Assessment and Application Technologies for Automotive Materials (Perforation) —Techniques for Corrosion Resistance and Perforation Feedback for Automotive Steel Materials—[†]

FUJITA Sakae[*1]   KAJIYAMA Hiroshi[*2]   KATO Chiaki[*3]

Abstract:

The effect of zinc and zinc alloy coated steel sheets on cosmetic corrosion and perforation corrosion in actual automobiles and the relevant corrosion mechanisms were studied. The main factor affecting cosmetic corrosion on the outside of outer panels was the coating weight of the Zn or Zn alloy coating rather than the type of coating. Perforation occurred in 6−7 years inside of door hems where Zn-rich primer coated steel panels were used, whereas perforation corrosion life was more than 14 years in galvanized steel sheets with a 120 g/m² Zn coating weight in lapped side-sills. Measurements of the perforation depth and analysis of the composition of the iron rusts formed on automobile bodies in North America showed that the perforation corrosion process in hot-dip galvanized steel sheets can be divided into 4 stages. The period during which Zn corrosion products control corrosion of the steel substrate plays a very important role in determining the period until perforation occurs in automobile bodies in regions where road deicing salt is used.

1. Introduction

In North America and Northern Europe, deicing salt is spread on roads in winter to secure automotive traffic safety. With increasing use of salt, automobile corrosion caused by deicing salt became manifest and was taken up as a social problem in the 1970s. Ironically, by causing corrosion in automobiles, use of deicing salt became a factor reducing the traffic safety it was intended to secure. In response, various corrosion-resistance quality targets for automobile bodies were established in the United States, Canada, and Northern Europe, including the Canada Code I (1978), Canada Code II (1981), Nordic Code (1983), and so-called 10-5-2-1 target of the U.S. Big Three (General Motors Corp., Ford Motor Corp., DaimlerChrysler Corp., 1989), and corrosion-resistance countermeasures for automobiles were actively adopted in regions where deicing salt was used. Recently, a "12-year guarantee against rust" was proposed by European automakers, and requirements for automotive corrosion-resistance quality in Europe and the United States have become increasingly strict. On the other hand, in Japan, the area where spiked tires are used has increased annually since 1990, and the amount of deicing salt spread on roads has increased rapidly in the last ten years, creating a corrosion environment for automobiles as severe as that in Europe and the United States.

In response to these trends, structural improvements in automobiles and development of chemical conversion coating and paint coating technologies and new coated steel sheets have been carried out to meet corrosion-resistance quality targets. JFE Steel also developed a variety of new zinc alloy coated steel sheets for automotive use, and among commercialized products alone, has

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[*1] Dr. Eng.,
Senior Researcher General Manager,
Coated Products Res. Dept.,
Steel Res. Lab.,
JFE Steel

[*2] Senior Researcher Deputy Manager,
Coated Products Res. Dept.,
Steel Res. Lab.,
JFE Steel

[*3] Ph. D.,
General Manager, Coated Products Res. Dept.,
Steel Res. Lab.,
JFE Steel

approximately 10 types of sheets, including Zn electro-galvanized steel sheets, Zn-Fe electrogalvannealed steel sheets, Zn-Ni alloy-coated steel sheets, organic composite coated steel sheets, and galvannealed steel sheets.

To investigate the actual effects of automotive corrosion-resistance technologies in regions where deicing salt is used, corrosion surveys of actual automobiles are conducted periodically in Europe and the United States, and have made relatively clear the respective corrosion resistance levels by automaker, the effects of using Zn and Zn alloy coated steel sheets, and the effectiveness of chemical conversion coating processes in improving corrosion resistance. However, the influence of the type of corrosion-resistant steel sheet, the effect of the coating weight, and the relevant corrosion mechanisms had not been clarified.

Therefore, beginning in the second half of the 1980s, JFE Steel carried out research on the effect of various types of corrosion-resistant steel sheets in preventing cosmetic corrosion and perforation corrosion and the relevant corrosion mechanisms by recovering automobiles which had used various Zn and Zn alloy coated steel sheets for extended periods for test purposes, as well as automobiles which had actually been used in regions of North America where deicing salt is employed. This paper describes the thinking on corrosion resistance in corrosion-resistant steel sheets at JFE Steel, centering on research results based on analyses of actual automobiles.

2. Current Status of Corrosion Testing for Automotive Steel Sheets

The salt spray test (SST) has generally been employed in corrosion testing of metal materials for many years. Although no automakers currently use the SST as the main standard for material evaluation in corrosion testing of automotive steel sheets, this method was formerly used as the basis for corrosion testing of automotive steel sheets. JFE Steel investigated the growth of the blister width (scribe creep) in various types of painted steel sheets which were produced by automotive electrodeposition coating in the SST and Okinawa Seashore exposure test, as shown in **Fig. 1**,[1] and demonstrated quantitatively that the SST does not reproduce actual environments. In actual environments, scribe creep is greatest on painted steel sheets with a cold rolled steel sheet (CRS), and is substantially prevented by Zn coating. However, in the SST, scribe creep is greatest with Zn coating. This is attributed to the fact that the sheet surface is constantly wet in the SST, but in contrast, the material is subject to cyclical wet and dry periods in actual environments, and the wet period is comparatively short. Because the SST does not repro-
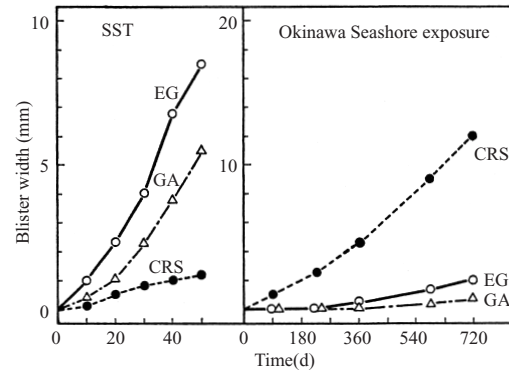

Fig. 1[1] Growth of the blister widths in the SST and Okinawa Seashore exposure

duce the corrosion of automobiles in regions where deicing salt is used, automakers have independently developed and standardized corrosion testing methods in each company.[2,3]

3. Corrosion-Resistance Effect of Coated Steel Sheets for Automotive Use in Actual Automobiles

3.1 Cosmetic Corrosion

In 1987, JFE Steel and a Japanese automaker jointly manufactured automobiles using various types of Zn and Zn alloy coated steel sheets for test purposes. These vehicles were used for 8 years at the raw material berth at JFE Steel's East Japan Works (Keihin District). The effect of the type of corrosion-resistant steel sheet and the coating weight on corrosion resistance in automobiles was investigated, and the relevant corrosion mechanisms were analyzed.[5,6] **Figure 2**[6] shows the relationship between scribe creep on the painted outer panel surfaces of the test automotive bodies and the coating weights of various type of corrosion-resistant steel sheets. As can be understood from the figure, use tests of actual automobiles revealed that alloying of the Zn coating with Fe or Ni has little effect on the painted corrosion resistance
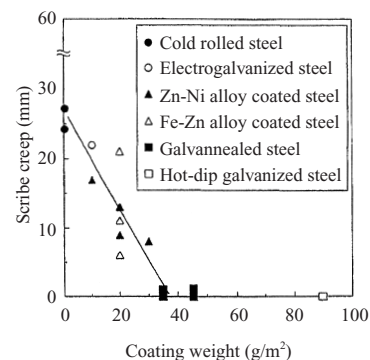

Fig. 2[6] Relationships between scribe creep and coating weight after actual 10 years use at the seaside of Kawasaki City in Japan

of the outer panel surface of the automobile body, and the effect of the coating weight is the controlling factor.

3.2 Perforation Corrosion

Perforation corrosion proceeds from the inner side of automotive outer panels to the outer side. Thus, when perforation corrosion is discovered by visual inspection, repair is extremely difficult. Perforation corrosion is considered the most important problem in automotive corrosion resistance. **Photo 1**[5,6] shows the cross section of a door hem in an automobile which was used for 5 years in a part of North America where deicing salt is employed. Here, in the door hem, a zinc rich primer (ZRP; film thickness: 8−10 μm) was applied on the inner surface of the outer panel, and a CRS was used as the inner panel. **Figure 3**[5,6] shows the corrosion depth profile at the inner surface of the outer panel (surface where ZRP was applied) and the inner panel (CRS) in the same part. It should be noted that the corrosion depth in the inner panel is a value corresponding to 1/2 of the total reduction in sheet thickness (because corrosion affects both sides of the inner panel). As is clear from the fig-
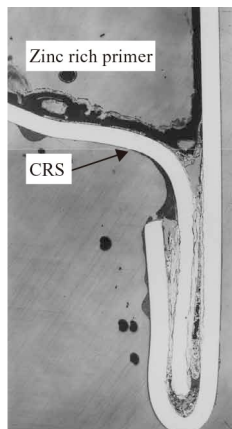
ure, during a 5-year use period, corrosion has progressed at the inner surface of the outer panel and at the lapped portion of the steel sheets in the inner panel. The lapped portions of steel sheets in a test automobile (including lapped portions in hem parts) were disassembled, the paint film was peeled off, and the corrosion products were removed. The corrosion depth was then obtained from the difference with the sheet thickness in normal parts, and an extreme value analysis (double exponential probability) of the maximum corrosion depth occurring in each part was carried out using the Gumbel distribution shown in Eq. (1).

$$F(x) = \exp\left\{-\exp\frac{-(x-\lambda)}{\alpha}\right\} \quad\cdots\cdots\cdots\cdots\cdots (1)$$

Here, x is the maximum corrosion depth at each location, λ is a location parameter (the mode of the maximum depth of corrosion occurring at each location), and α is a scale parameter. **Figure 4**[6] shows the results when the maximum corrosion depth occurring at each location on the inner surface of the outer panel in the door hem was plotted in Gumbel probability plots of the maximum depth occurring at each location. It can be understood that both the location parameter and the scale parameter increase as the use period increases. This means that the distribution of the maximum corrosion depth shifts to the large side (increase in location parameter) and deviation increases (increase in α) as the use period is extended. **Figure 5**[6] shows the mode of the maximum depth of corrosion occurring in each part when analyzed by extreme value statistics (double exponential probability) for the Gumbel distribution. Assuming a sheet thickness of 0.8 mm, the perforation corrosion life of the zinc rich primer in the outer panel of the door hem was estimated at 6−7 years, and the perforation corrosion life of a hot-dip galvanized steel sheet with a heavy coating weight (120 g/m²) in a lapped side-sill part (outer) was estimated at more than 14 years.

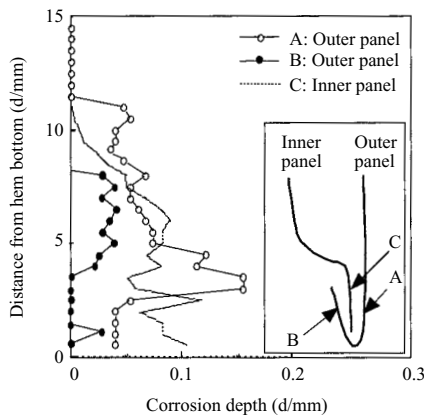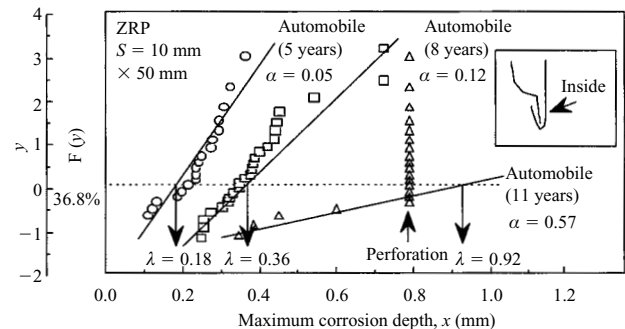Photo 1[6] Cross section of door hem in automobile used in North America for 5 years

Fig. 3[6] Corrosion depth profiles in the crevice of lapped portion of door hem in automobile used in North America for 5 years

Fig. 4[6] Gumbel distribution of maximum corrosion depth measured in the crevice of door hem (zinc-rich primer type coating) in automobiles used for 5 years, 8 years, and 11 years respectively
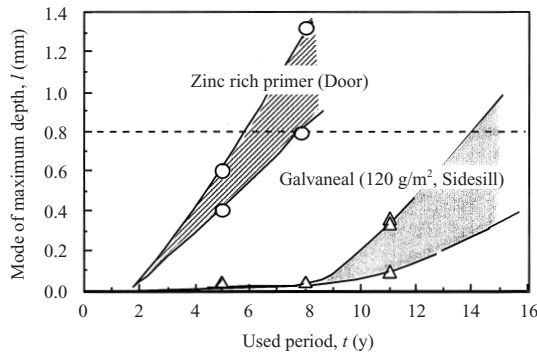
Fig. 5[6)] Estimation of maximum corrosion depth in the crevice of lapped panels of side sill (galvaneal) and door hem (zinc-rich primer) using double exponential probability

4. Corrosion Mechanism of Coated Steel Sheets in Automotive Environments

4.1 Cosmetic Corrosion Mechanism

Photo 2[6)] shows the results of observation of the progress of substrate corrosion which grew under the paint coating (underfilm corrosion) on automotive outer panels used for 8 years at the raw material berth at JFE Steel's East Japan Works (Keihin District). Prior to the test, the paint surface on the outside of the outer panel was artificially damaged with a cutter knife. From the photographs, filiform corrosion progressed in the CRS, but filiform corrosion did not occurred on the hot-dip galvanized steel sheet or galvannealed steel sheet. Thus, it can be understood that a Zn or Zn alloy coating prevents the growth of underfilm corrosion by preventing the occurrence of filiform corrosion.

4.2 Perforation Corrosion Mechanism

Corrosion of unpainted Zn coated steel sheets is generally divided into three stages, a corrosion process in which the Zn coating covers the entire surface and corrosion is caused by the Zn metal itself, a process in
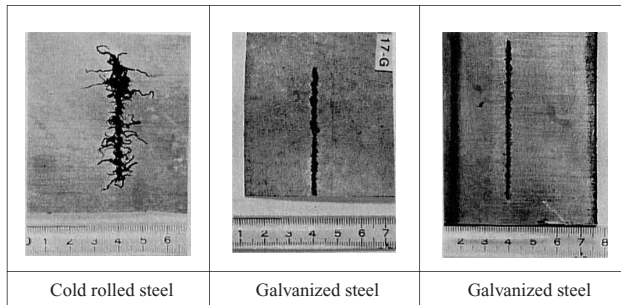
which the substrate metal is exposed and metallic Zn sacrificially corrodes the steel substrate, and a process in which the steel substrate corrodes. However, in the side sill made from galvanized steel sheets (coating weight: 120 g/m²), spotty red rust occurred partially in the crevice in the lapped panels beginning after 5 years of use, but growth of the red rust was controlled even after 8 years of use. In other words, even after initiation of corrosion of the steel substrate, corrosion of the steel is controlled for a certain period. Therefore, the corrosion process of Zn coated steel sheets in lapped steel panels of automobiles was divided into the four stages shown in **Fig. 6** ($\tau_1 - \tau_4$ indicate corrosion periods).[6)]

Stage 1: Stage in which the coating film of the corrosion-resistant steel sheet covers the entire surface and this coating film corrodes. (τ_1)

Stage 2: Stage in which the coating film has been partially consumed and the coating film sacrificially corrodes the steel substrate. (τ_2)

Stage 3: Stage in which the substrate steel sheet corrodes but corrosion is restrained. (τ_3)

Stage 4: Stage in which the substrate steel sheet corrodes at the same rate as in uncoated steel. (τ_4)

(1) Stage 1, 2

In the crevice in a lapped side-sill made from hot-dip galvanized steel sheets (coating weight: 120 g/m²), red rust occurred locally at approximately 5 years of use, and it can therefore be understood that the process of sacrificial corrosion of Zn is complete. Accordingly, the corrosion period ($\tau_1 + \tau_2$) of Stages 1 and 2 in galvanized steel sheets (coating weight: 120 g/m²) is approximately 5 years, which is roughly 1/3 of the total sheet life of about 14 years.

$$\tau_1 + \tau_2 \fallingdotseq 5 \text{ (years)} \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

Based on the corrosion period in Stage 4 (5 years) and the thickness of the steel sheet, the corrosion rate of the steel substrate is 0.78 mm/5 years. Assuming that Zn is corroded sacrificially by the same amount of electricity as in corrosion of iron, the corrosion rate attributable to sacrificial corrosion of Zn can be
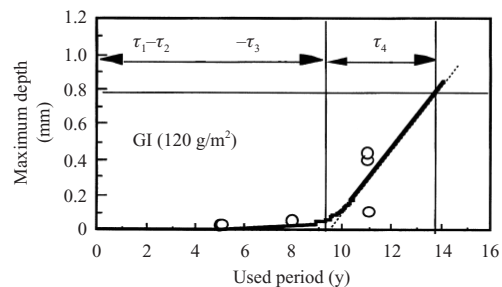

Photo 2[5,6)] Appearance of scab corrosion (where the paint was removed) on the upper surface of CRS, GI coated steel outer panel surfaces of the automobile body after 8 years use at the seaside of Kawasaki City in Japan

Fig. 6[5,6)] Schematic corrosion process in the crevice of lapped panels in automobiles

calculated at approximately 1 424 g/m² · year.

If the corrosion rate of the Zn coating in Stage 1 is v_1 (g/m² · year), the function given by the following equation is materialized between the coating corrosion rate and the coating weight.

$$\tau_1 \cdot v_1 + 1\ 424\ \tau_2 = 120\ (g/m^2) \quad\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

Because $\tau_1 \cdot v_1 > 0$, the following function is materialized for the sacrificial corrosion protection period of the coating, τ_2.

$$\tau_2 < 0.08\ (year) \quad\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (4)$$

Furthermore, the following function is materialized for the corrosion period of the Zn coating itself, τ_1.

$$4.92 < \tau_1 < 5.0\ (years) \quad\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

In other words, assuming that Zn corrodes sacrificially by an amount equivalent to the corrosion rate of the steel substrate, it is considered that the combined corrosion period of the two is supported almost completely by the corrosion period of the coating itself, τ_1, and the period of the sacrificial corrosion protection process in the corrosion process as a whole is short.

(2) Stage 3

The fact that corrosion of the steel substrate is controlled by the existence of Zn corrosion products has been reported in an example concerning a Zn-Fe coated steel sheet.[8] As the corrosion prevention mechanism in that case, it is explained that the corrosion environment becomes alkali due to the stable formation of basic zinc chloride ($ZnCl_2 \cdot 4Zn(OH)_2$), and corrosion of the steel substrate is inhibited by the change to this alkali environment. The present authors conducted a test simulating a lapped part which was packed in advance, before the corrosion test, with iron corrosion products and ZnO and $ZnCl_2 \cdot 4Zn(OH)_2$ detected in the crevice in the side-sills of recovered automobiles.[5,6] The lapped test piece comprised a CRS on one side, and placed on this, an acrylic sheet sandwiched between two sheets of polyethylene film (thickness: 40 μm). The crevice in the lapped part was packed uniformly with one of α-FeOOH, β-FeOOH, γ-FeOOH, Fe_3O_4, ZnO, or $ZnCl_2 \cdot 4Zn(OH)_2$ powder samples, or with an equivalent mixture of two of these substances, to a total weight of 0.3 g. A corrosion test was then performed under cyclical corrosion test conditions of immersion in a 5 mass% NaCl aqueous solution (25°C, 1 hour), followed by standing indoors (25°C, 23 hours). After performing the corrosion test for 20 cycles or 40 cycles, the corrosion products which

had formed in the crevice in the lapped test pieces were sampled, and quantitative analysis of the iron corrosion products was performed by X-ray diffraction using a JFE Steel internal-standard technique.[9] The reduction in mass due to corrosion of same test pieces was also measured. **Figure 7**[5,6] shows the mass loss of the corrosion test. As shown in the figure, in comparison with unpacked test pieces, corrosion was accelerated when the lapped portion was packed in advance with crystalline Fe(III) oxyhydroxides or with Fe_3O_4. However, when the lapped steel sheets were packed in advance with ZnO or $ZnCl_2 \cdot 4Zn(OH)_2$, corrosion of the steel substrate was reduced by approximately 1/3 to 1/2. Similarly, when $ZnCl_2 \cdot 4Zn(OH)_2$ was packed in the iron rust, it was found that corrosion was also reduced by approximately 1/3 to 1/2 in comparison with packing with simple iron rust. **Table 1**[5,6] shows the results of an analysis of the composition of the iron rusts in the
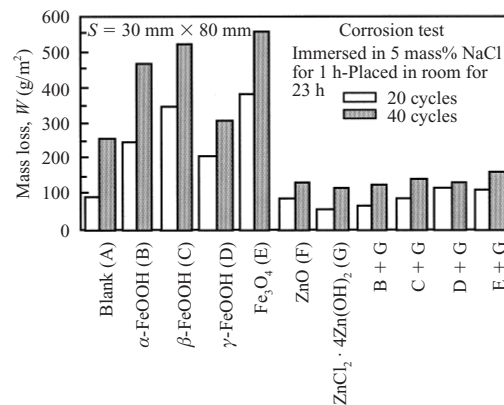

Fig. 7[5,6] Effect of zinc on corrosion of steel sheets in the crevices of lapped portions

Table 1[5,6] Composition of iron rust after 20 cycles of the test at the crevice part of the lapped steel sheets
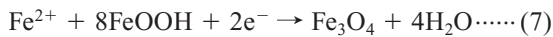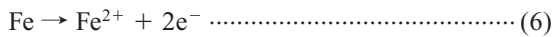
(mass%)

Packed products	α-FeOOH	β-FeOOH	γ-FeOOH	Fe_3O_4	Remainder
—	49	15	1	13	22
α-FeOOH	42	2	2	4	50
β-FeOOH	42	1	2	9	46
γ-FeOOH	25	5	17	7	46
Fe_3O_4	21	2	2	22	53
ZnO	0	0	0	0	100
$ZnCl_2 \cdot 4Zn(OH)_2$	0	0	0	0	100
α-FeOOH + $ZnCl_2 \cdot 4Zn(OH)_2$	34	0	0	0	66
β-FeOOH + $ZnCl_2 \cdot 4Zn(OH)_2$	0	15	0	0	85
γ-FeOOH + $ZnCl_2 \cdot 4Zn(OH)_2$	0	0	23	0	77
Fe_3O_4 + $ZnCl_2 \cdot 4Zn(OH)_2$	0	0	0	22	78

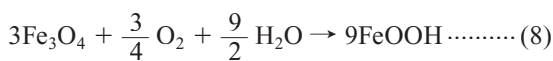— : No product was packed in the crevice of lapped panels.

20th cycle of the corrosion test. When no corrosion product of any kind was packed in the lapped steel sheets, α-FeOOH (49 mass%), β-FeOOH (15 mass%), γ-FeOOH (1 mass%), and Fe_3O_4 (13 mass%) formed. In contrast, in lapped portions packed with either ZnO or $ZnCl_2 \cdot 4Zn(OH)_2$, no α-FeOOH, β-FeOOH, γ-FeOOH, or Fe_3O_4 crystalline rusts formed, even though the steel substrate corroded, and the rust consisted entirely of amorphous iron rusts.

Atmospheric corrosion of iron and steel proceeds by a redox reaction between oxy-hydroxides of Fe (III) and iron corrosion products with valences lower than 3, such as Fe_3O_4.[8–21] Evans' model[11,12] is expressed by the following three reaction equations.

Wet processes (to anodic dissolution of iron and reduction rust):

$$Fe \rightarrow Fe^{2+} + 2e^- \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (6)$$

$$Fe^{2+} + 8FeOOH + 2e^- \rightarrow Fe_3O_4 + 4H_2O \cdots\cdots (7)$$

Dry process (air oxidation of iron rust):

$$3Fe_3O_4 + \frac{3}{4}O_2 + \frac{9}{2}H_2O \rightarrow 9FeOOH \cdots\cdots\cdots (8)$$

The composition of the iron corrosion products which formed in the lapped steel sheets is shown in Table 1. In samples containing no packed corrosion products, various types of crystalline Fe (III) oxy-hydroxides and Fe_3O_4 formed, but when ZnO or $ZnCl_2 \cdot 4Zn(OH)_2$ was packed, all of the formed iron rusts were amorphous. Based on the above facts, it is assumed that Zn-type corrosion products such as ZnO and $ZnCl_2 \cdot 4Zn(OH)_2$ suppress the redox reaction of iron rusts which are formed by corrosion of the steel substrate and thereby prevent corrosion of the steel substrate. Furthermore, because the corrosion-suppressing effect is the same with ZnO and $ZnCl_2 \cdot 4Zn(OH)_2$, it is thought that Zn ions are a factor in suppressing corrosion.

(3) Stage 4

The iron rusts which form in natural atmospheric environments are mainly α-FeOOH, β-FeOOH, γ-FeOOH, Fe_3O_4, and amorphous iron rusts. Based on the features of redox reactions involving various types of iron rusts and the composition of the iron rusts found in automobiles in North America, the authors classified the iron rusts detected in North American automobiles in a ternary phase diagram (I: α-FeOOH, II: $Fe_3O_4 + \gamma$-FeOOH, III: amorphous iron rusts $+ \beta$-FeOOH)[22], which considers the redox reactions of iron. The grounds for this are as follows. Among the rusts which were detected in North Amer-

ican automobiles, because α-FeOOH is the most thermodynamically stable in atmospheric environments and can be treated as a final oxy-hydroxide, in which the reduction reaction shown in Eq. (7) tends not to occur, it was separated from the other rusts. In contrast, because γ-FeOOH is reduced to Fe_3O_4 by the reaction shown in Eq. (7) in the wet process stage, γ-FeOOH and Fe_3O_4 were classified in the same rust group. In comparison with these rusts, β-FeOOH is easily changed to α-FeOOH or Fe_3O_4, but because the amount detected in the analysis of the North American automobiles was extremely small, it was classified as remainder products, together with amorphous iron rusts. **Figure 8**[6,23] shows a schematic diagram of the perforation corrosion process in lapped panels of Zn coated steel sheets, combining the results of the analysis of the corrosion process (Stages 1−4) in perforation corrosion and changes in the composition of iron rusts. First, after passing through the stages of corrosion of the Zn itself (Stage 1) and sacrificial corrosion of Zn (Stage 2), corrosion of the steel substrate begins locally in Stage 3. In an environment in which Zn corrosion products exist, iron rusts comprise mainly amorphous rusts, and some β-FeOOH forms as a crystalline iron rust. Zn corrosion products exist in this stage and have a suppressing effect on the redox reaction of iron rusts. Thus, during this period, β-FeOOH does not change to Fe_3O_4, which is a reduction product of β-FeOOH, α-FeOOH, which is the final iron rust composition, or γ-FeOOH. However, after the effect of Zn corrosion products in suppressing corrosion of the steel substrate is lost, corrosion of the substrate steel proceeds by formation of Fe_3O_4, α-FeOOH, and γ-FeOOH due to corrosion by the redox reaction of iron rusts.

If the corrosion-resistance period of coated steel sheets attributable to the existence of the 120 g/m² Zn coating film (Stage 1−3) is calculated at 9 years, and perforation by corrosion of the steel substrate occurs dur-
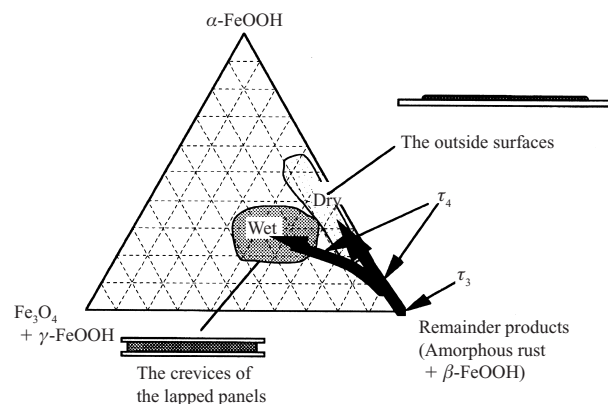

Fig.8[23] Change in rust composition and corrosion process of steel panels in automobile

ing the remaining 5 years, the corrosion rate of the Zn coating film is 13 g/m² · year, and that of the substrate steel sheet is 0.16 mm/year. If the corrosion rate is compared in terms of the reduction in sheet thickness, corrosion of the CRSs in lapped panels occurs at a corrosion rate approximately 1/80 that of Zn. Calculating for a coating weight of 70 g/m² on hot-dip galvanized steel sheets with a thickness of 0.7 mm, as generally used in the United States, the corrosion protection period from τ_1 to τ_3 is 5.4 years, and τ_4 is 4.5 years; hence, the period until perforation occurs can be predicted at approximately 10 years. This is considered to be the real corrosion-protection capability of Zn coated steel sheets in actual automobiles. In recent years reinforcements have been installed inside side-sills in order to improve crashworthiness, and securing the electrodeposition coating film thickness has become a problem. However, if the electrodeposition coating film thickness used to date can be secured even after this structural modification, corrosion-resistance design at the above-mentioned life is considered possible.

5. Appropriateness of Corrosion Testing Methods

Because corrosion testing methods for automotive steel sheets have been standardized by each automobile company, study of standardization is continuing. Cosmetic corrosion testing methods for automobiles have been established under several standards in Japan and other countries. In Japan, JASOM 609-91 was established in 1991 as a standard for cosmetic corrosion testing for automotive use, and in 1999, SAE-J2334 was standardized by the Society of Automotive Engineers in the United States.[2] However, corrosion testing methods for lapped steel sheets have not yet reached standardization. JFE Steel verified corrosion testing methods which reproduce the corrosion phenomena in automobiles referring to the results of its investigation of actual automobiles. As indexes for examining the appropriateness of the reproducibility of test methods, JFE Steel compared (1) the corrosion rate ratio of coated steel sheets and the substrate steel sheet in lapped steel sheets in actual automobiles, which was obtained by a corrosion analysis of actual automobiles, and (2) the similarity of the iron corrosion products which formed in lapped steel sheets. As a result, among the corrosion testing methods which have currently been standardized by public institutions, it was judged that SAE-J2334 is a practical test method with high reproducibility of the corrosion phenomena which occur in actual automobiles, both in cosmetic corrosion testing and as perforation corrosion testing.

6. Conclusion

Automobiles used in a seashore area in Japan and in parts of North America where deicing salt is employed were recovered, and the perforation corrosion life of corrosion-resistant steel sheets was analyzed by visual inspection of corrosion and extreme value statistics (double exponential probability), revealing the following:

(1) Underfilm corrosion on the outer surface of automotive outer panels proceeds by filiform corrosion in cold rolled steel sheets. However, application of a Zn coating prevented filiform corrosion. Corrosion was reduced by increasing the coating weight independent of the type of coating.

(2) The corrosion resistance of heavy coating weight hot-dip galvanized steel sheets (Zn coating weight: 120 g/m²) is satisfactory, and perforation corrosion life was approximately 14 years in lapped side-sill parts.

(3) The corrosion process in Zn coated corrosion-resistant steel sheets can be divided into a stage in which the coating film of the corrosion-resistant steel sheet covers the entire surface and this coating film corrodes (Stage 1), a stage in which the coating surface has been partially lost and the coating film sacrificially corrodes the substrate steel (Stage 2), a stage in which corrosion of the substrate steel sheet is restrained by Zn corrosion products (Stage 3), and a stage in which the steel substrate corrodes at the same rate as uncoated steel (Stage 4).

(4) In Stage 3, ZnO and $ZnCl_2 \cdot 4Zn(OH)_2$ inhibit the formation of crystalline iron rusts. A model experiment demonstrated that the redox reaction of iron rusts is suppressed when these corrosion products form in lapped steel panel parts, controlling corrosion of the steel substrate. Stage 3 plays a critical role in corrosion protection in heavy coating weight Zn coated steel sheets.

(5) The reproducibility of the corrosion phenomena which occur in actual automobiles by automotive corrosion test methods was examined based on an analysis of corrosion in actual automobiles, as described above.

With global alliances among automakers, automotive corrosion test methods are being actively studied. JFE Steel is confident that verification of the correctness of this company's proposals will be useful in the development of automotive corrosion test methods with higher reproducibility of corrosion phenomena in actual automobiles.

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