New Accelerated Corrosion Test "ACTE" for Zinc-Coated Steel Sheets Used in Electrical Appliances†

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Abstract:

Based on the actual corrosion behavior of electrical appliances and inadequacies of the conventional accelerated corrosion tests, which are the salt spray test (SST) and combined cyclic corrosion test (JASO M609-91), a new accelerated corrosion test for electrical appliances, "ACTE" (ACTE: Accelerated Corrosion Test for Electrical Appliances) was developed. A good correlation between ACTE and corrosion in actual environments was demonstrated. ACTE consists of a salt deposition process and cyclic wet/dry process. As distinctive features of ACTE, the test conditions simulate actual environments (use of artificial seawater, constant absolute humidity), and it is possible to estimate the corrosion life of materials in a wide range of use environments by obtaining dependency data on the main corrosion factors (amount of deposited sea salt, etc.) by varying the test conditions. ACTE makes it possible to appropriately evaluate the corrosion resistance of zinc-coated steel sheets with chromate-free coatings.

1. Introduction

Electrical appliances include white goods (air conditioners, washing machines, refrigerators), general electrical products (vacuum cleaners, rice cookers, microwave ranges, oil heaters, air purifiers, etc.), housing equipment (ventilation fans, gas devices, water heaters, etc.), and audiovisual and information technology devices (televisions, videotape players, personal computers, etc.). The use environments of these products are also diverse. Corrosion of electrical appliances can be broadly divided into corrosion of body panels and structural parts and corrosion of electronic components[1]. Painted steel sheets, chemical conversion coated steel sheets, and various types of zinc-coated steel sheets are used in great quantities in the body panels and structural parts of electrical appliances, and a wide variety of materials are used, corresponding to the type of product, the parts of the product, and the use environment[2,3].

Among recent developments affecting electrical appliances, the EU's Directive concerning Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment (RoHS Directive)[4] took effect in Feb. 2003, prohibiting the use of 6 substances, including hexavalent chromium (Cr(VI)) after July 1, 2006. In response, adoption of Cr(VI)-free (hereinafter referred to as chromate-free) Zn-coated steel sheets in electrical appliances is being promoted from the viewpoint of reducing the environmental load substances included in electrical appliances[5–12].

In order to appropriately evaluate the corrosion resistance of zinc-coated steel sheets with chromate-free coatings, which are a recent product with a short actual record of use, an accurate accelerated corrosion test based on actual use environments is necessary. If evaluations are carried out using test methods which have a low correlation with the actual environment, there may be cases where a material with adequate corrosion resistance for the intended use environment is not selected due to under-evaluation. Conversely, there is also a possibility that corrosion may occur before the product reaches its assumed design life due to selection of a material which does not show corrosion resistance in the actual environment.

The conventional methods used in evaluating the cor-

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rosion resistance of Zn-coated steel sheets for electrical appliances include standardized accelerated corrosion test methods such as the Salt Spray Test (SST)[13] and the Combined Cyclic corrosion Test (CCT)[14] and accelerated corrosion test methods established independently by appliance makers. Where the SST is concerned, it has been pointed out[15–18] that this test has a poor correlation with the corrosion behavior in actual environments, and there are cases in which the corrosion resistance ranking of materials being compared shows opposite results in the SST and actual environments. On the other hand, the correlation between the CCT and the actual corrosion behavior in use environments for electrical appliances had not necessarily been established. Moreover, as few reports concerning corrosion behavior in electrical appliances are available at present, the actual corrosion behavior of Zn-coated steel sheets used in electrical appliances and the corrosion environments for these materials had not been adequately clarified.

Therefore, envisioning expanded application of zinc-coated steel sheets with chromate-free coatings, JFE Steel and the Hitachi Research Laboratory, Hitachi, Ltd. jointly developed a new accelerated corrosion test method called ACTE (Accelerated Corrosion Test for Electrical Appliances) which has a high correlation with actual environments[19–28]. The new method was developed based on the actual corrosion behavior in Zn-coated steel sheets in electrical appliances and the inadequacies of the conventional accelerated corrosion test methods (SST; JASO M609-91, which is a type of CCT), to enable appropriate selection of Zn-coated steel sheets for electrical appliances, including chromate-free products. Details are described in the following.

2. Actual Corrosion Behavior in Electrical Appliances[19–23,25]

First, electrical appliances (air-conditioner outdoor units, washing machines, and refrigerators) were collected from the Main Island of Okinawa (Okinawa Pref.), Japan's Pacific Ocean coast (City of Choshi, Chiba Pref.), and the Sea of Japan coast (City of Niigata, Niigata Pref.), all of which are regions where salt attack is a problem, and from an inland area (City of Tsukuba, Ibaraki Pref.), where the effect of sea salt is slight, and the corrosion behavior in the Zn-coated steel sheets in these electrical appliances and the effect of the distance from the coast and amount of sea salt deposition were investigated in detail. **Figure 1** shows schematic diagrams of the locations of parts of the recovered electric appliances with high susceptibility to corrosion[19,20]. In the air-conditioner outdoor units (hereafter, referred to simply as air-conditioners), corrosion was observed at the air vents on the side cover and front

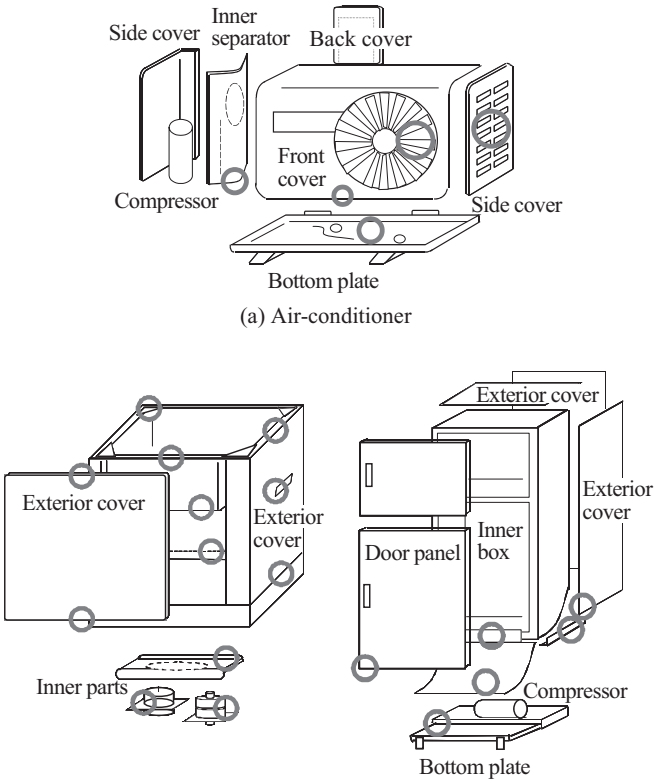

Fig. 1 Location of parts of electrical appliances with high susceptibility to corrosion[19,20]

cover, the upper side of the bottom plate, the edges of steel sheets, etc[19,25]. In the washing machines, corrosion was observed in the painted steel sheets at the edges of the exterior cover panels and around lapped portions, and in the chromate coated steel sheets used in interior parts[20,21]. In contrast to this, in the refrigerators, corrosion was limited to partial red rust at the bottoms of painted steel sheets used in the exterior cover panels in refrigerators with ages of 10 years or more[20]. The corrosion morphologies observed were occurrence of filiform corrosion on painted cold rolled steel sheets in the refrigerators collected from Okinawa and masses of fine paint film swelling in painted Zn-coated steel sheets in the air-conditioners collected from Okinawa[19,23,25]. The latter was a clearly different corrosion morphology from the blister corrosion (water-encapsulating swelling of the paint film) which is observed in the SST and similar tests.

An analysis of the relationship between corrosion of electrical appliances and the distance from the coast/amount of deposited sea salt revealed that, in air-conditioners, corrosion is more severe in air-conditioners sheltered under house eaves with limited exposure to rain in coastal areas, than in units installed in locations exposed to rain, and in inland areas, corrosion is generally slight in comparison with that in coastal areas[19,25]. Focusing on the corrosion of air-conditioners installed in sheltered locations under eaves in coastal areas, devia-

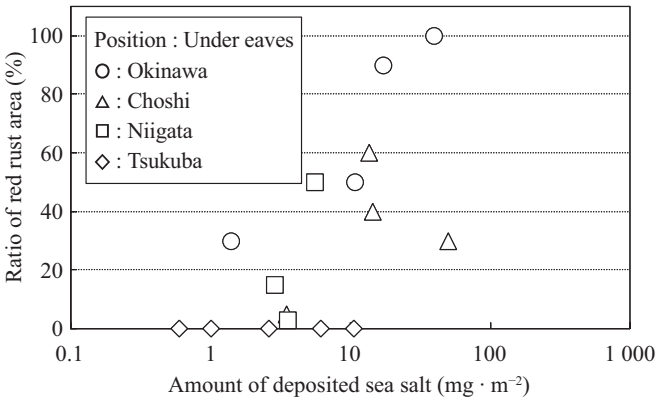

Fig. 2 Relationship between amount of deposited sea salt and corrosion of collected air-conditioners (air vent of side cover)[23,25]

tions were large and the effect of the distance from the coast was unclear. However, as shown in **Fig. 2**, when the results were arranged by the amount of deposited sea salt, it was found that the effect of the amount of salt deposition is large[25]. Similarly, with washing machines, an investigation of the relationship between the corrosion rate of painted steel sheets used in the exterior covers and the amount of deposited sea salt revealed that the amount of salt deposition also affects corrosion in washing machines[20,21]. On the other hand, corrosion was slight in the refrigerators collected from Okinawa Pref. in comparison with the air-conditioners and washing machines. However, it should be noted that the amount of sea salt deposited on the exterior covers of the refrigerators was also small, being less than 1 mg·m^{-2} (ref.19). Based on the above-mentioned results, as a parameter of corrosion in electrical appliances (air-conditioners, washing machines, and refrigerators), the amount of deposited sea salt is considered to have a large effect.

Furthermore, as shown in **Fig. 3**, monitoring of the temperature and relative humidity in the environments where these electrical appliances were used revealed

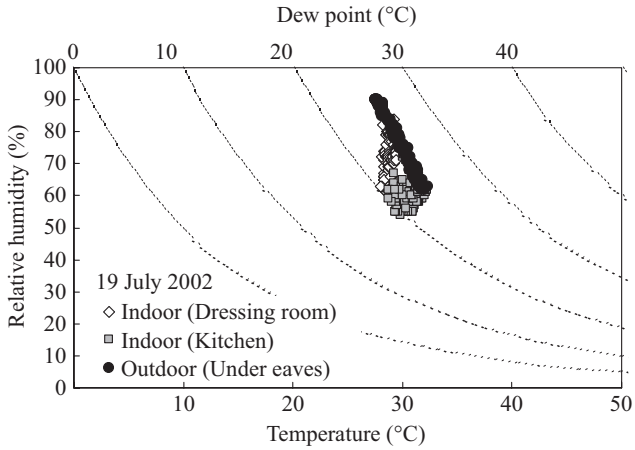

Fig. 3 Relationship between temperature and relative humidity in actual environment where electrical appliances were used

that changes in temperature/relative humidity follow the curve of the dew-point temperature; in other words, temperature and relative humidity changes occur under a condition in which the absolute humidity is substantially constant[23].

3. Development of New Accelerated Corrosion Test Method for Electrical Appliances "ACTE"[24–28]

3. 1 Features of New ACTE Test Method

Based on the results of the investigation of the corrosion behavior in electrical appliances in actual environments, the fact that the conventional accelerated corrosion test methods (SST; JASO M609-91, which is a type of CCT) have a low correlation with actual environments was confirmed, and a new accelerated corrosion test method, "ACTE," for Zn-coated steel sheets for electrical appliances which has a high correlation with actual environments was developed. **Figure 4** shows an example of the test conditions of the ACTE[24–28], and **Fig. 5** shows an illustration of the ACTE test method. The ACTE test conditions comprise (1) a process of periodically depositing sea salt containing chloride ions on the surface of the test specimen (salt deposition process) and (2) a repeated process of drying and wetting the test specimen by changing the temperature and relative humidity in an environmental testing device (cyclic wet/dry process). In the conventional accelerated corrosion tests (SST, JASO M609-91), specimens are sprayed with a 5 mass% NaCl solution, but in contrast, in the ACTE, salt deposition is performed by spraying or soaking the specimen with artificial seawater, considering the effect of airborne sea salt in the actual environment. The amount of deposited sea salt is set within a wide range, supposing corrosion environments ranging from coastal areas to the inland countryside and from outdoors to indoors. Moreover, as wet and dry conditions in the cyclic wet/dry process, a constant condition of absolute humidity is used, simulating the wet/dry cycle due to day-night temperature changes, and the cycle includes a certain transition period between the dry and wet stages in order to minimize deviations between various kinds of testing machines.

The new ACTE test method can also be used to estimate the corrosion resistance life of materials in a wide range of use environments by obtaining data on the dependency of the main corrosion factors (amount of deposited sea salt, etc.) by varying the test conditions. For example, it has now become possible to estimate the corrosion resistance (amount of corrosion, time to corrosion initiation, etc.) for a wide range of chloride

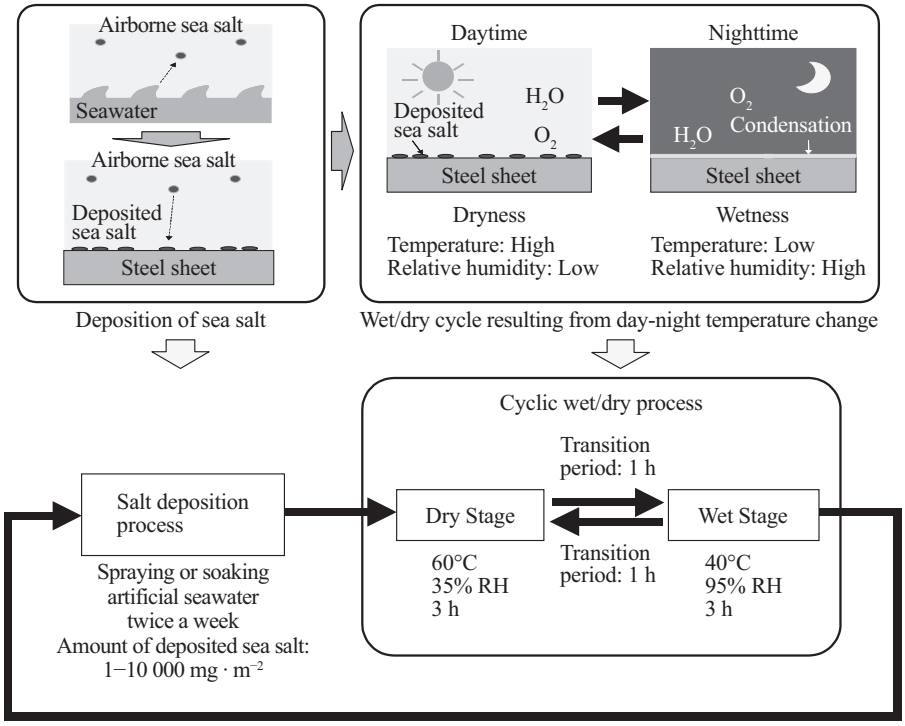

Fig. 4 Example of test conditions of new accelerated corrosion test “ACTE”[24–28]

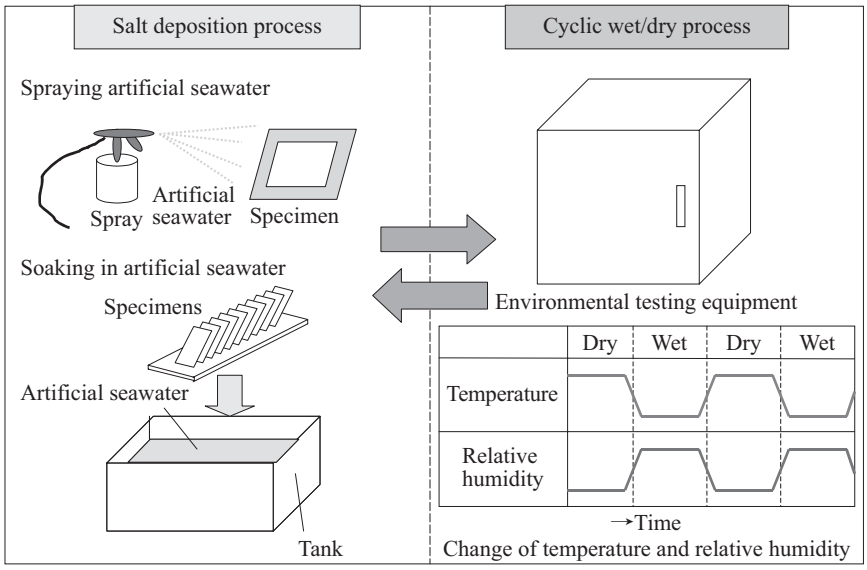

Fig. 5 Illustration of ACTE test method

amounts by obtaining dependency data for the effect of the chloride amount on the corrosion resistance of Zn-coated steel sheets. In this case, the corrosion resistance at low chloride amounts can be obtained from the relationship between the chloride amount and corrosion resistance by extrapolation based on the results of an evaluation at high chloride amounts. It is also possible to design the optimum corrosion resistance of materials corresponding to the use environment by investigating the dependency of the corrosion resistance of Zn-coated steel sheets on the Zn coating weight, paint film thickness, and similar factors.

3.2 Reproducibility of Actual Environments Using New ACTE Test Method

In order to verify the appropriateness of the evaluation results obtained with the ACTE test method, the reproducibility of actual environments was investigated by comparing the corrosion behavior in the ACTE and atmospheric exposure tests in Okinawa Pref.

As test specimens, painted steel sheets and chemical conversion coated steel sheets were used. Chromate-type pre-coated steel sheets (PCM: pre-coat metal), with hot-dip galvanized steel sheets (GI; coating weight: 30–90 g·m^{-2}) and a cold rolled steel sheet (CRS) as the

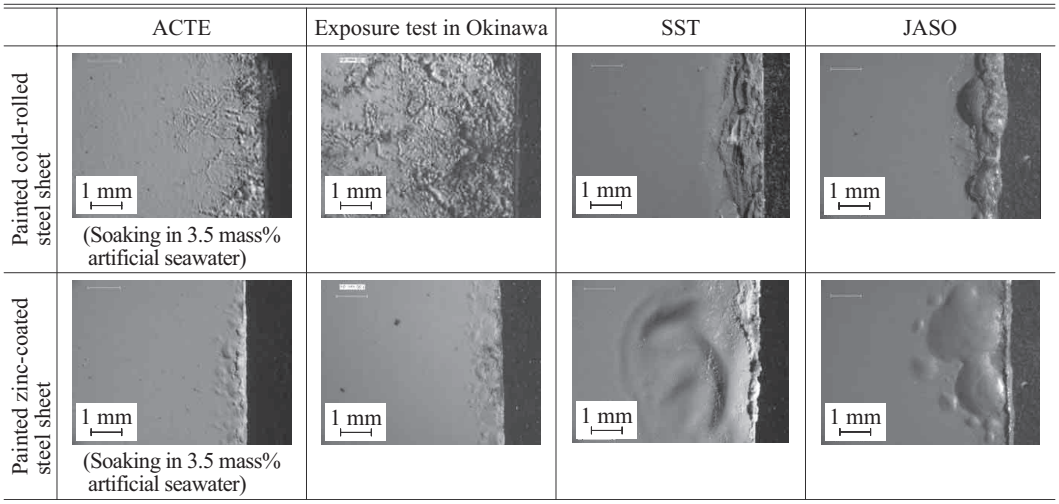

Photo 1 Comparison of corrosion morphology of painted steel sheets

types of substrates, were used as painted steel sheets. With the painted steel sheets, corrosion tests were performed after forming cut edges on the specimens. The zinc-coated steel sheets with chromate coatings and those with chromate-free coatings, with electrogalvanized steel sheets (EG: 20 $g \cdot m^{-2}$) as the type of substrate, were used as the chemical conversion coated steel sheets. The edges and the back of the specimens were sealed with corrosion-protection film.

The exposure test in Okinawa Pref. was conducted at a location approximately 1 km from the coast in Naha City. The average amount of airborne sea salt at the exposure site was 0.41 mdd ($mg \cdot dm^{-2} \cdot day^{-1}$). In the exposure test in Okinawa Pref., an exposure test in which the test specimens are protected from direct exposure to rain by a roof placed over the exposure rack (sheltered exposure) was performed in addition to a general exposure test which the test specimens are exposed to rain (open exposure). The average amounts of deposited sea salt with these respective types of exposure tests were 16 $mg \cdot m^{-2}$ for open exposure and 101 $mg \cdot m^{-2}$ for sheltered exposure. For comparison, the SST (JIS Z 2371) and JASO test (JASO M609-91), which is a type of CCT, were also performed. The test conditions in these respective tests were SST: continuous spraying with 5% NaCl solution at 35°C, and JASO test: repetition of a process comprising SST (35°C, 5% NaCl, 2 h) → Dry (60°C, 20–30% RH, 4 h) → Wet (50°C, >95% RH, 2 h) as one test cycle.

Photo 1 shows a comparison of the corrosion morphology which occurred on the painted steel sheets in the new ACTE test and the exposure test in Okinawa Pref. In the exposure test in Okinawa Pref., the corrosion morphology resembled that observed on the painted steel sheets in the electrical appliances (refrigerators, air-conditioners) collected from Okinawa, in that filiform corrosion formed on the painted cold-rolled steel sheets and fine swelling occurred on the painted Zn-coated steel sheets. Blister corrosion (water-encapsulating swelling of the paint film) was not observed with the latter type. In the ACTE, the same corrosion morphologies as in the actual environment were reproduced with both the painted cold rolled steel sheet and the painted Zn-coated steel sheet. On the other hand, with the conventional accelerated corrosion test methods (SST, JASO test), filiform corrosion was not observed on the painted cold rolled steel sheets, but blister corrosion was observed on the painted Zn-coated steel sheets. From this, it can be understood that these conventional tests displayed a low correlation with the actual environment from the perspective of the corrosion morphologies of the painted steel sheets.

Figure 6[27] shows a comparison of the results with

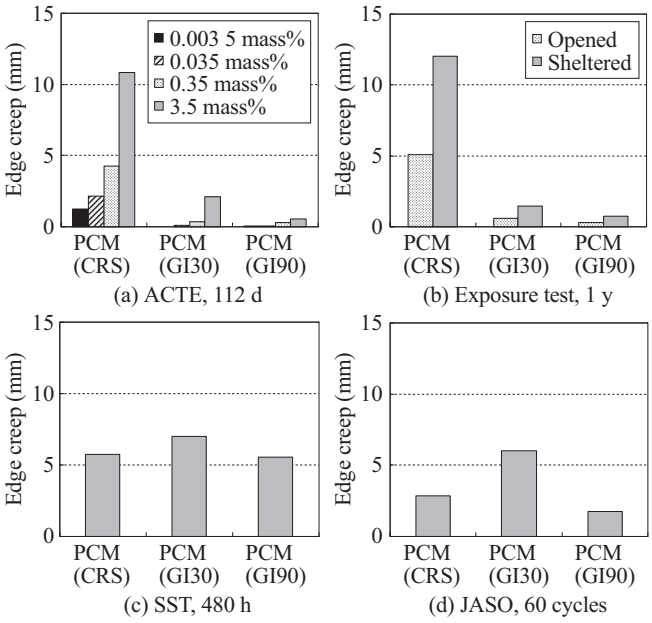

Fig.6 Comparison of corrosion from edges of painted steel sheets[27]

the new ACTE test method and the exposure test in Okinawa Pref. for edge creep from the cut edges of painted steel sheets. Here, the saltwater concentration used in the ACTE is the concentration of artificial seawater during immersion in saltwater. Both the ACTE and the exposure test in Okinawa Pref. confirmed that edge creep shows a tendency to decrease as the Zn-coating weight of the substrate steel sheet increases. In the exposure test in Okinawa Pref., edge creep was larger with sheltered exposure, in which the amount of deposited sea salt was relatively heavy, in comparison with open exposure. In the ACTE, edge creep tended to increase with the saltwater concentration, and as a tendency, this agreed with the behavior in the exposure test in Okinawa Pref. On the other hand, with the SST and JASO test, a reversal in the corrosion resistance rankings of the test materials was observed, demonstrating that these tests have low correlations with the exposure test in Okinawa Pref.

The corrosion area ratios of the various types of chemical conversion coated steel sheets, including chromate-free steel sheets, were compared in an exposure test in Okinawa Pref. (sheltered, 1 year) and various other types of corrosion tests. As a result, it was found that the ACTE showed a good correlation with the exposure test in Okinawa Pref., independent of the type of chemical conversion coating, but with both the SST and the JASO test, the corrosion resistance ranking did not agree with that in the exposure test in Okinawa[25].

These results confirmed that the new ACTE test method has a high correlation with actual environments from the perspectives of corrosion morphology, amount of corrosion, corrosion resistance ranking, and effect of chloride amount. On the other hand, since an early date, it has been pointed out that the results of evaluations by the SST show a low correlation with actual environments[15–18], and this research also found a low correlation with actual environments from the viewpoints of corrosion morphology and corrosion resistance ranking. The present research also confirmed that the results of evaluations by the JASO test, which is a type of CCT, have a low correlation with actual environments. In other words, particularly in evaluations of materials with a short actual record of use, such as chromate-free steel sheets, these results suggest that evaluation by the SST or JASO test may result in not selecting a material which possesses adequate corrosion resistance for its intended use environment due to under-evaluation of it corrosion resistance, or conversely, selecting a material which fails to display corrosion resistance in the actual environment. In the former case, the maker may select an uneconomical over-spec material, and in the latter, the product may fail due to corrosion before reaching its assumed design life. In contrast, application of the new ACTE method enables an accurate evaluation of chromate-free steel sheets based on the actual environment.

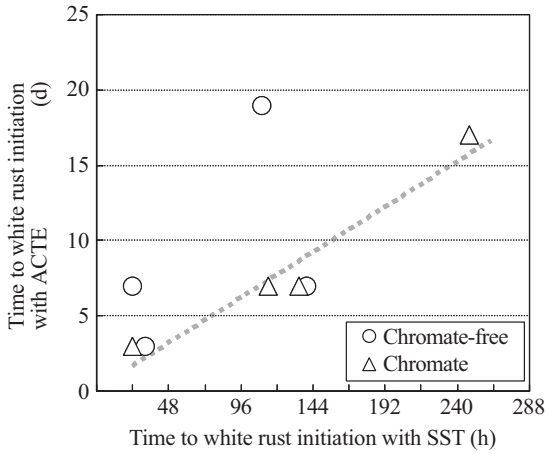

Fig. 7 Comparison of time to white rust initiation with ACTE and SST[24]

3.3 Examples of Evaluation of Corrosion Resistance of Chromate-free Steel Sheets by New ACTE Test Method

Figure 7[24] shows the results of a comparison of the new ACTE test method and the conventional SST for time to white rust initiation in chemical conversion coated steel sheets (chromate-coated and chromate-free). With the chromate-coated steel sheets, a certain degree of correlation was found between the ACTE and SST, but where the chromate-free steel sheets were concerned, the results tended to deviate from the correlation seen with the chromate-coated sheets, and in some cases, the corrosion resistance ranking of the materials was reversed. This suggests that it was possible to obtain evaluation results with a correlation with actual environments using the SST for chromate-coated steel sheets, but with chromate-free steel sheets, there is a possibility that evaluation by the SST may result in a corrosion resistance evaluation that does not reflect the actual environment.

4. Conclusions

(1) Based on the corrosion behavior in electrical appliances collected from various actual environments and the inadequacies of the conventional accelerated corrosion test methods, a new corrosion resistance test method called ACTE (Accelerated Corrosion Test for Electrical Appliances) was developed for Zn-coated steel sheets used in electrical appliances. The new method displays a high correlation with corrosion behavior in actual environments. Application of the new ACTE test method enables accurate evaluations of the corrosion resistance of Zn-coated steel sheets

used in electrical appliances, including chromate-free steel sheets.

(2) The conventional accelerated corrosion test methods (SST, JASO M 609-91) had a low correlation with corrosion in actual environments from the perspectives of the corrosion morphologies and corrosion resistance rankings of materials. Therefore, there is a danger that evaluations of chromate-free steel sheets by these methods may result in corrosion resistance evaluations which do not reflect the actual environment.

(3) With the new ACTE test method, it is possible to estimate the corrosion resistance life of materials in a wide range of use environments by obtaining dependency data for main corrosion factors (such as the amount of deposited sea salt, etc.) by varying the test conditions. It is also possible to design the optimum rust-prevention specifications of materials corresponding to the use environment of specific products.

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