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Some passenger vehicles, which were manufactured in 1989 and 1991 and used around Detroit area for 5 years, were submitted for a corrosion investigation. Panels forming the body shell have been classified into five categories with respect to the corrosion environment and were evaluated their cosmetic corrosion and perforation corrosion. It is confirmed that exterior panels made of two-side zinc coated steel sheet have excellent performance in cosmetic corrosion. It is shown that the corrosion depth at lapped parts under low humid condition decreases with increase in zinc coating weight. With precoated panels of zinc coating of more than 45 g/m2, the degree of corrosion was slight. It was found that the usage of zinc coating steel sheet improves the anti-corrosion performance of vehicles.

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Some passenger vehicles, which were manufactured in 1989 and 1991 and used around Detroit area for 5 years, were submitted for a corrosion investigation. Panels forming the body shell have been classified into five categories with respect to the corrosion environment and were evaluated their cosmetic corrosion and perforation corrosion. It is confirmed that exterior panels made of two-side zinc coated steel sheet have excellent performance in cosmetic corrosion. It is shown that the corrosion depth at lapped parts under low humid condition decreases with increase in zinc coating weight. With precoated panels of zinc coating of more than 45 g/m^2, the degree of corrosion was slight. It was found that the usage of zinc coating steel sheet improves the anti-corrosion performance of vehicles.

1 Introduction

Zinc-coated steel sheets and corrosion protection systems are used to improve the anticorrosion performance of motor vehicle body shells in severe corrosive environments in which deicing salts are sprayed on roads, as in North America. As a result of an extension of the anticorrosion guarantee period, the percentage of zinc-coated steel sheets forming the vehicle body has been increased and improved paint and corrosion protection systems, as shown in **Table 1**, have been adopted[1,2]. The percentage of zinc-coated steel sheets forming the vehicle body shell, which was about 10% around 1985, increased to about 40% around 1988 and to more than 70% in the 1990s.

Table 1 Improvements in corrosion preventive specifications

Material	Precoated steel sheet
Paint	Dip type zinc phosphate pretreatment Cathodic electrodeposition painting Anti-chipping primer Underfloor protection wax
Protection schemes	Adhesive (Hem flange) Sealer (Lapped together) Wax injection

There have been many studies of the corrosion mechanism of zinc-precoated steel sheets used in vehicle bodies[3,4] and investigations of monitor vehicles exposed in Okinawa and North America to automotive corrosion[5–9]. In order to evaluate the ten-year guarantee against rusting and perforation and to estimate the corrosion life of zinc-coated steel sheets, Kawasaki Steel conducted investigations of corroded parts of 1989 model cars, whose bodies contained 55–70% zinc-coated steel sheets, and 1991 model cars, whose bodies contained more than 80% of these sheets. All of these vehicles had been operated in North America.

Because the panels within a vehicle body are welded and assembled into it after forming, the corrosive environment differs from one body part to another depending on the design of the formation of weld points and box members. For this reason, even with the same zinc-coated steel sheet, the degree of corrosion differs according to the body part, the shape of lapped parts and whether or not corrosion protection systems are in place. In this paper, the corrosion behavior of specific areas is classified into five categories in terms of dampness conditions and design, and the anticorrosion performance of zinc-coated steel sheets in each corrosive environment is evaluated.

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Table 2 Vehicles investigated

	Vehicle-A (1989)	Vehicle-B (1989)	Vehicle-C (1989)	Vehicle-D (1991)	Vehicle-E (1991)
Body style	2 doors	4 doors	2 doors	2 doors	4 doors
Period of running	1989–1995 5 years	1989–1995 5 years	1989–1995 5 years	1991–1997 5 years	1991–1997 5 years
Odmeter	211 628 km	190 563 km	283 264 km	185 709 km	181 632 km

2 Experimental Procedure

2.1 Selection of Vehicles

Five vehicle types were selected for the experiment. These vehicles were made with hot-dipped galvannealed steel sheets, organic composite coating steel sheets (base: zinc-nickel alloy electroplated steel), and electrogalvanized steel sheets. Telephone surveys were conducted with the aid of the new car registrations in the State of Michigan. Form the results of the survey, 30 vehicles of each of the 5 types were selected from vehicles meeting the following conditions:

(1) All of the vehicles had to be 1989 models.
(2) All of the vehicles had to be manufactured in Japan.
(3) All of the vehicles had to have been operated primarily in the State of Michigan.
(4) Each vehicle had to have been run at least 80 000 miles.
(5) None of the vehicles had experienced significant body damage.

For these 150 vehicles, automotive body corrosion was visually inspected. For each type, the vehicle which showed the severest degree of corrosion (5 vehicles in all) was investigated. An outline of these investigated vehicles is given in **Table 2**.

2.2 Survey Method

The visual inspections of the automotive body corrosion of the 150 vehicles were carried out on the basis of a survey form[7]. There were 12 vehicle parts that were surveyed, including hoods, fenders and doors. The condition of corrosion was classified according to the following four items: the degree of visible rust (%), number of scabs, width of blisters (mm), and degree of perforation. In addition, a separate investigation was carried out to determine whether or not corrosion protection was added by automobile dealers.

The degree of corrosion in the investigated vehicle parts was evaluated on the basis of the following criteria:

(1) Degree of visible rust: 0%, 0–1%, 1–10%, 10–50%, >50%
(2) Number of scabs: Counting the number of corroded portions
(3) Grade of corrosion attack: 0 = no corrosion, 1 = insignificant corrosion, 2 = superficial corrosion, 3 = heavy (deep) corrosion, 4 = perforation
(4) Creep: Maximum creep length (mm)

2.3 Method of Dismantling Vehicles

The engines, wheels and suspensions of the recovered vehicles were dismounted and the bodies in white panels forming the vehicle body shell were obtained. Each of these bodies in white panels was divided into right and left portions. After that, all welds in the driver's half (left side) were removed and this half was dismantled to investigate corroded portions.

2.4 Method of Evaluating Perforation Corrosion

For evaluation, the panels were dismantled into inner and outer parts taken from the vehicle.

To evaluate perforation corrosion, the corroded portions were cut from the panels. The corrosion depth of corroded portions of panels was measured using a point micrometer after paint films and corrosion products were removed with a film remover and a 5% citric acid solution, respectively. The average of the ten largest corrosion depths was used to evaluate perforation corrosion.

2.5 Classified Corrosion of Specific Areas

The behavior of cosmetic corrosion and perforation corrosion in motor vehicles was classified for evaluation according to the corrosive environment (degree of wetness/dampness) and design shown in **Fig. 1**. Portions of cosmetic corrosion were classified into lapped part, outer panel (chipping corrosion), and hem flange. Portions of perforation corrosion were divided into hem flange (in which corrosion is generally considered to be severe), a lapped part with a box structure in which humidity is high because of stagnant water (side sill, member and rear wheel), and other lapped parts.

3 Results of Experiment and Discussion

3.1 Results of Survey

The percentage of three types of 1989 model cars with corroded portions in each body part by visual inspection is shown in **Fig. 2**. Here, there were 90 vehicles in all, i.e., 30 of each type.

Among all of the vehicles (90 vehicles), the corroded portions observed in the largest number of vehicles were door hem lower corners (49%), door hem flanges (38%) and side sills (bottom rails) (36%). These portions showed a great difference in the percentage of vehicles with corroded portions, which depends on the vehicle

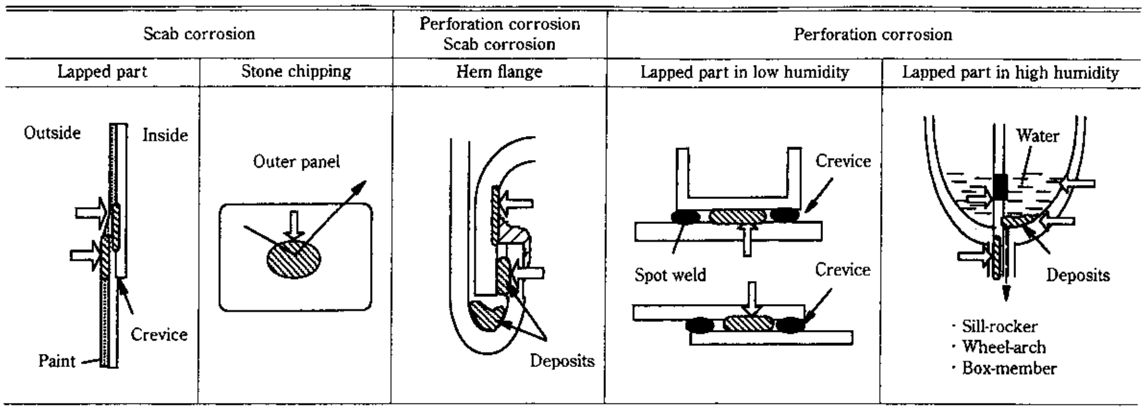

Fig. 1 Schematic design of corrosion of specific area of parts classified into a design and humid condition

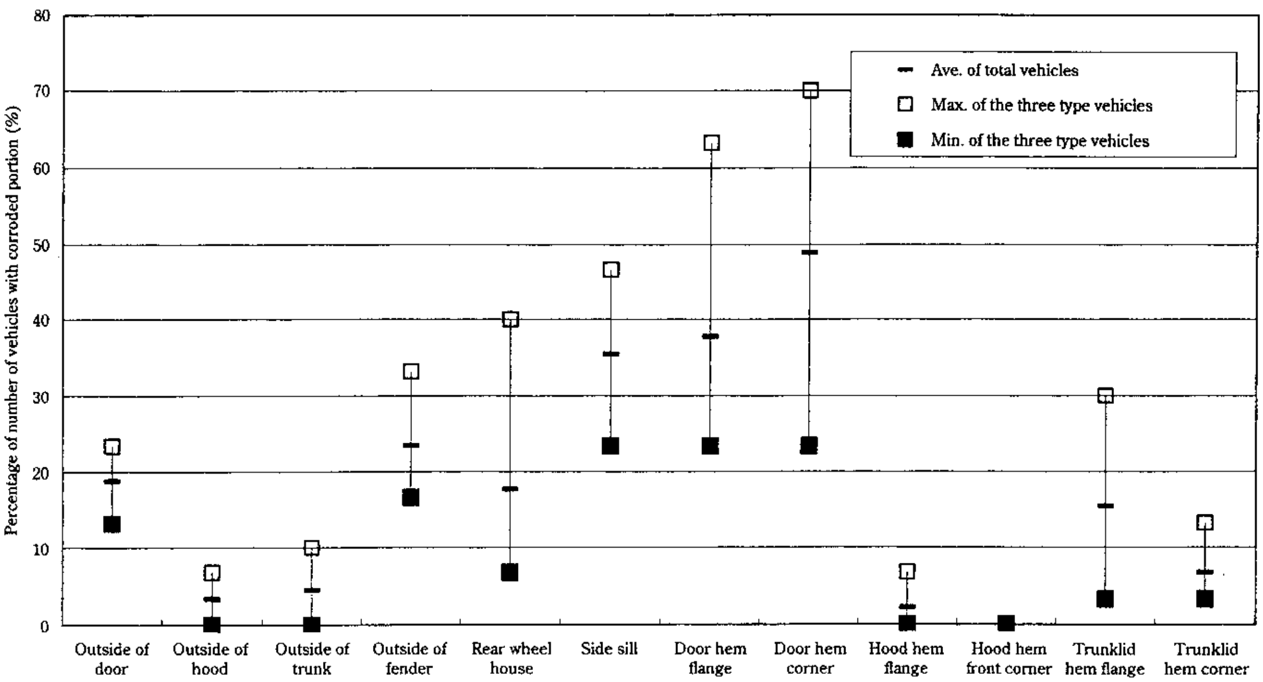

Fig. 2 Comparison of survey results at each of body part

type, from other portions. The difference in design and corrosion protection systems probably affected this corrosion behavior.

3.2 Results of Visual Inspection

3.2.1 Cosmetic corrosion

The number of scab-corroded parts in each body part before the dismantling is shown in **Table 3**. The number of scab-corroded parts classified by the corrosive environment is shown in **Fig. 3**. As is apparent from Fig. 3, scab corrosion was observed most frequently in lapped parts. This corrosion was under film corrosion initiated in lapped parts. Damage by chipping was observed in hoods, doors, fenders, etc. Scab corrosion with removed paint was observed in only some of the vehicles.

The data shown in Fig. 3 were rearranged with respect to the effect of combinations of types of steel sheets on the occurrence of scab corrosion and the effect of zinc coating on the occurrence of scab corrosion in chipped portions (**Fig. 4**). Although cold-rolled steel sheets alone and the combination of a non-precoated surface (including a one-side precoated steel sheet) and a zinc-coated surface showed the same number of scab-corroded parts, this number decreased to about half for zinc-coated steel sheets alone. In other words, in the corrosive environment of lapped parts of exterior panels, the anticorrosion performance of zinc-coated steel sheets could not manifest itself sufficiently when a non-precoated surface was

Table 3 Number of scab corroded parts

Corrosion type	Parts	Vehicle-A	Vehicle-B	Vehicle-C	Vehicle-D	Vehicle-E
Lapped part	Pillar outer	2	5	4	1	4
	Side sill outer	3	1	3	1	1
	Quarter panel	4	5	2	2	0
	Rear end panel	5	2	2	0	2
Stone chipping	Hood outer front	4	0	0	0	0
	Door outer	3	0	1	0	0
	Front fender	2	0	0	0	1
Hem flange	Hood hem	2	0	0	0	0
	Door hem	1	3	1	0	0
	Trunklid hem	2	1	0	2	0
Number of scab corroded parts		28	17	13	6	8

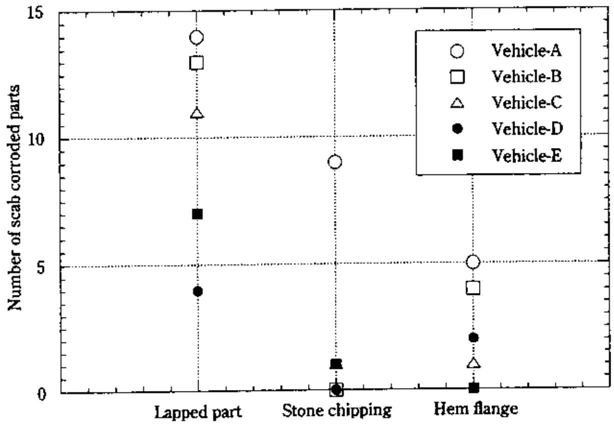

Fig. 3 Scab corrosion at each of the part

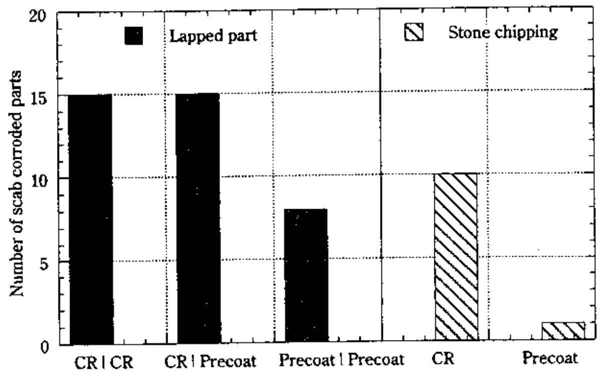

Fig. 4 Effect of zinc coating on anti-scab corrosion

present, whereas two-sided zinc coating showed excellent performance in cosmetic corrosion. Zinc coating had a great effect on the scab corrosion in chipping portions and the number of scab-corroded parts of a zinc-coated surface was 1/10 that of a non-precoated surface. In other words, two-sided zinc coating was effective in preventing the occurrence of scab corrosion in body panels.

3.2.2 Perforation corrosion

The body parts where perforation corrosion occurred and the number of perforation-corroded parts are shown in **Table 4**. There were 10 perforation-corroded parts in lapped parts without a box structure, but 23 in lapped parts with a box structure. From this, it is clear that perforation corrosion was accelerated in the box structure. This may be because water does not easily flow out when it once enters a box structure, that is, water and road salts which accelerate perforation corrosion are present in the box structure for a long time.

The number of perforated panels as a function of zinc coating weight is shown in **Fig. 5**. In lapped parts without a box structure, perforation corrosion occurred in cold-rolled steel sheets and zinc-coated steel sheets with coating weight of less than 20 g/m^2, whereas perforation corrosion was not observed in zinc-coated steel sheets with coating weight of at least 30 g/m^2. Even in very damp box members, the number of perforated panels showed a tendency to decrease with increasing zinc coating weight. However, some perforation corrosion was observed even in zinc-coated steel sheets with coating weight of more than 30 g/m^2.

Figure 6 shows the relationship between corrosion depth and zinc coating weight in lapped parts without a box structure. It is apparent that corrosion depth decreases with increasing zinc coating weight. In lapped portions without a box structure in a low dampness condition, the effect of zinc coating weight can be observed, and zinc-coated steel sheets with coating weight of at least 45 g/m^2 show excellent anticorrosion performance.

Figure 7 shows the relationship between zinc coating weight and corrosion depth in lapped parts with a box structure in a high dampness condition. In contrast to lapped parts without a box structure, there was no clear tendency for corrosion depth to decrease with increasing zinc coating weight. In box members, perforation corrosion was observed even in zinc-coated steel sheets with a coating weight of 100 g/m^2. When the condition of heavily perforated corrosion was investigated, mud was observed in the corroded portions.

Table 4 Comparison of a performance of perforation corrosion

	Vehicle-A (1989)	Vehicle-B (1989)	Vehicle-C (1989)	Vehicle-D (1991)	Vehicle-E (1991)
Lapped part in low humidity	Cowltop outer (CR) Front pillar outer (CR) Front pillar inner-up (CR)	Center pillar outer (CR)	Cowltop inner (CR) Strut house panel (precoated) Front side member (precoated) Rear floor pan (2) (CR) Rearend panel (CR)		
Lapped part in high humidity	Dash side (CR) Front floor pan (precoated) Side sill outer (precoated) Side sill inner-rein-forcement (precoated) Rear wheel house outer (precoated) Rear wheel house inner (precoated)	Quater panel (3) (precoated) Rear wheel house outer (precoated) Rear wheel house inner (CR)	Rear floor side member (3) (CR) Side sill outer (precoated) Side sill inner-ext (precoated) Rear wheel house outer (precoated) Rear wheel house inner (CR)	Sidepanel (side sill) (precoated)	Front pillar outer-low (CR) Center pillar outer (CR) Center pillar rein-forcement lower (CR) Rear wheel house outer (precoated)
Number of perforation occurred parts	9	6	13	1	4

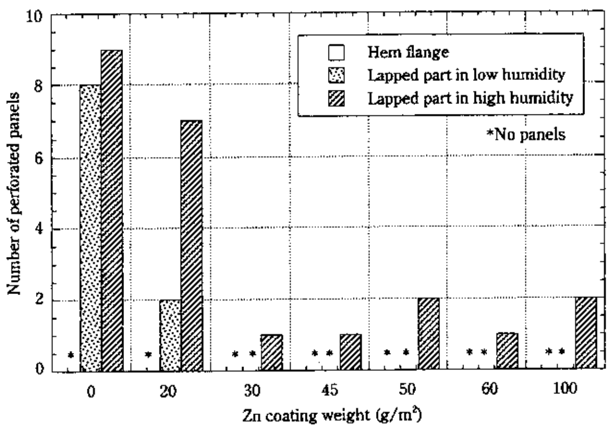

Fig. 5 Effect of zinc coating weight on anti-perforation corrosion

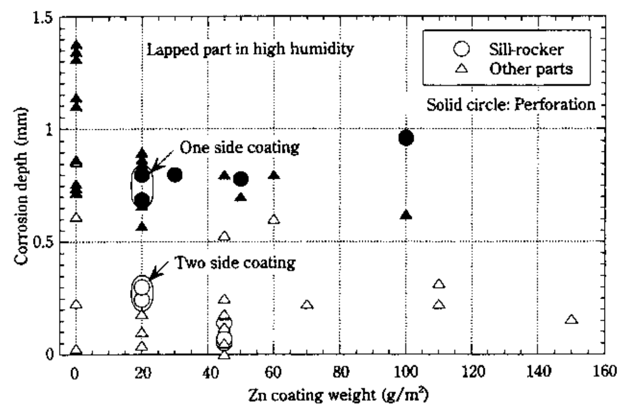

Fig. 7 Relation between Zn coating weight and corrosion depth at the lapped part in hight humidity of field vehicles for 5 years

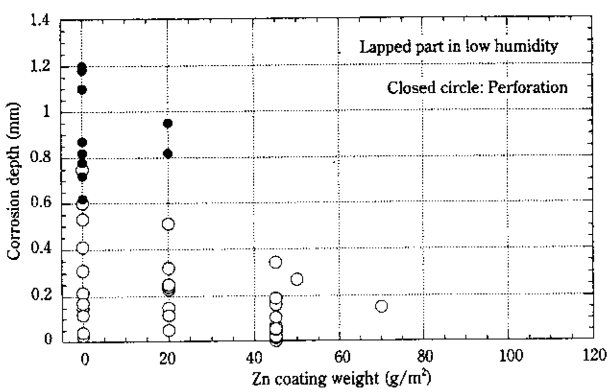

Fig. 6 Relation between Zn coating weight and corrosion depth at the lapped part in low humidity of field vehicles for 5 years

The results of a chemical analysis of the mud adhering to panels are shown in **Table 5**. It was found that the mud contained chlorine ions (Cl^-), which accelerate corrosion as anions, and an alkaline metal (Na^+) and an alkaline-earth metal (Ca^{2+}) as cations. Nothing that road deicing salts including sodium chloride and calcium chloride are used in the cold districts of North America in winter, Sakauchi[10] reports that the water and mud containing chloride ions are splashed by motor vehicle wheels at the time of thawing and adhere to body panels, causing corrosion.

The chemical analysis of the mud which adhered to the dismantled vehicles was in agreement with the chemical analysis of deicing salts. This means that the chlorine ions in the mud originated from the deicing

Table 5 Quantitative analyses of the mud adhered to panel

(mass%)

	Cl	Na	Ca	Mg	Fe	Zn
Front side member outer	8.16	—	—	—	—	—
Front side member outer-rear	1.50	1.31	6.96	2.13	5.38	2.35
Front side member inner	16.90	10.86	7.27	1.55	2.35	0.61
Front floor side member-front	1.84	—	—	—	—	—
Front floor side member-rear	1.51	0.98	8.92	2.32	2.53	4.22
Side sill outer	3.26	1.42	8.92	2.46	3.52	7.74
Center pillar inner lower	1.51	1.02	8.60	2.18	3.06	7.79
Rear floor cross member	3.92	—	—	—	—	—
Rear wheel house outer	0.29	0.86	7.96	2.04	1.79	0.12
Rear wheel house inner	0.07	0.83	7.16	1.82	5.42	0.79

salts sprayed on roads. It is concluded that the water and mud containing deicing salts splashed by rear wheels enter the vehicle body, with the result that box members such as side sills are in a damp condition for a long period of time. The corrosive environment in which chlorine ions exist in a damp condition for a long time can be very severe for zinc-coated steel sheets.

As shown in Fig. 7, even in some two-side coated steel sheets with zinc coating weight of 20 g/m^2, perforation corrosion did not occur in a box member (lapped part between a sill and a rocker). Mud was not observed in the body panels, thus the lapped part with a box structure was not in a damp condition for a long time, in contrast to the body panels in which perforation corrosion occurred.

Incidentally, in body panels formed from one-side coated steel sheets with coating weight of 20 g/m^2 in which mud was not observed, perforation corrosion was observed in the lapped parts between sills and rockers which had been assumed to have not been in a humid condition for a long time. Thus, even in the same corrosive environment, two-sided coating may have a greater effect on perforation corrosion protection than one-side coating.

As shown in Table 4, perforation corrosion in the present survey did not occur in door hem flanges, despite the general belief that severe perforation corrosion occurs in hem flanges. In addition, it has been reported that in cold-rolled steel sheets without corrosion protection systems, perforation corrosion occurs after three years of use in North America (corrosion rate: 0.3 mm/y)[11,12].

Table 6 shows a summary of additional corrosion protection of the investigated vehicles. In almost all vehicle types, corrosion protection systems (adhesive, seam seal, injection wax) were used in door hem flanges and, they apparently were effective.

The relationship between corrosion depth in hem flanges and zinc coating weight is shown in **Fig. 8**. In zinc-coated steel sheets with zinc coating weight of 20 g/m^2, the corrosion depth in body panels with corrosion protection systems decreased. Further, a decrease in corrosion depth due to an increase in zinc coating weight was observed. The corrosion depth of cold-rolled steel sheets was about 0.4 mm, whereas that of coated steel sheets with zinc coating weight of more than 45 g/m^2

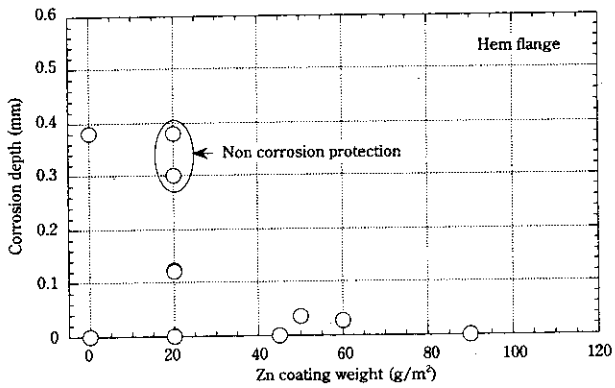

Fig. 8 Relation between Zn coating weight and corrosion depth at the hem flange of field vehicles for 5years

Table 6 Summary of additional corrosion protection

Protection schemes	Vehicle-A	Vehicle-B	Vehicle-C	Vehicle-D	Vehicle-E
Door hem-adhesive	○	×	○	○	○
Door hem-wax	○	×	○	○	○
Engine room-seam seal	×	○	○	○	○
Dash panel-seam seal	×	○	○	○	○
Under floor-seam seal	×	○	×	○	×
Under floor-wax (black)	×	×	○	○	○
Side sill + floor-seam seal	○	○	○	○	○
Wheel house-coat (black)	○	×	○	○	○
Wheel house-seam seal	○	○	○	○	○

○ : Add, × : Non

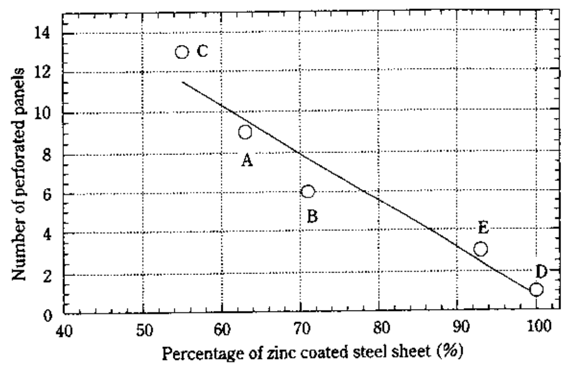

Fig. 9 Correlation between percentage of zinc coated sheet forming the vehicle body shell and number of perforated panels

was less than 0.1 mm.

It can be said that the use of zinc-coated steel sheets also has a great effect on the perforation corrosion of hem flanges. Excellent anticorrosion performance can be obtained by the combined use of zinc-coated steel sheets with coating weight of more than 45 g/m^2 and corrosion protection systems.

3.3 Effect of Percentage of Zinc-Coated Steel Sheets Forming the Vehicle Body Shell

Figure 9 shows the relationship between the percentage of zinc-coated steel sheets forming the vehicle body shell and the number of perforated panels. The number of perforated panels decreased with increasing percentage of zinc-coated steel sheets forming the vehicle body shell. It is clear that the anticorrosion performance of body panels was improved by the use of zinc-coated steel sheets. Such use also contributed greatly to the improvement of the anticorrosion performance of body panels although other corrosion protection measures (design, additional corrosion protection, improvement of paint systems) have also been effective.

4 Conclusions

The corroded parts of vehicles which had been operated for 5 years in North America were investigated. The cosmetic corrosion resistance and perforation corrosion resistance of zinc-coated steel sheets were evaluated by classifying the corrosion behavior according to body parts. The following findings were obtained.

(1) With respect to cosmetic corrosion resistance, the anticorrosion performance of zinc-coated steel sheets used in the lapped parts of exterior panels was not sufficient when a non-precoated surface was present, whereas it was greatly improved by two-side zinc coating. Furthermore, zinc coating also had a great effect on the cosmetic corrosion resistance of chipped portions.

(2) In lapped parts without a box structure, perforation corrosion resistance was improved by increasing the zinc coating weight. This was especially true when the coating weight was at least 45 g/m^2; perforation corrosion was not observed and excellent perforation corrosion resistance was obtained.

(3) In the box members of some of the investigated vehicle panels, chlorine ions considered to have originated from road deicing salts were present, indicating that these parts had been exposed to a humid environment for a long time. In box members, an improvement in the perforation corrosion resistance was obtained by the use of two-side coating in place of one-side coating.

(4) In the perforation corrosion resistance of hem flanges, the effect of corrosion protection systems was observed. The perforation corrosion resistance could be improved by increasing the zinc coating weight.

(5) The number of perforated panels of a whole vehicle clearly decreased with increasing percentage of zinc-coated steel sheets forming the vehicle body shell. The use of zinc-coated steel sheets helped to significantly improve anti-corrosion performance.

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