
		2	9.588		54.089	
		3	11.476		58.059	
C (B)	Back	1	10.145	9.583	54.900	55.682
		2	8.045		43.535	
		3	10.560		51.927	

2.3 Surface coating

Prior to paint on the blasted surface, each specimen was degreased using abrasive paper, and then rinsed thoroughly with the help of fresh water, consequently the specimens were kept in hot air to be dried according to the cleaning standard specified by ASTM G1. Prior to painting application, the temperature has also been measured by sling psychrometer. The details have been presented in Table 4. The anti-corrosive paint which is high solid polyamine cured pure epoxy with Abrasion resistant, is chosen to carry out the painting on each of the blasted specimen.

Table 4 Temperature and relative humidity measured by sling psychrometer

Material	Dry Temperature (^{0}C)	Wet Temperature (^{0}C)	Steel Temperature (^{0}C)	Relative Humidity (%)
Mild Steel (Grade A)	25	20	21	63.8

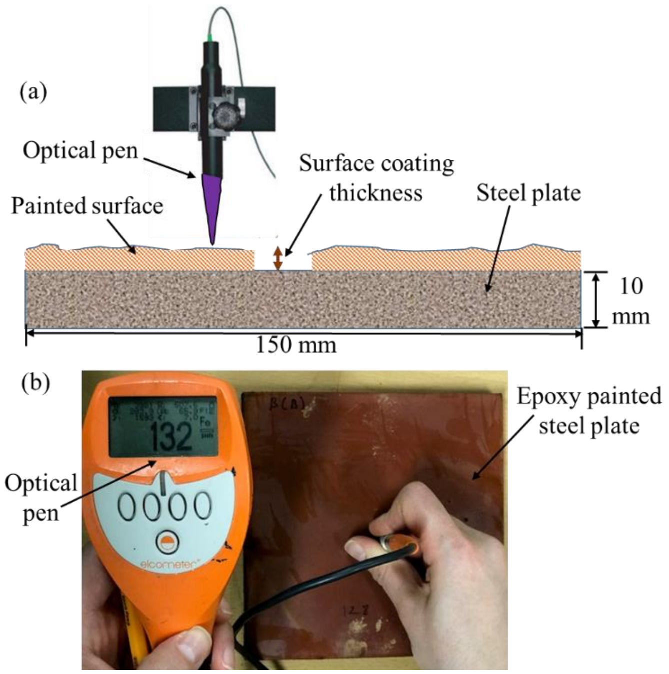

Figure 5(a) Schematic representation of profilometry method (b) typical coating thickness measurement of the specimen.

The mild steel plates of varying surface roughness were carefully sprayed by a layer of epoxy paint (organic coating) by airless spray method on the front and rear surface, however, brush up were used on the edges of each specimen where airless spraying is impracticable. The epoxy coating was carried out at the room temperature with relative humidity (RH) below 85% inside closed paint shop. The pressure of spray nozzle tip (inch/1000) 21,was determined 15 MPa and spray angle were kept 50°- 70° from the front and rear surface of the specimen.

Thereafter, the specimens were allowed to dry for 48 hours to gain the adequate bond strength between blasted surface and layer of epoxy coating. Before putting the specimen in the sea submerged condition, the thickness of epoxy coating was also measured through Elcometer Dry Film Thickness (DFT) Gauge, see Figure 5. After random DFT readings in several points of each specmiens, the obtained average thickness of the epoxy paint coating was found to be 108 μm, 105 μm,107 μm on the front surface and 115 μm, 106 μm, 105 μm on the back surface of test specimen A, B and C respectively.

2.4 Test specimens in sea submerged condition

The test specimens were fully immerged in sea water to analyze the durability of epoxy coating on three different surface profile of steel ship plates. In the present study, mild steel ship plates (Grade A) with 150mm x 150mm x 10mm dimensions painted by epoxy through airless spray method were considered. All the considered test plates have been kept under similar submerged condition in 3000 ml seawater at room temperature in the laboratory. The seawater used in the present experiments was brought from the seashore at Yongho-dong, Busan city, Republic of Korea. Moreover, to maintain actual field condition, the seawater has been changed on regular basis in every week until the last observation noticed after 25th weeks. The salinity of seawater has also been measured through salinity meter and the average value of salinity was found approximately 2.9%.

3. Test results and discussions

Present study has been carried out to assess the resistance of single epoxy paint layer on ship steel plates dwelled in 3000 ml sea water. Surface roughness of the steel plates is straightly associated with the durability of coating layer which is directly exposed to the sea environment. Therefore, in the present experimental study, a detailed analysis of surface roughness has also been performed through various methods namely replica tape, contactless and contact method. The front and back surface roughness R_a was measured through replica tape are 110, 114, 135, 140, 120 and 127 μm for A, B and C mild steel plates respectively. The specimens were blasted to achieve different roughness which is more clear through replica tape method. According to the specifications given in Tables 1 and 2 of ISO 8503-1-2012, the plates B and C fall under the coarse surface grade, but the plate A remains close to medium surface roughness grade. However, the maximum roughness was realized with specimen B followed by C and A. The average roughness R_a value obtained through contactless and contact method were mentioned in Tables 2 and 3.

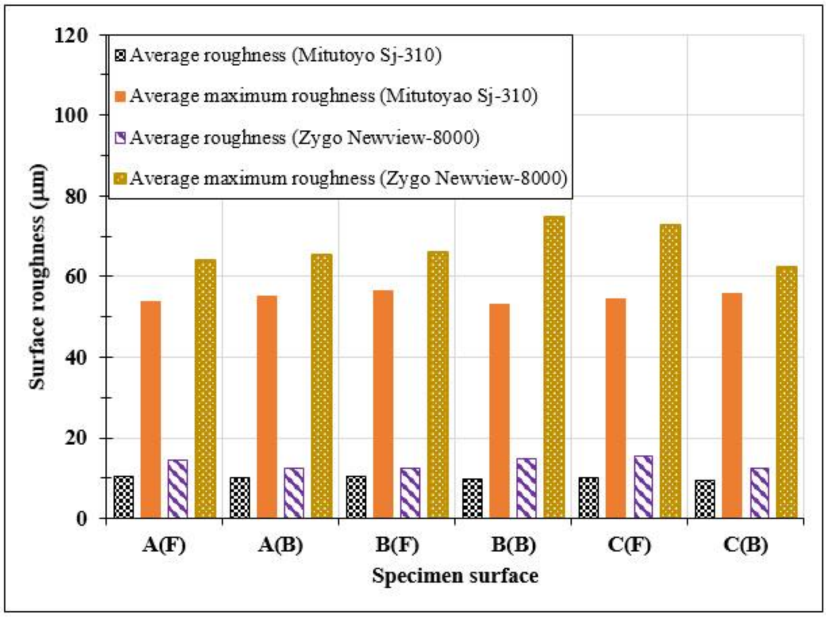

Figure 6 Comparison of Average roughness (R_a) and average of maximum surface roughness (R_{Max}) measured by contact (Mitutoyo) and contactless method (Zygo).

In general, measurement of non-contact type and contact type is necessary considering improvement of surface roughness. The measurement result of the non-contact type equipment (Zygo) shows a very large variation in the value depending on how the cross section is formed in the high magnification measurement in accordance with the measurement principle. In this case, it is preferable to evaluate the measurement deviation slightly by using 5 times magnification measurement data rather than 20 times magnification. However, the non-contact type is somewhat less reliable because the surface roughness of this specimen is considerably large with a large deviation even with a 5 magnification measurement. Although the measurement results of the contact type equipment (Mitutoyo) show almost similar trend values of the non-contact type measurement results, illustrated in Figure 6. Therefore, the results of future coating experiments must also be evaluated in three groups namely A, B and C.

3.1 Failure modes of coating

It is observed that the performance of single layer epoxy coating is significantly influenced by the surface roughness of the mild steel plates under fully sea submerged conditions. The failure mode was recognized as blistering and paint creep on the edges, however, slight erosion of the epoxy layer was also measured on the front and back surface of the specimens. The first occurrence of blistering was observed on the edges of the specimens after the 7th week in fully immerged condition in sea water, presented in Figure 7. It is readily noticed from Figure 7 that the specimen A, B and C has experienced a random, continuous and very small blistering on the middle surface at edges correspondingly. The coating breakdown is not found on the surface of any specimen until the 12th week. The area of blistering has increased with passing the time and finally leads to breakdown of epoxy coating in almost circular shaped chips, which further enabled a direct contact between sea water and steel surface on the edges. Subsequently, the corrosion starts to develop slowly on the area of steel which is directly exposed to seawater, illustrated in Fig. 8. With passing age, the corrosion was noticed most prominent on the edges of specimen C followed by A and B respectively. After 21st week the corrosion could be easily noticed on almost the entire edge of ship mild steel plates which leads to complete failure of the paint layer on the edges, see Figure 8.

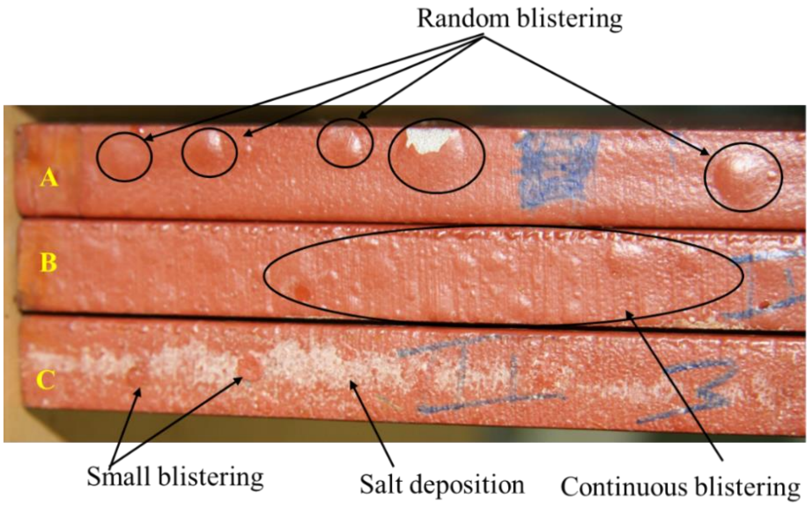

Figure 7 First occurrence of blistering on the edges after 7th week in fully sea submerged condition.

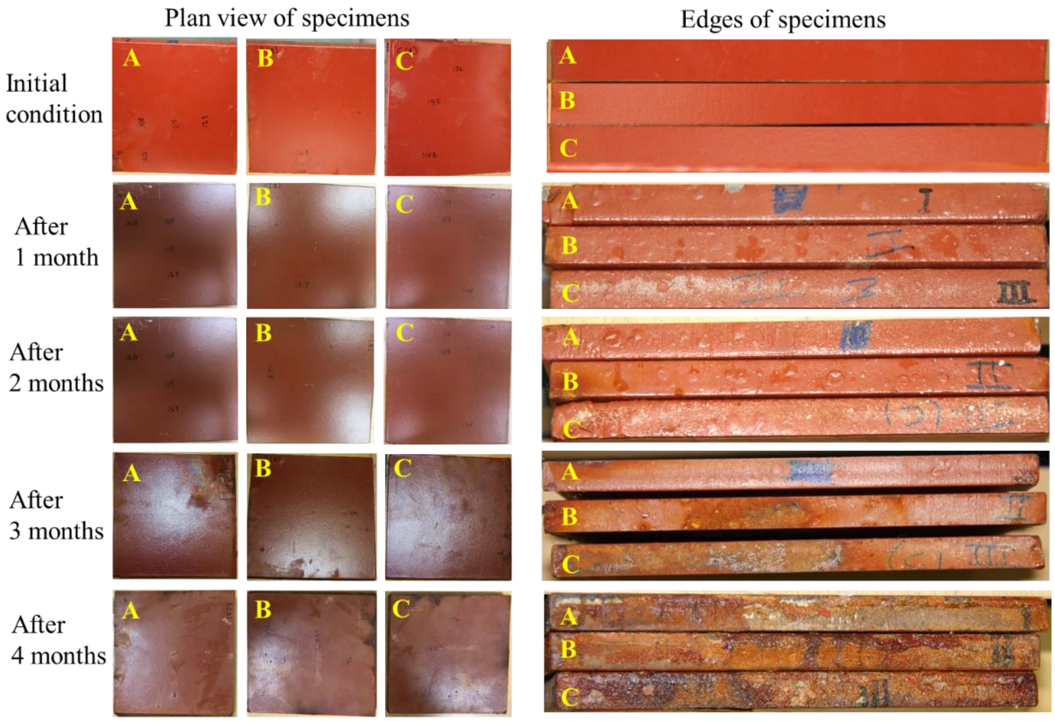

Figure 8 Progressive erosion process of the epoxy coating surface of each specimen A, B and C under sea submerged condition, Plan view (left), Side view (right).

The performance of epoxy coating is found to be satisfactory in the considered six-month time duration as any of the specimen did not experienced any blistering or paint creep on front and back surface of the ship steel plates. Although, erosion of epoxy coating from the surface of the specimens were noticed with passing the time duration in fully immerged plates under sea water. The paint thickness on front and rear surface of each specimen was measured in the interval of each one month with the help of optical pen, see Figure 9. The epoxy layer thickness was measured at five different locations on each surface to calculate the average thickness of the coating at the regular interval of one month, Readings are written in Table 5. An obtained trend among the reduction of coating thickness with increasing the age of specimen has also been plotted in Figure 9.

Table 5 Epoxy coating layer thickness measured through optical pen

Surface thickness in (μm)							
Time (Months)	Zero Month	One Month	Two Month	Three Month	Four Month	Five Month	Thickness loss (%)
Specimen							
A(F)	109	107	105	103	100	96	11.91
A(B)	115	113	112	109	106	102	11.30
B(F)	108	107	106	104	103	101	6.48
B(B)	106	104	102	100	96	93	12.26
C(F)	107	104	100	97	92	86	13.08
C(B)	105	103	100	98	93	89	15.21

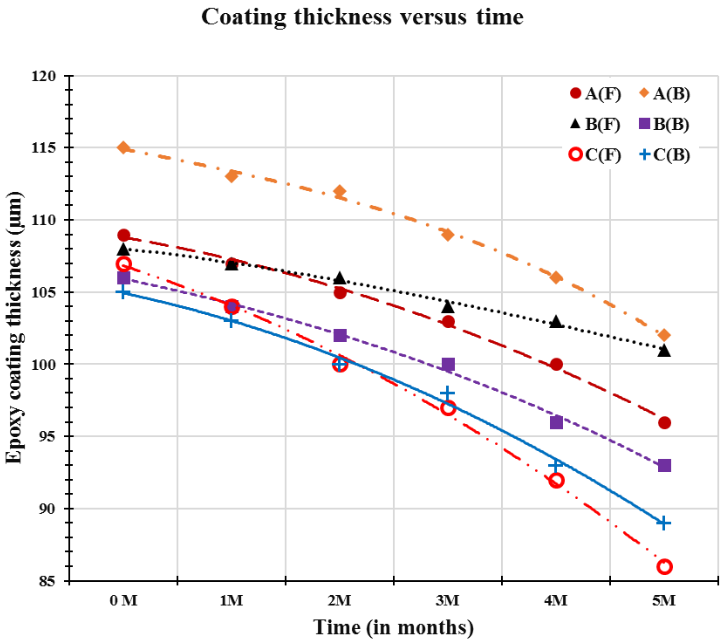

Figure 9 Loss in epoxy coating thickness under sea submerged condition.

4. Concluding remarks

In the present study, the resistance of epoxy single layer coating was experimentally examined in association with different surface profile of ship steel plates A, B and C in sea submerged condition. the surface roughness has been measured through three different methods. The replica tape method was found the most effective to identify the surface roughness of front and rear surface of specimens. It shows that specimen B had highest surface roughness as 135 μm and 140μm at front and back face respectively, then followed by specimen C with 120 μm and 127 μm and the lowest roughness observed on specimen A with 110 μm and 114 μm. The roughness of specimens B and C is very close and falls under coarse grade as per ISO 8503-1:2012. The other two measurement methods (non-contact and contact) were applied to calculate R_a values in the range of wavelength of the light by optical sensors and microscope. However, no significant differences between them have been observed through these methods.

The surface roughness of ship steel plates significantly affected the resistance of epoxy paint against corrosion under sea submerged condition. Failure of the epoxy layer has started as small blistering occurred on the middle surface of the edges, leading to break down of coating. Among all three cases, the specimen C experienced the maximum corrosion on the edges followed by the specimen B and A. However, during six months in sea submerged condition, any of the specimen did not experience epoxy paint creep on the front and rear surface. On the other hand, erosion of the epoxy paint layer thickness has happened as a loss of coating thickness, see Table 5. The erosion of epoxy coating layer on the front and back surface was found to be 11.91, 11.30, 6.48, 12.26, 13.80 and 15.21 %, respectively for specimen A, B and C. The maximum resistance was offered by the front surface of specimen B(F) when compared with that of the other specimens. It is could be concluded that the high peak-to-valley distance of rough surface provides good bonding strength to the coating film which improves the durability of epoxy coating.

Although the present study with laboratory test database is useful to understand the fundamentals of surface preparation affecting the coating life, further studies are certainly recommended. The scope of the results obtained from the present study opens to consider various parameters related to surface preparation, effect of specimen size, and realistic field conditions associated with waves and other submerged environments.

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