

Evaluation of Corrosion Resistance Using Image Processing and Coating Degradation Curves

MIZUSHINO Kotaro : Advanced Manufacturing Process Department, Technology Platform Center, Corporate Research and Development Division, IHI Corporation
KITAMURA Shunya : Advanced Manufacturing Process Department, Technology Platform Center, Corporate Research and Development Division, IHI Corporation
AKAMINE Kenichi : Doctor of Fisheries, Advanced Manufacturing Process Department, Technology Platform Center, Corporate Research and Development Division, IHI Corporation
YUSE Fumio : Doctor of Engineering, Kobe Steel, Ltd.
MATSUBAYASHI Takuto : Kobe Steel, Ltd.

Coated specimens of alloy-added steel and conventional SM steel were subjected to an outdoor exposure test for five years and seven months. By applying image processing to photographs of the specimens taken at different time intervals, the degraded areas were quantified, and coating degradation curves were generated. These curves revealed the progression of degradation for each coating system and demonstrated that alloy-added steel exhibits superior corrosion resistance compared to SM steel.

1. Introduction

As the lifespan of social infrastructure increases, high strength and high corrosion resistance are required for steel materials used in infrastructure such as bridges. In addition, coating steel improves its corrosion resistance; however, the service life of the coating is shorter than that of structures, and recoating must be carried out at appropriate intervals. Therefore, when estimating the life-cycle cost of coatings, it is necessary to consider the recoating cost in addition to the initial coating cost. Extending the service life of coatings allows for less frequent recoating, thereby reducing life-cycle cost. For example, if a bridge with a service life of 100 years requires recoating every 30 years, it will require recoating three times during its service life. In contrast, if the recoating interval is approximately 50 years, the bridge can complete its service life with only one recoating.

The “Manual for Recoating General Coatings to Heavy-Duty Anti-Corrosion Coatings”⁽¹⁾ requires infrastructure managers to evaluate the condition of coatings through periodic inspections and to determine the timing of recoating so that the corrosion protection function is appropriately maintained. During inspections, it is common to visually examine coatings for rust, peeling, discoloration, and other defects, and to evaluate their condition on a multi-level scale by comparing them with standard photos or the like. However, since coatings deteriorate continuously as they are exposed to the surrounding environment, making it often difficult to determine the appropriate timing for recoating. To accurately estimate the service life of coatings, it is important to quantitatively determine the extent of degradation and how it progresses over time for various combinations of steel materials and coating systems. The

“Manual for Inspecting Coatings of Steel Structures”⁽²⁾ proposes the use of image processing techniques to objectively evaluate the deterioration state and morphology of coatings.

In this study, the corrosion resistance of coatings was evaluated and their service life was predicted using data from outdoor exposure tests conducted over a period of five years and seven months. In this process, the validity of the results was verified using image processing of the test specimens and data analysis based on coating degradation curves.

2. Method

2.1 Preparation of test specimens

SM steel and alloy-added steel specimens with dimensions of L150 × W70 × t6 mm were used as the substrate material. In this study, SM490, which is widely used for bridges and other structures, was used as the SM steel, whereas a steel containing Cu and Ni was used as the alloy-added steel. As shown in **Table 1**, each steel specimen was coated with one of three coating systems: an alkyd resin coating (total film thickness: 125 μm), a urethane resin coating (total film thickness: 250 μm), and a fluororesin coating (total film thickness: 250 μm). For the alkyd resin coating system, a rust-preventive paint was applied as the primer, and phthalic acid resin-based coatings were used for the intermediate and top coats. For the urethane resin and fluororesin coating systems, an inorganic zinc-rich paint was applied as the first layer, followed by an epoxy resin-based primer, and urethane resin and fluororesin coatings were applied as the intermediate and top coats, respectively. The coating intervals were set to the standard values specified for each coating material. To assess the progression of deterioration

Table 1 Coating specifications of the test specimens

(a) Alkyd resin coating			(b) Urethane resin coating			(c) Fluororesin coating		
Process	Specifications	Target film thickness (μm)	Process	Specifications	Target film thickness (μm)	Process	Specifications	Target film thickness (μm)
Blast	ISO Sa2 1/2	—	Blast	ISO Sa2 1/2	—	Blast	ISO Sa2 1/2	—
1st layer	Rust-preventive paint	35	1st layer	Inorganic zinc-rich paint	75	1st layer	Inorganic zinc-rich paint	75
2nd layer	Rust-preventive paint	35	Mist coat	Epoxy resin primer for mist coat	—	Mist coat	Epoxy resin primer for mist coat	—
3rd layer	Phthalic acid resin intermediate coat	30	2nd layer	Epoxy resin primer	120	2nd layer	Epoxy resin primer	120
4th layer	Phthalic acid resin topcoat	25	3rd layer	Urethane resin intermediate coat	30	3rd layer	Fluororesin intermediate coat	30
			4th layer	Urethane resin topcoat	25	4th layer	Fluororesin topcoat	25

from damaged areas in the coating, a cross-cut was introduced on half of each specimen using a Clemens-type hardness tester (ERICHSEN Model 639), as shown in **Fig. 1**. The cross-cut consisted of two intersecting cuts, each 60 mm in length, crossing at 90 degrees.

2.2 Outdoor exposure test

The prepared test specimens were subjected to outdoor exposure tests. The tests began in February 2017, when the specimens were installed on a rack at the Miyakojima Exposure Test and Research Center of the Japan Weathering Test Center. In May 2019, the specimens were relocated to a rack at the Miyakojima Seashore Exposure Site, which is closer to the sea. **Figure 2** shows the specimens during the exposure tests. The test specimens were installed with the cross-cut facing downward to prevent rust runoff from adhering to the other areas.

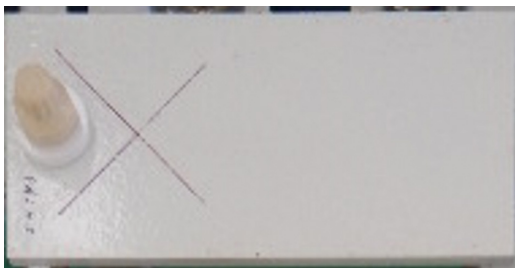
2.3 Image processing

The area of surface deterioration around the cross-cut on the

test specimens was evaluated. In this context, the “area of surface deterioration” refers to the region where the red rust spreading from the cross-cut is visually observed. The following two methods, A and B, were employed.

After five years and seven months of outdoor exposure tests, the area of surface deterioration of the test specimens was evaluated by photographing them, since the specimens were available on hand (method A). A color camera with a prime lens and ring lighting was used for imaging. The imaging equipment and conditions are shown in **Tables 2** and **3**, respectively. The imaging setup is shown in **Fig. 3**. Although **Fig. 3** appears bright, the photographs of surface deterioration were actually taken in a darkroom.

For the captured images, half of the area of the region where the cross-cut was introduced, as shown in **Fig. 4**, was selected as the evaluation area. This is because, near the specimen edge, the cross-cut region was strongly affected by rust that had formed at the edge and flowed onto the specimen. For this evaluation area, a brightness histogram was generated as shown in **Fig. 5**. Furthermore, a brightness threshold was set in the histogram to create a binary image of bright and dark areas. Areas with a brightness lower than the threshold were displayed in white, while those with a brightness higher than the threshold were displayed in black.

**Fig. 1** Test specimens**Fig. 2** Appearance during testing**Table 2** Imaging equipments

Camera	5-megapixel industrial color camera (Argo DFK 27BUP006)
Lens	Prime lens (VS-0818VM, focal length : 8 mm)
Lighting	Ring light (AI Tec System TR250X202-16WD-4, radius : approx. 109 mm)

Table 3 Imaging conditions

Camera height	140 mm
Lighting height	120 mm
Lighting power setting	Set the power supply (TCDP2B-2430NCW) to 2
F-number	8
WB	R82, G63, B102
Saturation	100
Exposure	1/13 s
Gamma	100
Gain	0 dB

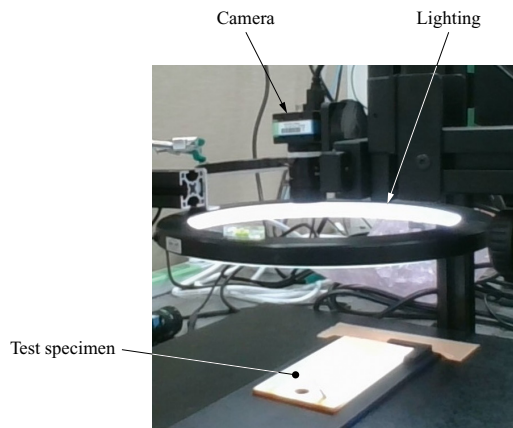


Fig. 3 Imaging setup

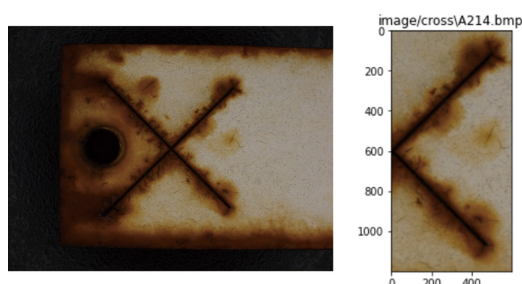


Fig. 4 The imaged specimen and the evaluation target area

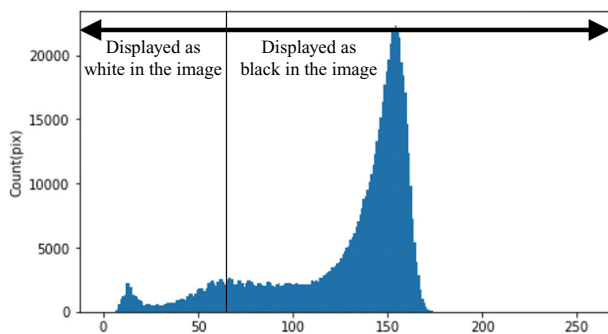


Fig. 5 Brightness histogram

The threshold was visually determined so that areas where red rust has formed could be distinguished from areas where red rust has merely flowed (rust runoff). **Figure 6** shows examples of binary images obtained with different threshold values. When the threshold was set to 25, only the initial

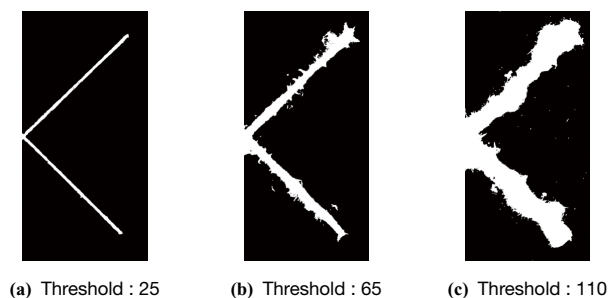


Fig. 6 Binary images

cross-cut area was evaluated as the area of surface deterioration. In contrast, when the threshold was set to 110, areas including rust runoff were evaluated as the area of surface deterioration. When the threshold was set to 65, it was possible to evaluate the rusted area excluding rust runoff as the area of surface deterioration. Based on these considerations, a brightness threshold of 65 was adopted for the evaluation. The area of surface deterioration was calculated from the number of pixels in the white areas of the binarized image, which were identified as rusted areas. For example, for the test specimen shown in **Fig. 4**, the area of surface deterioration was calculated to be 133.96 mm².

To analyze the degree of degradation of the specimens over time, data past specimens are required. Therefore, image data previously captured with a handheld camera were used to calculate the area of surface deterioration (method B). Images of the test specimens after one, three, and four years of outdoor exposure tests were collected, and the evaluation areas were extracted by cropping the images as shown in **Fig. 7**. In this process, the scale was adjusted so that the length of the longer side of each test specimen was 150 mm. As with method A, a brightness histogram was generated for the evaluation area. Since imaging conditions differ for each test specimen, it is necessary to determine a threshold for each image. To minimize subjective judgment, the brightness of the intact coating areas (non-deteriorated coated areas) of the test specimen was used as a reference. Specifically, for the first test specimen, the threshold was determined visually so that areas with actual red rust could be distinguished from those where red rust had merely flowed. For the other specimens, assuming that the actual brightness of the intact coating areas (non-deteriorated coated areas) is uniform, the threshold was calculated based on the ratio of the brightness of the intact coating areas in the image. A binary image was then generated based on the threshold, and the area of surface deterioration was calculated from the number of pixels in the white areas.

A comparison of methods A and B suggests that method A, in which the imaging environment was controlled, enables more accurate evaluation. Images of all the test specimens used in the measurements are shown in **Table 4**.

2.4 Creation of coating degradation curves

The Gompertz curve was used as a mathematical model for predicting the service life of coatings. This curve has been used to approximate the relationship between the blistered area of the cross-cut and accelerated exposure time⁽³⁾. In this

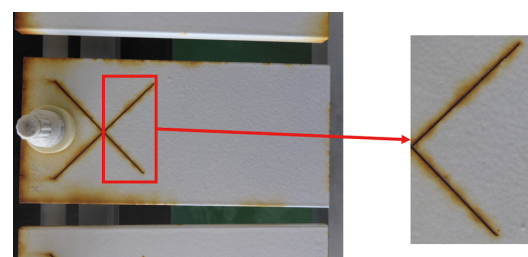
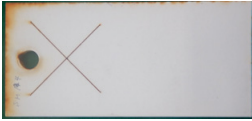
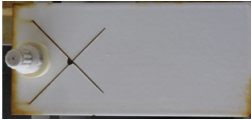
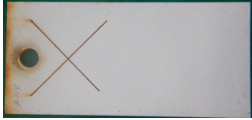
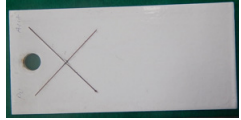
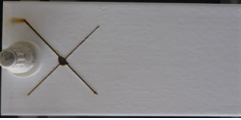
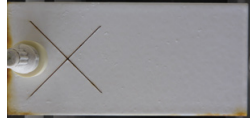
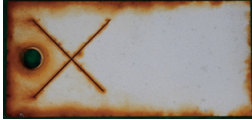
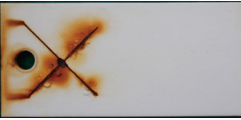


Fig. 7 Trimming from previous images

Table 4 Images of the test specimens used for measurement

		(a) SM steel		
		Alkyd resin coating	Urethane resin coating	Fluororesin coating
SM steel	1 year			
	3 years			
	4 years			
	5, 6 years			
		(b) Alloy-added steel		
		Alkyd resin coating	Urethane resin coating	Fluororesin coating
Alloy-added steel	1 year			
	3 years			
	4 years			
	5, 6 years			

study, it was applied to the relationship between the area of surface deterioration and outdoor exposure time to estimate long-term deterioration based on the initial degradation rate of the coating. The Gompertz curve is given by Equation (1): where y is the area of deterioration, t is time, and K is the area corresponding to complete deterioration.

$$y = K \cdot a^{b^t} \dots\dots\dots (1)$$

Assuming an initial degradation area rate of 0.5%, a in the equation was set to 0.005. In addition, K was calculated using the average area of the measurement data of the initial test specimens with cross-cuts. Furthermore, b was determined using the least-squares method from the data on the area of surface deterioration obtained by image processing. On the

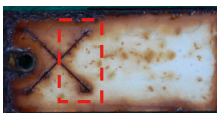
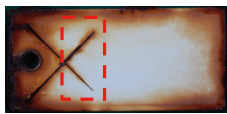
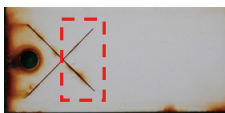
Gompertz curve, the point at which the degradation area rate reaches 6.6% corresponds to the point of rapid increase, and the point at which it reaches 36.8% corresponds to the inflection point. The range from the point of rapid increase to the inflection point has been proposed as the practical recoating interval; based on this, guideline values for the recoating timing of various coating systems were determined.

3. Results and discussion

3.1 Relationship between test specimen images and area of surface deterioration

Table 5 shows the relationship between the test specimen images and the surface deterioration areas. This confirms

Table 5 Relationship between test specimen images and rusted area

		Alkyd resin coating		Urethane resin coating		Fluororesin coating	
SM steel	Appearance						
	Binary image / surface deterioration area (mm ²)		384.6		129.3		80.2
Alloy-added steel	Appearance						
	Binary image / surface deterioration area (mm ²)		140.8		102.0		40.5

(Note) : Evaluation area

that there is good agreement between the degree of deterioration observed in the images and the calculated rust area. For example, the test specimen coated with an alkyd resin coating on SM steel, which was evaluated as having the largest surface deterioration area, shows significant rusting in the image, whereas the test specimen coated with a fluororesin coating on alloy-added steel, which was evaluated as having the smallest surface deterioration area, shows the least rusting.

3.2 Differences in degree of degradation among coating systems

Figure 8 shows the coating degradation curves of painted SM steel test specimens. This figure shows the change in the degradation area rate over time for each coating system. The dotted lines at 6.6% and 36.8% indicate the range of the practical recoating timing on the Gompertz curve. Among the three coating systems, the alkyd resin coating system exhibited the shortest service life. This is likely because, compared to other coating systems, it had a thinner film

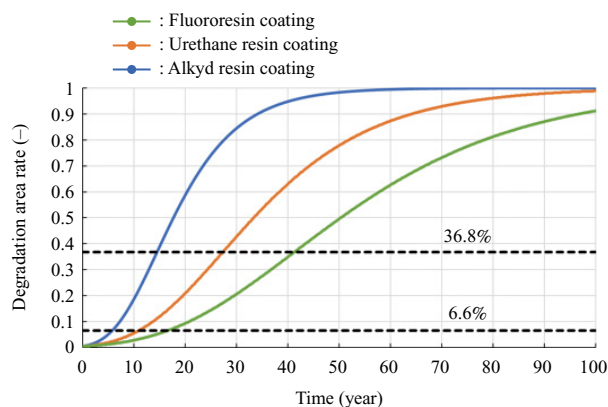


Fig. 8 Coating degradation curves for each coating system on SM steel

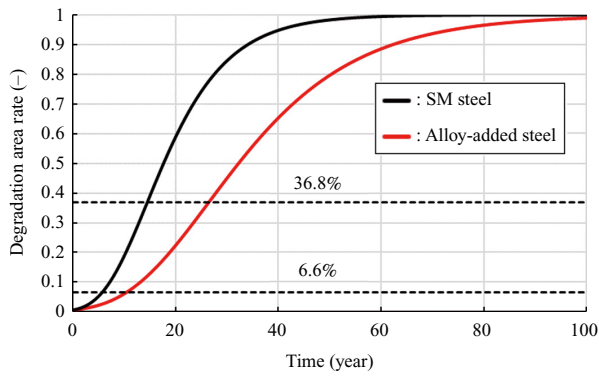
thickness and did not include an inorganic zinc-rich paint that provides sacrificial corrosion protection, resulting in more significant rust progression. A comparison of the urethane resin and fluororesin coating systems shows that the latter exhibits a lower degradation rate. This is thought to be due to the fluororesin coating's ability to suppress the adhesion of rust runoff and its excellent weather resistance, which reduces UV-induced deterioration. It is presumed that the fluororesin coating system showed the smallest increase in the deteriorated area originating from the cross-cut region, because the expansion of this area is governed not only by the lateral propagation of degradation from the damaged region but also by coating deterioration progressing from the surface.

3.3 Differences in degree of degradation by steel type

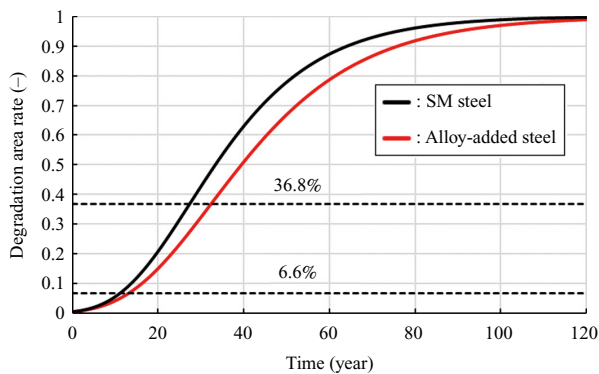
Figure 9 shows the coating degradation curves for test specimens of coated SM steel and alloy-added steel specimens. For all coating systems, alloy-added steel exhibited a longer service life, indicating superior corrosion resistance. The alloy-added steel contains Cu and Ni, which improve its corrosion resistance. This effect is considered to have suppressed the spread of the surface deterioration area in the coated test specimens as well.

3.4 Recoating timing

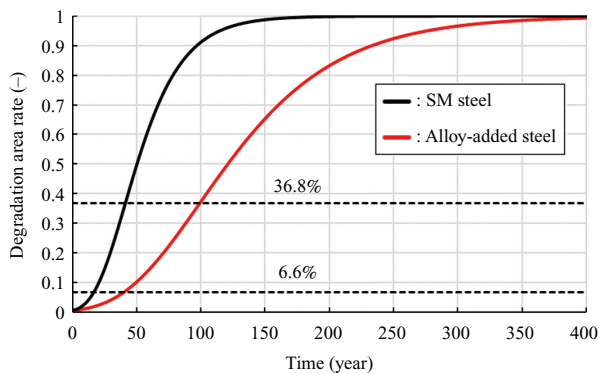
Figure 10 shows the recoating timing estimated from the coating degradation curves. This estimate is based on an evaluation of the expansion behavior of surface deterioration from the cross-cut in specimens exposed at two locations on Miyakojima Island, using Gompertz curves, and it should be noted that this evaluation is based on highly limited conditions. For SM steel, the estimated recoating timing ranges from 6 to 15 years for alkyd resin coatings, 11 to 27 years for urethane resin coatings, and 16 to 41 years for fluororesin coatings. Based on calculations using the degradation rate and target film thickness of the topcoat, the



(a) Alkyd resin coating



(b) Urethane resin coating



(c) Fluororesin coating

Fig. 9 Coating degradation curves for SM steel and alloy-added steel

service life is estimated to be 12.5 to 25 years for urethane resin coatings and 25 to 50 years for fluororesin coatings⁽⁴⁾. The results obtained were generally consistent with these estimates. In this study, because the threshold was determined visually, the results are considered to be close to the recoating timing determined by visual inspection. However, the development of a more precise and objective method for determining the threshold remains a subject for future work. In addition, it was found that the recoating timing for alloy-added steel was extended for all coating systems compared to SM steel, indicating the potential for a longer coating service life and reduced life-cycle cost. On the other hand, the recoating timing for fluororesin coatings applied to alloy-added steel was estimated to be 40 to 99 years, which

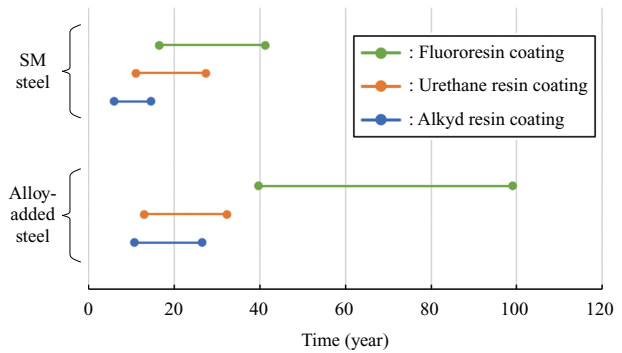


Fig. 10 Estimated recoating intervals

is considerably longer than expected. Since this estimate was based on short exposure durations, the number of data points may have been insufficient for reliable long-term prediction. Therefore, it is necessary to continue collecting data to validate the model and improve the accuracy of service life prediction.

4. Conclusion

The corrosion resistance of various coated test specimens subjected to outdoor exposure tests was evaluated using image processing and the concept of coating degradation curves. The results are as follows:

- The area of surface deterioration was quantified by setting a brightness threshold and binarizing both images of actual test specimens and previously captured images. Gompertz curves were then created using the quantified rust areas to estimate the degradation behavior of the coatings. The recoating timing estimated from the coating degradation curves was generally consistent with commonly accepted guidelines.
- Steel materials containing Cu and Ni exhibited improved corrosion resistance compared to SM steel for all coating systems. This indicates the potential for longer coating service life and reduced life-cycle cost.

REFERENCES

- (1) Japan Society of Steel Construction : Manual for Recoating General Coatings to Heavy-Duty Anti-Corrosion Coatings, JSS IV 11-14, 2014, p. 109 (in Japanese)
- (2) Japan Society of Steel Construction : Manual for Inspecting Coatings of Steel Structures, JSS IV 03-2018, 2018, p. 74 (in Japanese)
- (3) Y. Ito, I. T. Kim, S. Kainuma, Y. Kadota : Corrosion Deterioration of Painted Steels with Different Surface Preparations of Steel Substrates, Japanese Journal of JSCE, No. 766/I-68, 2004, pp. 291-307 (in Japanese)
- (4) Japanese Society of Steel Construction : Heavy-Duty Anti-Corrosion Coatings - From Corrosion Prevention Principles to Design -, Construction, and Maintenance, 2012, p. 170 (in Japanese)

(Reprinted from Rust Prevention & Control, 2024, Vol. 68, No. 7, pp. 21-26 (in Japanese))