Automotive Corrosion and Accelerated Corrosion Tests for Zinc Coated Steels

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(Received on March 6, 2018; accepted on April 5, 2018)

Numerous studies on zinc and zinc alloy coated steel sheets have appeared since corrosion problems were widely recognized in the automotive industry in the 1970s. In general, accelerated corrosion tests including the Salt Spray Test and Cyclic Corrosion Tests have been applied to evaluate the corrosion resistance of coated steels in the laboratory in order to shorten the product development period. However, the reproducibility of corrosion in actual use conditions by corrosion tests is always a controversial issue. In this paper, author’s previous studies regarding corrosion of coated steel sheets in automobiles and corrosion tests are reviewed. The perforation corrosion behaviors of coated steels at lapped parts in snowy and tropical regions were clarified on the basis of an analysis of corroded vehicles. Several types of accelerated corrosion tests used in the automotive industry were conducted for comparison with the corrosion observed in the actual vehicles. The Perforation Corrosion Index (PCI), which is the corrosion rate ratio of steel and zinc coating, was introduced as an index for comparing the correlation of corrosion behaviors. Coating weight is the major factor determining the perforation corrosion resistance of existing coated materials in automobile use environments. Corrosion tests that have a PCI value close to that in the use environment can simulate similar corrosion tendencies. The influence of the specimen configuration is also a key factor for adequate evaluation of corrosion resistance. Specimens without an intentional large clearance and bare metal surface in the lapped portion are recommended for perforation corrosion tests.

KEY WORDS: zinc; coating; automobile; perforation corrosion; PCI; corrosion test.

1. Introduction

The anti-rust and corrosion quality of automobiles became a focus of attention in the 1970s since the deicing salt spread on roads to prevent accidents in snowy areas often caused corrosion problems in the US, Europe and Japan. In order to improve the anti-rust quality of vehicles, many types of coated steels, chemical conversion treatment and paint system were developed in line with optimization of automobile design and also anti-rust treatments such as sealers and waxes were applied. Developing corrosion resistant materials in a short period involves a dilemma of contrary requirements. In general, accelerated corrosion tests are used to judge the corrosion resistance of zinc and zinc alloy coated steels in a short time. In the early period, the salt spray test (SST) was used in industry as a quick, easy evaluation method. In the wake of the recognition that the SST has a poor reliability and a poor correlation with real environments, cyclic corrosion tests (CCT) that consist of “wet” and “dry” conditions combined with SST started to be applied. A large number of CCT have been developed as corporate and industrial standard test methods in the automotive industry. In Japan, JASO M609-1991 was standardized as a cosmetic corrosion test for automotive parts. SAE J2334 was developed as a cosmetic corrosion test that has a good correlation with on-vehicle tests in the US. Automakers use a variety of original CCT to evaluate various types of corrosion phenomena in automotive parts. In recent years, VDA 233-102 (formerly called N-VDA), which was designed by modifying VDA 621-415, was standardized in Germany. However, the reproducibility of the corrosion behaviors of automotive parts in actual use environments by CCT is still a remaining issue to be solved.

Investigations of corrosion in vehicles in snowy areas have been carried out and reported in some publications. Those investigations clarified the fact that the coating thickness is a more crucial factor than the alloy composition of the coating for prevention of cosmetic and perforation corrosion in automotive parts. On the other hand, corrosion of vehicles in tropical environments has not been fully understood, in spite of increasing sales of automobiles in Southeast Asia.

This paper reviews author’s previous studies regarding corrosion of coated materials in vehicles and tests by CCT. Perforation corrosion, which occurs at lapped portions and is still a major corrosion issue in the automotive industry, is discussed. Perforation corrosion of corroded vehicles used in different regions and test specimens tested by various CCT were quantitatively investigated. The corrosion resistance of zinc and zinc alloy coated...
steels was compared under different CCT conditions and use environments. In order to select an appropriate CCT and predict the corrosion resistance of coated materials in actual automobiles, the corrosion rate ratio of zinc and steel was considered as a correlation index. The configuration of test coupons is also significant for appropriate evaluations and influences the results of CCT evaluations.\(^3\) In this paper, the appropriate test coupon configuration proposed for perforation corrosion evaluations in author’s previous study is reviewed.

2. Corrosion Behaviors of Actual Vehicles in Different Environments

2.1. Analysis of Corroded Vehicles

Since corrosion of vehicles was recognized as a problem in the 1980s, many types of coated steels have been developed and applied to automotive parts.\(^3\) It has been reported that the alloy composition of existing zinc alloy coatings does not have a significant impact on corrosion prevention in use environments. An investigations of corroded vehicles used in snowy areas showed that perforation corrosion of automotive parts tends to be prevented as the coating thickness increases.\(^26,27,29,30\) Although sales of automobiles in tropical regions in Asia have increased in the last 10 years, there are still few reports on corrosion of vehicles in those environments. Therefore, this paper reports the corrosion of vehicles used in two different regions, snowy areas in Europe (Austria, Denmark and Sweden) and a tropical area in Asia (Thailand). More than 70 vehicles were observed in those two regions, and corroded vehicles were selected for analysis. Vehicles used for 5 to 9 years and for 10 to 20 years were collected in Europe and Thailand based on the conditions of the targeted portions for analysis.

In this study, the perforation corrosion of doors and side-sills was investigated. The coatings used in these parts were identified by analyzing portions without corrosion. The hemming of the doors and spot welded part of the side-sills were disassembled, and the corrosion inside the lapped portions was investigated. The corrosion products formed on the steel were removed by using a hydrochloric acid solution with an inhibitor in accordance with ISO 8407 C.3.1.\(^43\) The thickness of the steel was measured along the lapped areas with a needle-type micrometer, and the corrosion depth was determined from the difference with the thickness of non-corroded parts.

2.2. Perforation Corrosion Behavior of Vehicles

Corrosion of vehicles in the snowy regions was investigated\(^28,30\) and the perforation corrosion process of zinc coated steels in the lapped parts was reported, as shown in Fig. 1.\(^27\) The time to perforation corrosion is divided into the protection period by the zinc coating and the corrosion period of the steel substrate. The protection by the zinc coating is attributed to the good corrosion resistance of the zinc itself under the atmosphere (\(\tau_1\)), sacrificial corrosion of zinc (\(\tau_2\)) and protection by the deposited zinc corrosion products (\(\tau_3\)). The apparent corrosion rates of the zinc coating and steel in the lapped portion are estimated by following equations.

\[
V_{zn} = \frac{V_{coating}}{(\tau_1 + \tau_2 + \tau_3)} \quad \text{(1)}
\]

where, \(V_{zn}\) is corrosion rate of zinc coating and \(V_{coating}\) is thickness of zinc coating.

![Fig. 1. Perforation corrosion process of zinc coated steels.\(^27\)](image)

![Fig. 2. Corrosion in lapped portions of doors and side-sill outer panels.](image)
where, $V_{steel}$ is corrosion rate of steel, $t_{steel}$ is thickness of steel and $\tau_4$ is period during which the steel starts to corrode and reaches perforation.

Taking the side-sills of GI 120 g/m$^2$ shown in Fig. 1 as an example, $V_{Zn}$ and $V_{steel}$ are obtained by the following calculations.

\[
V_{Zn} = \frac{120 \text{ g/m}^2}{9 \text{ years}} = 13.3 \text{ g/m}^2/\text{year} \quad \ldots \ldots \quad (3)
\]

\[
V_{steel} = \frac{750 \mu m}{5 \text{ years}} = 150 \mu m/\text{year} \quad \ldots \ldots \quad (4)
\]

As is obvious from these results, corrosion of the steel in automotive parts is far more rapid than corrosion of the zinc coating. Specifically, the corrosion rate of the steel is 80 times higher than that of the zinc coating.

In this paper, corroded vehicles collected in Europe and Thailand were analyzed for comparison with the above-mentioned results. The corrosion on the disassembled outer panels of the doors and side-sills is shown in Fig. 2. Severe corrosion was seen in the lapped portions of both the door and side-sill outers in Europe, and a large area of the inside was covered with red rust. On the other hand, the corrosion area of the lapped portions was very small in Thailand, even though the samples were taken from 10-year use vehicles.

**Figure 3** shows the corrosion depth in the hemming of door outers as a function of the vehicle use period.$^{35}$ It is noted that no heavy anti-rust treatment of oil wax was applied in all investigated parts. The numbers in parentheses represent the coating thickness on one side. In the previous studies in North America$^{27,32}$ it was clarified that zinc and zinc alloy coatings suppress corrosion of the steel in the early years of use period. Similar tendency was obtained in different regions in this study. In Europe, the coating of 70–80 g/m$^2$ was consumed and the steel started to corrode in the lapped portion in approximately 7 years. Considering the difference in the coating thickness, the effect of the coating thickness on corrosion prevention in snowy areas in Europe was similar to that in North America. In Thailand, on the other hand, the coating prevented corrosion for approximately 8 years, even though the coating thickness was only 40–45 g/m$^2$. Thus, these results confirmed again that the deicing salt used in snowy areas causes severe corrosion of vehicles, whereas corrosion of vehicles in Thailand seems much milder than that in snowy areas, in spite of the high temperature and humidity in that tropical country.

3. **Accelerated Corrosion Tests**

3.1 **Corrosion Tests and Post Evaluation Procedures**

Accelerated corrosion tests are generally used to shorten the development period of coated materials. However, the correlation of the corrosion that occurs in corrosion tests with that in actual environments has not been fully understood. Therefore, the corrosion resistance of zinc and zinc alloy coated steel sheets was evaluated by corrosion tests, and their correlations with the corrosion observed in actual vehicles was investigated. **Tables 1** and **2** show the materials and the accelerated corrosion tests examined in this study, respectively. Perforation corrosion of cold-rolled carbon steel and four types of coated steels was evaluated by using lapped specimens in which two panels of the same steels were overlapped and joined by spot welding, followed by phosphating and electrodeposition. The corrosion tests were cyclic corrosion tests (CCT) specified in industrial and corporate standards. After a specific test period, the lapped specimens were withdrawn from the test chamber and disassembled. The electrodeposited coating and corrosion products were removed with a solvent-based paint remover and the solution specified in the ISO 8407 C.3.1. The corrosion depth of the test coupons was measured with a needle-type micrometer, and the maximum corrosion depth was determined by an extreme value analysis of the Gumbel distribution.

| Test No. | Corrosion test | cycle count | remarks |
|----------|----------------|-------------|---------|
| T1       | JASO M609-91   | 3 cycles/day | Industrial standard in Japan |
| T2       | SAE J2334      | 5 cycles/week | Industrial standard in USA |
| T3       | SAE J2334      | 7 cycles/week | Industrial standard in USA |
| T4       | VDA 621-415    | 1 cycles/week | Industrial standard in Germany |
| T5       | CCT-1          | 3 cycles/day | Corporate standard. |
| T6       | CCT-2          | 1 cycles/day | Corporate standard. |

| Materials tested by accelerated corrosion tests. |
|-----------------------------------------------|
| Steels | Symbol | Coating thickness (g/m$^2$) |
|--------|--------|-----------------------------|
| CRS    | EG     | 0                           |
| Electro-galvanized | ZnNi (Ni:11–13%) | 18 to 68 |
| Galvannealed | GA (Fe:10–11%) | 43 to 51 |
| Hot dip Galvanized | GI | 64 to 100 |

**Table 1.** Materials tested by accelerated corrosion tests.

**Table 2.** Cyclic corrosion tests used for perforation corrosion evaluation.
3.2. Corrosion Test Results and Comparison with Actual Vehicles

The insides of the lapped specimens tested in T1 and T3 are shown in Fig. 4. In the T1 test, similar appearances consisting of red rust and white rust were seen on the three types of coated steels. However, in the T3 test, the three steels showed different appearances. In the case of GA 45 g/m², the entire surface was covered with red rust, whereas white rust of the coating still remained on GI 100 g/m². These results imply that the conditions of the CCT strongly influence the corrosion resistance of coated steel sheets, as shown in this Figure.

Figures 5 and 6 show the corrosion depth of the lapped specimens as a function of the number of test cycles in the T1 and T3 tests. The lines representing the progress of perforation corrosion were obtained by fitting the linear regression for carbon steel to the data of the coated materials at 150 and 120 cycles. In the T1 test, thin coatings of ZnNi and GA effectively suppressed perforation corrosion, and the corrosion depth of ZnNi at 150 cycles was close to that of thick GI 100 g/m². This result suggests that the coating composition is more significant than the coating thickness for preventing perforation corrosion under this test condition. In addition, the steel substrates of the coated materials started to corrode in a relatively short time. It seems that the steels of the coated materials have different corrosion behaviors from that of the carbon steel. On the other hand, the protection period by the coatings was obviously seen, and corrosion of the steel was small in the early period in the T3 test. The protection period by GI 100 g/m² was approximately double that of GA 51 g/m². Thus, under this condition, the coating thickness has a larger impact on corrosion prevention compared to the alloy composition of the coatings.

The corrosion rates of the steel $V_{\text{steel}}$ and the zinc coating $V_{\text{Zn}}$ were calculated in the same way as mentioned in 2.2 and are summarized in Table 3. In addition to the corrosion rates, the Perforation Corrosion Index (PCI), defined as the corrosion rate ratio ($V_{\text{steel}}/V_{\text{Zn}}$ coating), was calculated for the CCT and the actual automotive parts (doors and side-sills) from the different countries. To obtain the PCI values accurately, the corrosion depth data obtained with thick coatings such as GI 100 g/m² were used in these calculations. It is noted that the corrosion rates in the CCT are high, and close PCI values do not necessarily give values close to the actual corrosion rates, since PCI represents the corrosion balance of the steel and the zinc coating. CCT with different test conditions give a wide range of PCI values from 16 to 98,
Table 3. Corrosion rates of steel and zinc coating and PCI values.

| Test No. | Corrosion test | $V_{steel}$ ($\mu$m/cycle) | $V_{Coating}$ ($\mu$m/cycle) | PCI |
|----------|----------------|----------------------------|-----------------------------|-----|
| T1       | JASO M609-91   | 3.4                        | 0.18                        | 19  |
| T2       | SAE J2334 5 cy/w | 6.6                        | 0.23                        | 29  |
| T3       | SAE J2334 7 cy/w | 7.2                        | 0.13                        | 56  |
| T4       | VDA 621-415    | 20                         | 0.53                        | 38  |
| T5       | CCT-1          | 7.7                        | 0.47                        | 16  |
| T6       | CCT-2          | 7.3                        | 0.07                        | 98  |

Vehicles in service (North US, Europe, Thailand) 75–120

while PCI values ranging from 75 to 120 were obtained from the analysis of the corroded vehicles used in different environments. The PCI values of the T3 and T6 tests were relatively close to the values obtained from the vehicles, which implies that the corrosion behaviors of the coating and the steel in actual environments are well reproduced, whereas the PCIs for the T1 and T5 CCT were much smaller than the range from the actual vehicles. These test conditions are believed to be too severe for the zinc coating; that is, corrosion of only the zinc coating is aggressively accelerated in comparison with the corrosion that occurs in actual vehicles. In order to reproduce the corrosion of coated materials in use environments, test conditions that provide PCI values close to those of actual vehicles must be selected.

3.3. Corrosion Resistance of Zinc Alloy Coatings

Here, it should be recalled that PCI is considered to represent the correlation between CCT and corrosion of actual vehicles from the viewpoint of the corrosion balance of steel and zinc. Figure 7 shows the effect of various coatings on perforation corrosion as a function of the PCI determined for CCT and actual automotive parts.33) As shown in Table 3, the PCI values of CCT with different test conditions ranged from 16 to 98, whereas corrosion of actual vehicles resulted in PCI values ranging from 75 to 120. The effect of the coating $P$ for pure zinc coatings of GI and EG was calculated directly from the following relation:

$$ P = \frac{(t_1 + t_2 + t_3)}{t_3} = PCI \cdot \left(\frac{t_{coating}}{t_{steel}}\right) \ldots \ldots (5) $$

where, $t_{coating}$ is the coating thickness and $t_{steel}$ of 0.7 mm is assumed. $P$ for EG and GI is uniquely determined by the PCI depending on the coating thickness, which is represented by the broken lines in the Figure. Assuming that the corrosion rate does not depend on the coating thickness, $P$ is proportional to the coating thickness, and the perforation protection period by the zinc coating becomes longer as the coating thickness increases. The relative corrosion resistance performance of GA and ZnNi to a pure zinc coating changes depending on the PCI conditions. The PCI dependency of the corrosion resistance of the coatings is shown in the Figure. Under conditions with a low PCI, the alloy coatings of GA and ZnNi to a pure zinc coating changes depending on the CCT conditions. The PCI dependency of the corrosion resistance of the coatings is shown in the Figure. Under conditions with a low PCI, the alloy coatings of GA and ZnNi behave as if they were thick GI and EG coatings. When PCI is around 20, the corrosion resistances of GA 45 g/m² and ZnNi 30 g/m² are equivalent to those of GI 140 g/m² and GI 60 g/m², however the protection periods by the coatings were short under those conditions. As PCI increases, the corrosion resistance of GA and ZnNi tends to be consistent with that of GI and EG with the same coating thickness. This reproduces the fact that the coating thickness is more crucial than the alloy composition under conditions with PCI close to that of the actual vehicle. In order to secure a good correlation with the actual environment, a corrosion test must have a PCI value close to that of the use environment and correctly reproduce the effect of existing alloy coatings on perforation corrosion.

3.4. Influence of Specimen Configuration

Test coupons for CCT have various shapes depending on the purpose of the evaluation. For perforation corrosion, test coupons with a crevice are used to simulate lapped portions of automotive parts. In most cases, the specimens have an intentional bare metal area in the crevice and a wide crevice gap, since it is believed that these controlled conditions lead to less variation of the test results. However, they do not necessarily reflect the structures of actual automotive parts. If the crevice at the lapped portion is wide, the inside will be covered by electrodeposition, and a bare metal area will not be formed in the crevice. Therefore, the influence of the specimen configuration on perforation corrosion was investigated. The corrosion resistance of zinc and zinc alloy coated steels was evaluated by using two types of test coupons with different configurations. One was prepared by overlapping two plates directly without an intentional gap (configuration A). The other had the bare metal area in the crevice and a wide crevice gap of approximately 300 µm (configuration B). The bare metal area was the surface of the zinc or zinc alloy coating without phosphating and electrodeposition.

Figure 8 shows a comparison of the corrosion appearances with configuration A and B after 60 cycles of the SAE J2334 test.34) With configuration A, red rust covered the entire surface of the specimens with thin coatings, however thicker coatings tended to suppress the occurrence of red rust, and white rust of the coating remained. With this test coupon confirmation, the alloy composition of the existing coatings did not have a significant impact on corrosion prevention. The tendency observed in this evaluation is similar to the corrosion experienced in actual automotive parts. On the contrary, in the evaluation with configuration...
B, the occurrence of red rust on the ZnNi coated steel was much smaller compared to the other coatings. Thus, the alloy composition of the coatings is considered to be more significant than the coating thickness when the specimens have the wide crevice and bare metal area.

Figure 9 shows the influence of the coating thickness on perforation corrosion with the two configurations. The coating thickness dependency of corrosion on pure zinc coatings, EG and GI is represented by the regression line and curve. With both configurations, an increase in the coating thickness improves corrosion resistance. However, the corrosion depth of the pure zinc coatings was deeper with configuration B than with configuration A. The larger crevice and bare surface in the crevice tended to significantly accelerate corrosion of EG and GI. As shown in Fig. 8, the corrosion depth of ZnNi was remarkably suppressed and was approximately one-third of the corrosion depths of EG and GI. Contrary to this, with configuration A, the corrosion depths of ZnNi and GA fall on the regression line obtained from EG and GI, which implies that the coating thickness is the dominant factor determining perforation corrosion resistance. In order to evaluate corrosion resistance in actual automotive parts, specimens that reproduce the effect of the coating thickness, including existing alloy coatings, must be used for CCT evaluations. Therefore, the intended wide crevice and bare metal area in the specimen should be avoided in order to obtain an appropriate evaluation.

4. Conclusions

Corrosion of coated steel sheets in vehicles used in different regions was analyzed quantitatively. Obvious suppression of corrosion by the zinc coating until the steel substrate started to corrode was confirmed in actual use environments, which is similar to the results in the previous literature. Severe corrosion was observed in Europe, while corrosion in Thailand was milder than that in the snowy regions, in spite of the high temperature and relative humidity in Southeast Asia.

Accelerated corrosion tests were employed to evaluate the corrosion resistance of several types of coated steels for automobiles. In some cases, different test conditions showed significant disagreements in the test results. In order to assess the correlation of CCT with corrosion of actual vehicles, the Perforation Corrosion Index, PCI, which is calculated by the corrosion rate ratio of steel and zinc, was introduced. Although the PCI values calculated for actual vehicles were 75 to 120, some CCT showed much lower PCI values than those of the actual vehicles. Zinc alloy coatings such as GA and ZnNi tend to show better corrosion resistance under low PCI conditions, giving results similar to those for GI and EG with heavy coating weights. CCT must have PCI values close to those obtained from actual automotive parts to enable reliable evaluations that reproduce the corrosion phenomena which occur in actual use environments. In addition, test coupons without an intentional wide crevice and bare metal surface are preferable for perforation corrosion evaluations.
REFERENCES
1) F. O. Wood: Corrosion 78, Paper No. 7, NACE International, Houston, TX, (1978).
2) R. Dietz and C. Strobl: SAE Technical Paper No. 862029, SAE International, Warrendale, PA, (1986).
3) S. Sagimoto: Proc. 4th Int. Conf. on Zinc and Zinc Alloy Coated Steel Sheet, (GALVATECH’98), ISIJ, Tokyo, (1998), 64.
4) S. Suzuki: Proc. 20th Annual Conf. of Japan Association of Corrosion Control, Japan Association of Corrosion Control, Tokyo, (2000), 83.
5) A. Ando, J. Uchida, H. Entani, C. Kato, H. Kuroda, T. Sato, M. Shimizu, S. Fujita, A. Miyasaka, Y. Morimoto and M. Yamashita: Tetsu-to-Hagané, 89 (2003), No. 1, 3.
6) K. Murata: 186th Corrosion and Protection Symp., JSCE, Tokyo, (2017), 4.
7) K. Sygusa: J. Surf. Finish. Soc. Jpn., 53 (2002), No. 5, 7.
8) E. Okada and H. Hosono: J. Surf. Finish. Soc. Jpn., 55 (2004), No. 11, 25.
9) K. Miki, K. Shimogori, H. Satoh, K. Ikeda, S. Nomura and M. Terada: Tetsu-to-Hagané, 72 (1986), 1090.
10) S. Kurokawa, T. Ban, K. Yamato and T. Ichida: Tetsu-to-Hagané, 72 (1986), 1111.
11) S. B. Lyon, G. E. Thompson and J. B. Johnson: ASTM special technical publication, No. 1134, ASTM, West Conshohocken, PA, (1992), 20.
12) F. M. Androsch, K. Kosters and K.-H. Stellnerber: Stahl Eisen, 121 (2001), No. 6, 37.
13) S. Fujita: 186th and 187th Nishiyama Memorial Seminar, ISIJ, Tokyo, (2005), 127.
14) N. LeBozec, N. Blandin and D. Thierry: Mater. Corros., 59 (2008), 889.
15) JASO M609: 1991, Material and surface treatment - Corrosion test method for automotive materials.
16) SAE J2334: 1998, Cosmetic corrosion lab test.
17) L. A. Roadabush, D. C. McCune and H. E. Townsend: ASTM special technical publication, No. 1238, ASTM, West Conshohocken, PA, (1995), 61.
18) H. E. Townsend and D. C. McCune: SAE Technical Paper, No. 970734, SAE International, Warrendale, PA, (1996), 53.
19) VDA 233-102: 2013, Cyclic corrosion testing of materials and components in automotive construction.
20) F. Zhu, B. Rendahl and D. Thierry: Br. Corros. J., 35 (2000), No. 3, 195.
21) N. LeBozec, N. Blandin and D. Thierry: Mater. Corros., 59 (2008), No. 11, 889.
22) N. LeBozec and D. Thierry: Mater. Corros., 61 (2010), No. 10, 845.
23) T. C. Simpson, A. W. Bryabt, G. Hook, R. J. Swinko and R. W. Millar: Corrosion 95, Paper No. 394, NACE International, Houston, TX, (1995).
24) M. Uchida, S. Kurokawa, K. Mohizuki and N. Morito: CAMP-ISIJ, 7 (1994), 1540.
25) M. Nakazawa, Y. Miyoshi and D. Davidson: Corrosion 95, Paper No. 375, NACE International, Houston, TX, (1995).
26) B. Rendahl: Corrosion 98, Paper No. 741, NACE International, Houston, TX, (1995).
27) S. Fujita and H. Kajiyama: Zairyō-to-Kankō, 50 (2001), 115.
28) S. Umezawa and T. Mitani: 44th Symp. on Reliability and Maintainability (R&MS), Union of Japanese Scientists and Engineers, Tokyo, (2014), 171.
29) W. Honda, K. Nishimura, K. Hayashi, F. Yamazaki, K. Yuasa and I. Inoue: CAMP-ISIJ, 9 (1996), 475.
30) K. Sasai, A. Mabuchi, S. Fujita, H. Kajiyama and M. Yamashita: CAMP-ISIJ, 9 (1996), 474.
31) P. Leematawekool and U. Uchigata: Proc. Int. Pacific Conf. on Automotive Engineering, Vol. 1, Society of Automotive Engineers of Japan, Tokyo, (1995), 327.
32) S. Fujita and D. Mizuno: Corros. Sci., 49 (2007), 211.
33) D. Mizuno, K. Hoshino, S. Otsuka and S. Fujita: Zairyō-to-Kankō, 60 (2011), 202.
34) D. Mizuno, K. Hoshino, S. Otsuka, S. Fujita and N. Hara: Corrosion, 71 (2015), No. 1, 92.
35) N. Mizuno: Proc. 11th Int. Conf. on Zinc and Zinc Alloy Coated Steel Sheet, (GALVATECH 2017), ISIJ, Tokyo, (2017), 553.
36) H. Sato, K. Shimogori, H. Nishimoto, K. Miki, K. Ikeda, M. Iwai, H. Sakai and S. Nomura: Tetsu-to-Hagané, 72 (1986), 1098.
37) E. Almeida and M. Morcillo: Surf. Coat. Technol., 124 (2000), 169.
38) D. Davidson, L. Thompson, F. Lutze, B. Tiburcio, K. Smith, C. Meade, T. Mackie, D. McCune, H. Townsend and R. Tuszyński: SAE Trans., 112 (2003), No. 6, 1236.
39) M. Kiyama: 106th and 107th Nishiyama Memorial Seminar, ISIJ, Tokyo, (1985), 101.
40) S. Wakanaka and M. Nishihara: Sumitomo Met., 41 (1989), No. 2, 11.
41) D. Davidson, L. Thompson, F. Futze, B. Tiburcio, K. Smith, C. Meade, T. Mackie, D. McCune, H. Townsend and R. Tuszyński: SAE Special Publication, Corrosion Prevention SP-1770, Paper No. 2003-01-1238, SAE International, Warrendale, PA, (2003), 45.
42) M. Strom, G. Strom and G. Strannhage: Proc. Eurocorr 2006, Nederlands Corrosie Centrum (NCC), Zoetermeer, (2006), 25.
43) ISO 8407: 2009, Corrosion of metals and alloys - Removal of corrosion products from corrosion test specimen.