Corrosion Performance of Metallic Coating Systems for Steel Bridges

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Abstract
This study examined to evaluate corrosion durability of metallic coatings system for steel bridges. Accelerated cyclic corrosion tests were carried out on four types of metallic coating systems, zinc hot dip galvanizing, zinc-aluminum alloy thermal spraying, low-temperature zinc-aluminum alloy thermal spraying, and aluminum thermal spraying. X-scribe lines reaching underlying steel substrate and uncoated region of 20×70mm were made on steel plates coated by the coating systems. The coated test specimens were exposed into the S6-cycle corrosion environments specified in Japanese Industrial Standards (JIS) K5621 for 100, 200 and 300 days, respectively. The variation of the surface conditions and thickness of the metal coating films were examined at the testing times of 0, 100, 200, and 300 days. After removing corrosion productions on the surface of the test specimens, the surface conditions and the thickness loss were also examined. From the test results, relative corrosion performance of the metallic coating systems was discussed.
Keywords: Steel structure, corrosion, metal coating, accelerated cyclic corrosion test

1. Introduction

Corrosion is one of the most important causes of deterioration for steel structures. Organic and metallic coating systems have been widely used to prevent corrosion attacks, and to maintain the functional ability of the steel structures to bear loads. In recent years, metallic coating systems, such as zinc hop dip galvanized coating, thermal sprayed coating, and low-temperature thermal sprayed coating systems are also applied to corrosion protection for steel bridges, since reducing coating cost at the maintenance stage of steel bridges is expected. However, experimental data of the metallic coating systems are not available, and understanding the corrosion characteristics and evaluating the lifecycle cost with high accuracy are difficult at present time.

The corrosion performance of organic and metallic coating systems has been often determined by atmospheric exposure tests. Although they allow field examinations, it takes long time to obtain any deterioration data of the coating systems. In addition, it is difficult to obtain fundamental information on corrosion characteristics since the combination of various environmental factors, such as temperature, humidity, flying salt, and carbon dioxide affect corrosion process in each site and its individual effect are not available. For these reasons, accelerated cyclic exposure tests in the laboratory are employed to obtain the fundamental data and to complement the data of the field exposure tests.

In recent years, Fujiwara and Tahara (1997) performed accelerated exposure tests of 7 sets of test conditions, called SS, S6, DS, JASO, NS, seawater-NS, and ASTM-cycles. Based on the results of painted steels corroded by field exposure tests at 5 sites in Japan, they presented the correlation between laboratory and field tests and proposed that S6-cycle test condition is applicable for simulating the field exposure tests with good correlation. The S6-cycle corrosion test condition shown in figure 1 was proposed by the Ministry of International Trade and Industry and was specified in JIS (Japanese Industrial Standards). Itoh et al. (2002) performed the S6-cycle corrosion tests on unpainted steel plates, and proposed that acceleration factors of the S6-cycles against field exposure tests is expressed by weight of flying salt. These studies open the way to prediction of corrosion performance of coating systems under atmospheric exposure condition in short time.

This study performed laboratory accelerated tests to examine corrosion characteristics and performance of metallic coating systems for steel bridges: zinc hop dip galvanizing, zinc-aluminum alloy thermal sprayed coating by JIS method, low-temperature zinc-aluminum alloy sprayed coating, and aluminum thermal sprayed coating systems. The coated steel plates were exposed to the S6-cycle corrosion environments during 100, 200, and 300 days. Based on the test results, the corrosion resistance of the metallic coating systems is presented.

2. Test procedure

2.1. Fabrication of test specimens

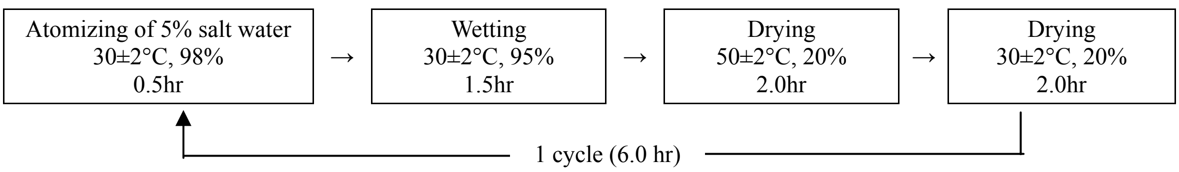


Figure 1. S6 cycle corrosion test condition

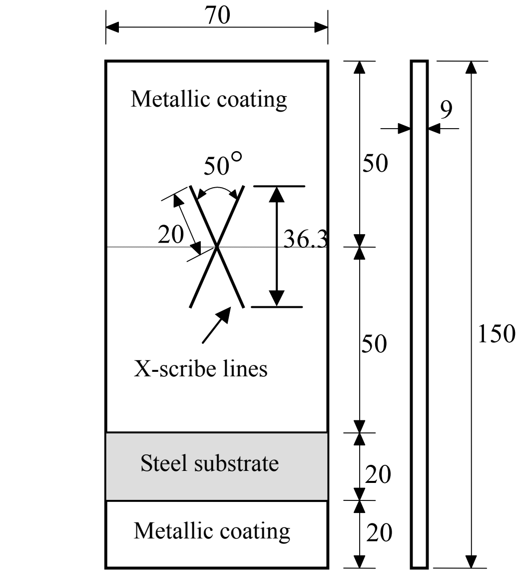


Figure 2. Configuration of test specimen (units in mm)

Figure 2 illustrates the configuration of test specimen used in the tests. Substrate steel plates of 70×150×9 mm were made of Japan Industrial Standards (JIS) SM490A structural steels (JSA, 1999). The chemical composition of the steel is listed in table 2. All the steel plates were grit-blasted by No.50 grit specified in JIS S-G50 or surface-treated by a power tool machine. The steel plates were coated conforming to four metallic coating systems, zinc hop dip galvanizing, zinc-aluminum alloy thermal sprayed coating by JIS method, low-temperature zinc-aluminum alloy sprayed coating, and aluminum thermal sprayed coating, as shown in table 2. X-scribe lines through the coating films to expose the underlying substrate steel using an automated milling machine were made on the coated specimens (12 specimens per coating system). The width of the scribe line is 3mm. The X-scribe lines are often used in corrosion tests to evaluate corrosion performance of coating system. In addition to these exposed lines, in this study 20×70 mm rectangular region at the lower part of all specimens were also exposed by a disc grinder for the zinc hop-dip galvanized coated specimens or by peeling off the masking tape, which was attached on steel substrate prior to the coating works, for other specimens.

Table 1. Chemical properties of the used material (%)

Material	C	Si	Mn	P	S
JIS G3106 SM490A	0.16	0.37	1.44	0.01	0.001

Table 2. Metallic coating systems used in the tests

Coating system	Coating process	Treatment	Designed thickness(μm)	Specimen No.
Zinc hot dip galvanizing	Surface preparation	Blast, SIS Sa2 1/2 Class	-	12
	Metal plating	Zinc hot dip galvanizing (JIS H8641)	100(550g/m^2)	
Zinc-aluminum alloy sprayed coating by JIS thermal spraying (so-called JIS method)	Surface preparation	Blast, SIS Sa2 1/2 Class	-	12
	Rough surface preparation			
	Metal spraying	Zinc-aluminum alloy coating	100	
	Sealing treatment	Epoxy resin sealing coating	-	
Zinc-aluminum alloy sprayed coating by low-temperature spraying (so-called MS method)	Surface preparation	Brush Off Blast, SIS Sa1 Class	-	12
	Rough surface preparation	Non-brass #21	-	
	Low-temperature metal spraying	Zinc-aluminum alloy coating	100	
	Sealing treatment	Non-brass sealing coating	-	
Aluminum sprayed coating	Surface preparation	Blast, SIS Sa2 1/2 Class	-	12
	Rough surface preparation			
	Metal spraying	Aluminum coating	100	
	Sealing treatment	Epoxy resin sealing coating	-	

Table 3. Initial thickness of coating films (μm)

Test specimen	Average	Standard deviation
Zinc hot dip galvanizing	108.3	19.8
Zinc-aluminum alloy sprayed coating by JIS thermal spraying (JIS method)	154.5	23.5
Zinc-aluminum alloy sprayed coating by low-temperature spraying (MS method)	170.2	11.7
Aluminum sprayed coating	172.4	36.7

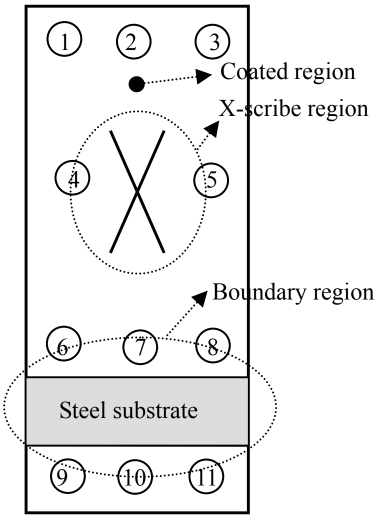


Figure 3. Classification of test specimen

The exposure region were made to observe rusting from uncoated regions, which are difficult to clean, phosphate and coat in coating process because of limited assess, in crevices of which dirt, salt and moisture are collected. For comparison with the coated steel plates, 12 of uncoated steel plates were also prepared and were corroded under the same corrosive environments.

2.2. Test Procedure

In this study, a Combined Cyclic Corrosion Test Instrument made by SUGA Test Instruments Co., Ltd. was used. This equipment can operate automatically the conditions of atomizing of salt water, temperature, and humidity in arbitrary order and combination. It has an environment chamber of 2000 × 1000 × 500 mm, in which 188 test specimens of 70 × 150 mm can be arranged. The corrosion environments of the chamber was controlled conforming to the S6-cycle test condition specified in JIS K5621, as shown in figure 1. Fujiwara (1997) proposed from the comparison of 7 types of accelerated tests in laboratory and field exposure tests that the S6-cycle corrosion test gave the best correlation with outdoor exposure tests, among the accelerated corrosion tests.

9 of 12 test specimens from each coating systems were placed in the chamber at an angle of 15 degree from the vertical. 3 specimens were exposed during 100, 200, and 300 days, respectively. After completion of 100, 200, and 300 day corrosion tests, the visual inspection was performed on front side with X-scribe lines and the exposure region on the test specimens. After removing the corrosion production attached on the test specimens, the visual inspection and the measurement of thickness of coating films by a Laser Focus Measuring Instrument were also carried out. The thickness was measured at 11 points shown in figure 3.The average and standard deviation of the initial thickness of coated films for each test specimen are listed in table 3.

3. Experimental results

The surface conditions of coated specimens corresponding to the testing time of 0, 50, 100, 200, and 300 days are shown in figure 4. During the corrosion tests, the visual inspection was carried out every 25 days. The variation of the surface conditions is separately discussed on 3 regions, coated region, X-scribe region and boundary region, as shown in figure 3.

3.1. Visual inspection for coated region

When uncoated specimens and zinc and/or aluminum coated specimens are corroded, rust formed, and eventually covered the surfaces of the test specimens. It is well known that red rust ($Fe(OH)_2$) for uncoated specimens and white rust ($Zn(OH)_2$, $Al(OH)_3$) for zinc and/or aluminum coated specimens are formed by anodic corrosion-reaction, respectively.

In the uncoated specimens, red rust were irregularly created at multiple parts on the surface, completely covered the surface after 5 days, and eventually formed rust layer. The rust layer became thicker with the increase of testing time and the red of the rust layer changed to deep red or black. At 50 days the rust layer was blistered partially, and peeled off at 250 days.

In three types of coated specimens, Zinc hop-dip galvanized specimens (ZHG specimens), zinc-aluminum alloy thermal sprayed specimens by JIS method (ZAS specimens), and low-temperature zinc-aluminum alloy sprayed specimens (LZAS specimens), white rust completely covered the surfaces at 25, 100, 50 days, respectively. Red rust produced by corrosion of underlying steel substrate was observed at 50 days for ZH, 200 days for ZAS, and 150 days for LZAS specimens, respectively. However, no white and no red rust were observed from the surface of aluminum thermal sprayed specimens (AS specimens). Therefore, it is assumed from this comparison that the aluminum thermal spraying steel plates without any defects have the best cosmetic performance relative to other coating systems.

3.2 Visual inspection for X-scribe region

As shown in figure 4, in the early stage of the corrosion tests white rust was formed near the X-scribe line and covered the exposed lines. No red rusting from the exposed lines of all coated specimens was observed. This is attributed to that the exposed lines are galvanically protected by the preferential anodic dissolution of the zinc and/or aluminum coating and isolated from the corrosive environment by the white rust layer covered. It is assumed from this result that no corrosion of exposed steel substrate occurs in coating systems with the width of the initial defect below 3mm.

3.3 Visual inspection for boundary region

Rusting at the 20×70 mm exposure region is expected to be similar to that of uncoated specimens. At the early stage of the corrosion tests, however, no rusting at upper and lower parts of the exposure region was observed from ZH, ZAS, and AS specimens and rusting was limited at the central part of the region. In the LZAS specimens, red rusting was delayed by white rust covering the exposure region. These are attributed to galvanic corrosion of metal coating near upper and lower exposure region. When the testing time increased, rest rust completely covered the exposure region and propagated from the exposure region to the metal coating layers. The rust propagation length from the boundary of metal coating and the upper exposure region was measured. The mean (M) and the standard deviation (S) of the maximum length are shown in figure 5. In LZAS specimens, the maximum rusted length for 200 and 300 days was taken as 35mm since the rusting reached X-scribe line at 200 days. The average of the maximum length for AS, ZAS, and LZAS specimens tends to increase linearly with increase of the testing time.

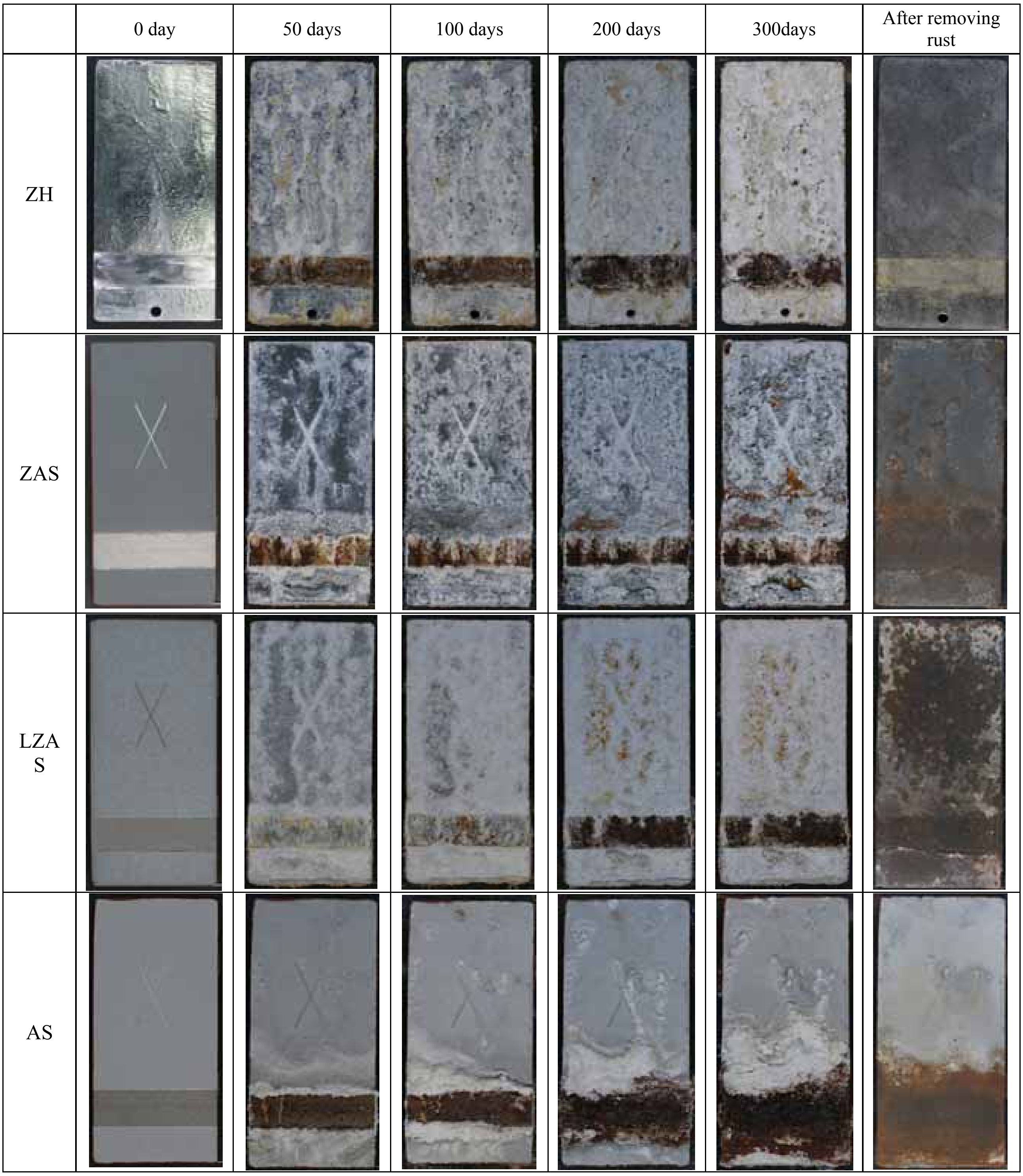


Figure 4. Photographs illustrating the surface condition of test specimens

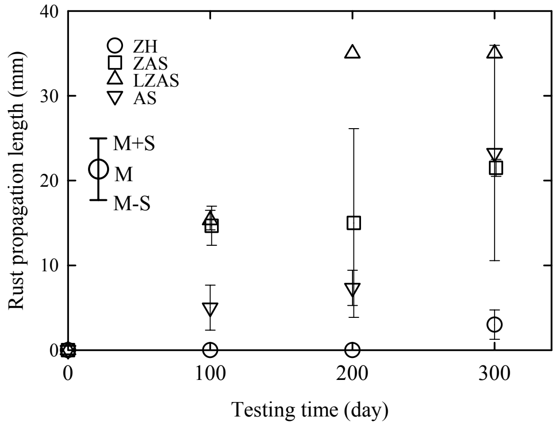


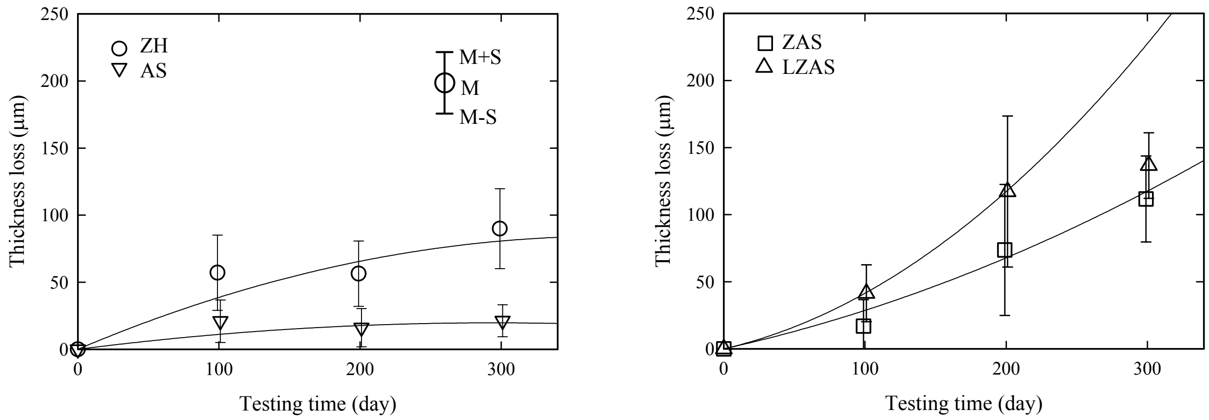
Figure 5. Rusted length from the exposure region

For ZH specimens the rusting propagation length from the exposure region is short: 3mm at 300 days. The average of the maximum length is longer in the order, ZH, AS, ZAS, and LZAS specimens.

3.4 Thickness loss at the coated region

After completion of corrosion tests during 100, 200, and 300 days, corrosion productions on the surface of test specimens were removed chemically and mechanically. Thickness of metal coating layers was measured at point 1 to 5 shown in figure 3. The remained thickness for the ZH and AS specimens and for the ZAS and LZAS specimens is shown in figure 6 (a) and (b), respectively. The regression curves ($y = ax^b$, where a and b are constant) obtained by the least squares method are also plotted. Figure 6(a) indicates that the thickness loss for the ZH and AL specimens increased before testing time was 100 days, but after that the increase is slight. On the other hand, the thickness loss for the ZAS and LZAS specimens show approximately linear increase with the increase of the testing time, as shown in figure 6(b). In the LZAS specimens, the data for 300 days is not considered in calculating the regression, since thickness at 5 of 6 measurement points is almost zero and the thickness loss is meaningless.

For comparison, the data for all specimens are replotted in figure 7. This figure shows that the thickness loss tend to increase in the order of the AS, ZH, ZAS, and LZAS specimens. For example, compared with the AS specimens, the thickness loss for the ZH, ZAS, and LZAS specimens increases by 4.2, 5.3, and 6.4 times, respectively.



(a) ZH and AS specimens

(b) ZAS and LZAS specimens

Figure 6. Thickness loss at the coated region

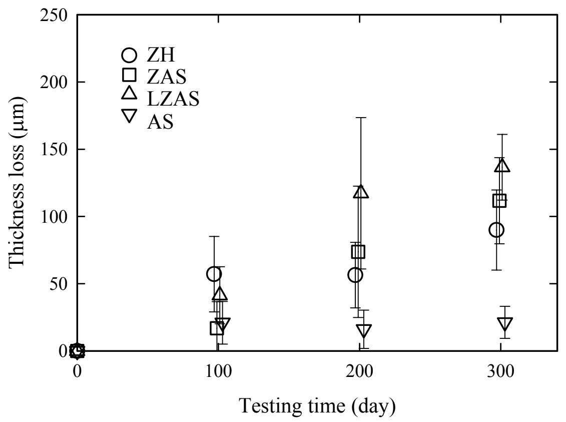


Figure 7. Comparison of thickness loss

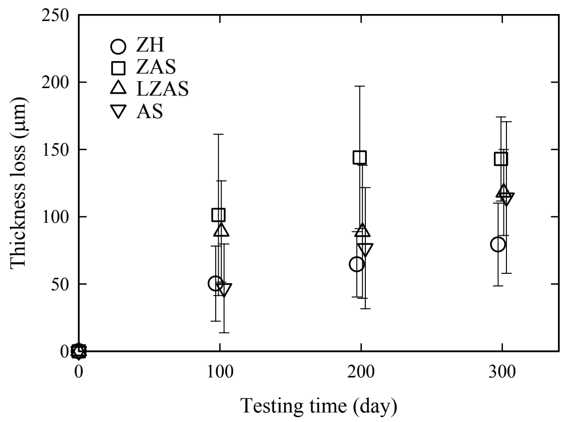


Figure 8. Thickness loss in the boundary region

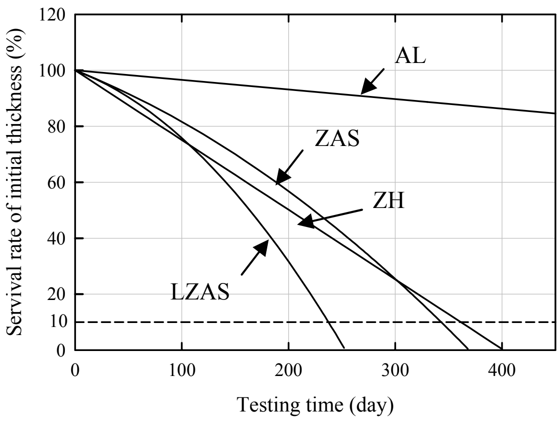


Figure 9. the survival rate

3.5 Thickness loss at the boundary region

The thickness measurement was also carried out on the point 7 to 11 in the boundary region, and the measured results are plotted in figure 8. The thickness loss at the boundary region increases in the order of ZH, AS, LZAS, and ZAS specimens.

3.6 Prediction of service life

When evaluating service life of the metallic coating system, the testing time to 10% survival rate of initial coating thickness is often taken as its service life. The survival rate was calculated based on each regression curve and is plotted in figure 9. It is predicted from the figure that the service life is 230 days for LZAS specimens, 340 days for ZAS specimens, 360 days for ZH specimens, and 2640 days for AS specimens, respectively. Therefore the service life increases in the order of LZAS, ZAS, ZH, and AS specimens.

4. Summary

This study performed laboratory accelerated cyclic corrosion tests to examine corrosion characteristics and performance of metallic coating systems for steel bridges. Four types of steel plated coated with metallic coating systems, Zinc hop dip galvanizing, zinc-aluminum alloy thermal spraying by JIS method, low-temperature zinc-aluminum alloy spraying, and aluminum thermal spraying systems, were corroded under the S6-cycle corrosion environments during 100, 200, or 300 days. Based on the test results of visual inspection and thickness measurements of coating layers, rusting from coated region, X-scribe region lines and exposure region was presented. The corrosion characteristics and the relative service life for metallic coating systems for steel bridges were discussed. In order to apply the present results to corrosive field environments, further study is necessary.

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