Development of dense corrosion resistant coatings by an improved HVOF spraying process

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Abstract

For 6 years, we have developed corrosion resistant coatings to protect steel structures in the marine environment by using a thermal spray technique. This paper summarizes the major developments and results obtained. Such a coating requires primarily impermeability and secondarily homogenous and clean microstructure. In order to make denser and highly corrosion resistant coatings, we selected spray materials and improved fabrication processes. Hastelloy C was a suitable material for High Velocity Oxy-Fuel (HVOF) spraying to form corrosion resistant coatings because of its high resistance against thermal oxidation as well as seawater corrosion, especially crevice and pitting corrosion. An inert gas shroud system was attached with a commercial HVOF apparatus and this attachment increased the in-flight velocity of spray particles over 750 m s\(^{-1}\) and simultaneously suppressed oxidation significantly. In addition, some new methods were designed to evaluate the sprayed particle’s state and the coating properties with high accuracy and sensitivity. Thermal energy of in-flight spray particles was revealed by molten fraction of spray particles, determined by quantitative analysis of melted and unmelted particles captured in an agar gel. Through-porosity of the coatings with open porosity below 0.1% was determined by using Inductively Coupled Plasma analysis of dissolved substance from substrate through the penetrating path of the coatings. The coating of Hastelloy C nickel base alloy by the HVOF spraying with the gas shroud attachment had zero through-porosity and 0.2 mass% of oxygen content. The laboratory corrosion tests showed that the on-shroud Hastelloy C coating was comparable to the bulk material of Hastelloy C in terms of corrosion resistance. This coating, formed on steel, demonstrated an excellent protective performance over 10 months in the marine exposure test.

Keywords: High velocity oxy-fuel; Thermal spray; Gas shroud; Nitrogen; Flight velocity; Through-porosity; Oxygen content; Corrosion resistance; Seawater

1. Introduction

Nowadays in Japan, long service life over 100 years is often required of infrastructures because the environmental regulation and labor costs on repairing are expected to become increasingly severe and high hereafter. In order to obtain such a long lifetime, corrosion of structural steels is one of the problems to be solved. Especially in the marine environment, the structural steels are subject to severe corrosion damage because there are sea salt and water abundant to cause corrosion. Up to now, cathodic protection, thick anticorrosion paint and cladding have been mostly used for corrosion protection for marine corrosion. However, it is questionable whether these methods can provide 100 years’ service life without any maintenance.

Since 1995, we have researched and developed coatings of anticorrosion materials such as stainless steel and nickel base alloy. These types of coatings demand impermeable nature above all. This is because if a sprayed coating has a penetrable path to the substrate, the corrosive media such as seawater can permeate the coating beneath the splash zone of a marine structure and reach the interface between the coating and substrate. When a conductive solution contacts different conductive material, it forms a galvanic cell and a combination of the noble coating and the less-noble substrate accelerates substrate corrosion more than, for example, a bare substrate with the same surface area. As a coating method, we selected High Velocity Oxy-Fuel (HVOF) thermal spraying technique because we expected it to be able to deposit a dense metal coating with comparatively little change in the composition of sprayed...
materials during spraying. This high performance is caused by the characteristics of this technique that enable us to obtain sprayed particles with a supersonic speed over 500 m s\(^{-1}\) and with a comparatively lower temperature up to 2000 °C, compared to other conventional methods such as plasma spraying. The particles are heated and accelerated by a jet flame made from high-pressured mixture of oxygen and fuel. In many cases, a large portion of particles impinges to a target substrate in the semi-molten state. The impinged particles piled up to form the coating. The HVOF process is often used for coating hard materials of cermets such as WC–Co in order to increase wear resistance of the material surface.

In order to use this process to apply anticorrosion metal coatings, we improved coating fabrication processes in several aspects [1–4]: parameter optimization, post-treatment, and in particular a gas shroud attachment developed by us. Its principle is the surrounding of in-flight sprayed particles by a high flow rate of an inert gas [1–3]. So far, some types of gas shrouding techniques have been reported [5–7]. Their aim was mainly control of oxidation of flying particles during thermal spraying, leading to improvement of the coating performance such as service life in corrosive environment. The reason for the improvement was explained by the decrease in oxidation level of the resulting coatings.

As the spray material, AISI 316L stainless steel (SUS316L) and nickel base alloy, HastelloyC (HstC) were selected because of their well-known corrosion resistance of bulk materials, especially high resistance of HstC against crevice and pitting corrosion in the presence of chloride.

We investigated particle states upon spraying in terms of in-flight velocity, temperature and molten fraction because the particle states are related closely to the coating properties. In particular, we developed an accurate method to determine the molten fraction of sprayed particles [8]. The physical and chemical properties of the coatings were determined in terms of porosity and chemical composition. We also developed a highly sensitive method to evaluate the particle states are related closely to the coating properties. In particular, we developed an accurate method to determine the molten fraction of sprayed particles [8]. The physical and chemical properties of the coatings were determined in terms of porosity and chemical composition. We also developed a highly sensitive method to evaluate the through-porosity of the coatings [9].

As for the corrosion resistance of the coatings, actual marine tests as well as laboratory corrosion tests were carried out to investigate the anticorrosion performance of our coatings.

2. Experimental

2.1. Coating fabrication

We used an HVOF spraying apparatus (TAFA JP5000). In order to optimize spray condition, we varied some spray parameters such as combustion pressure, fuel/oxygen ratio, spray distance, barrel length, substrate temperature, coating thickness and so on [1]. The typical range of deposition conditions examined is listed in Table 1.

| Parameter                  | Unit       | Range       |
|----------------------------|------------|-------------|
| Fuel flow rate             | dm\(^3\) min\(^{-1}\) | 0.25–0.49   |
| Oxygen flow rate           | mm\(^3\) min\(^{-1}\) | 760–1080    |
| Combustion pressure        | MPa        | 0.43–0.86   |
| Fuel/oxygen ratio          | —          | 0.7–1.3     |
| Barrel length              | mm         | 102, 204    |
| Powder feed rate           | g min\(^{-1}\) | 60–70       |
| Torch velocity             | mm s\(^{-1}\) | 700         |
| Spray distance (\(a\))    | mm         | 200–450     |
| Powder feed gas            | —          | Nitrogen (N\(_2\)) |
| Substrate temp.            | K          | 373–873     |
| Coating thickness          | μm         | 50–400      |

* 1.0 corresponds to stoichiometric mixture ratio.
* \(a\) From exit of combustion chamber.

The feed stock powder of SUS316L and HstC were 25–53 μm in size and their chemical composition were listed in Table 2.

We examined the effect of post-treatments of the coatings [1,10,11]. The coatings were heated at 1023, 1173, and 1323 K at 1 h under an evacuated atmosphere. The coatings were polished and finished in the mirror-like face.

A pipe was attached to one end of the barrel of a commercial HVOF gun, as shown in Fig. 1. Inert gas was injected from both the ends of this pipe. In this paper, this mechanism was termed as the ‘gas shroud mechanism’ or the ‘shroud mechanism’, and a nitrogen gas was injected into the shroud at the flow rates of 1.5–2.5 m\(^3\) min\(^{-1}\) from upstream and at 0.3 m\(^3\) min\(^{-1}\) from downstream.

2.2. Evaluation of spray process

The in-flight velocity of sprayed particles was measured by using the in-flight diagnostic equipment (TECNAR DPV-2000). The velocity of individual particles is calculated by dividing the interval (160 μm) of two slits by the time between two radiation signals detected when the image of one particle passes tin front of the slits.

The surface temperature of in-flight particles during spraying could be also determined by using DPV-2000. It was calculated from the amplitude ratio at two wavelengths on the basis of the relation between the temperature and blackbody radiation of substance. This was originally developed for measuring the temperature of ceramic

Table 2

| Chemical compositions of feedstock powders |
|------------------------------------------|
| Material                  | Composition |
|----------------------------|-------------|
| HastelloyC (TAFA1286F)     | Ni, bal; Mo, 16.95; Cr, 16.57; Fe, 6.2; W, 4.5; Mn, 0.72; Co, 0.31; Si, 0.73 |
| SUS316L (TAFA 1236F)       | Fe, bal; Cr, 16.8; Ni, 10.8; Mo, 2.05; N, 0.131; O, 0.026 |
particles by plasma spraying and we should be careful when applying this technique to metals and alloys. Since metal particles tend to be oxidized during spraying and the spectral emittance of the surface can change, the calculated temperature may be different from the actual temperature of metal parts. Therefore, we found out a simple and highly accurate measuring technique of in-flight particles’ thermal state by their molten fraction [8]. The molten fraction could be evaluated by capturing the sprayed particles softly by an agar gel as the target material, followed by separating their melted and unmelted parts. A cross-sectional view of the sprayed gel shows clearly that spray particles were captured by the gel target separately at a shallow and a deep part, as seen in Fig. 2. The gels containing the particles captured at each part were separated by shaving with a cutter. The amount of the particles in each part was determined by the chemical analysis and the molten fraction of the sprayed particles was calculated from the ratio of the particle’s mass in each part.

2.3. Evaluation of coating property

The chemical composition of the coatings was determined by X-ray fluorescence spectrometric analysis with respect to metallic elements and by the inert gas fusion method with respect to carbon and nitrogen and oxygen elements.

The porosity was determined by mercury intrusion porosimetry (Micromeritics Autopore II 9220). Although it measures open pores comparatively precisely, it could not determine the open porosity of HVOF sprayed HastelloyC coatings because these coatings had extremely low open porosity below 0.1 vol% under the detection limit for mercury intrusion porosimetry. This analytical method also requires that a coating be at least 1 mm thick and that the coating be stripped from the substrate. We thus required detection with higher sensitivity to estimate through-pores. The through-porosity of such dense coating was determined by using Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES, Seiko Instruments Inc. SPS 3000) to analyze substances dissolved from the substrate through the penetrating path composed of connecting pores during immersion in hydrochloric acid (HCl) [9].

2.4. Evaluation of corrosion resistance

Corrosion resistance of the coatings was compared with respect to corrosion potential and polarization resistance [10]. The polarization resistance of the coating samples was obtained by the AC impedance measurement, and was calculated by subtracting one impedance value at the frequency of 10 kHz from another at 100 mHz with the corrosion monitor (Riken Denshi Model CT-5). The alternating current was applied to the sample electrode at the corrosion potential with amplitude of ±10 mV. The electrolyte was artificial seawater of pH 8.3 at 300 K. In addition, corrosion rate of the coatings was calculated from the average dissolution rate of metal elements of the coatings in acid solution. The dissolution amount of metal elements was determined by the ICP atomic emission spectroscopy.

In order to estimate the protective performance of the coating in the actual marine environment, we have carried out the exposure test of coated steel at Chikura coast, which is situated in the middle latitude of Japan and faced to Pacific Ocean [12]. The test pieces with A4 sheet size were prepared and fixed to three height levels of frames at the test site, which are situated in the splash, tidal and submerged zones. Carbon steel SS400 was used as the substrate. SUS316L and HstC were coated at both sides of test pieces. The edges and the bolt-holes for fixing were coated with the thick anticorrosion painting.

3. Results and discussion

3.1. Fabrication process for dense and clean coatings

We obtained a general tendency that the porosity of the coatings is inversely related to their oxygen content, as shown by the curve in Fig. 3. As mentioned in Section 1,
impermeability is required for anticorrosion shield coatings and is closely related to the porosity of the coating. In order to decrease the coating porosity, we increased flame energy by increasing combustion pressure and barrel length and by making fuel/oxygen ratio close to 1.0. In general, the higher flame energy increases both the kinetic and the thermal energies of in-flight spray particles. As a result, the coating porosity decreased whereas the oxygen content increased as the flame energy increased. In addition, the shorter the spray distance was, the smaller the porosity became because of the decrease in in-flight velocity of the particles with the spray distance. The oxygen content, however, increased because the deposited coating was heated directly by the flame. The decrease of the substrate temperature caused the slight decrease of the oxygen content. From this result, the oxidation of sprayed particles occurred mainly during flying and the sprayed particles were oxidized slightly in case of their insufficient cooling on the substrate. The coating thickness influenced the impermeability and the oxygen content of the coatings. Fig. 4 shows that the dissolution rate of the steel substrate through the coating thickness influenced the connecting pores of the coatings. We measured dissolved ions once for the same experimental conditions but twice for coatings about 400 μm thick. The results for the coatings about 400 μm thick were consistent and measurement was satisfactorily replicable. The impermeability increases with the coating thickness because chances for connecting open pores decrease stochastically as sprayed layers accumulate. In addition, the oxygen content increases with the thickness because the target temperature increases when the spray gun traverses repeatedly and the deposited particles become oxidized with the coating thickness.

As for the coating material, SUS316L is an unfavorable material to make dense and clean coatings by the HVOF process because SUS316L is more susceptible to thermal oxidation. In this paper, ‘clean’ means less contaminated, i.e. comparatively little change in the composition of sprayed materials during the spray process. Lower resistance against thermal oxidation indicates difficulty in adopting higher flame energy essential for making dense deposits by the HVOF process because the sprayed particles tend to be highly oxidized, i.e. deteriorated, upon spraying with the higher flame energy. At the lower flame energy, oxidation of the sprayed particles was suppressed whereas there remain considerable amount of pores between deposited particles. On the other hand, HstC was a comparatively suitable material to make dense and clean coatings by the HVOF process because HstC is more resistant against thermal oxidation. The high resistance of HstC against thermal oxidation allowed us to raise the flame energy up to a comparatively large level. Therefore, a lower open porosity below 0.1 vol% was attained for coatings prepared under higher flame energy conditions. In this case, however, the oxygen content was over 0.5 mass%.

Adoption of the nitrogen gas shroud mechanism to HVOF spraying succeeded in the decrease in both porosity and oxide content of SUS316L and HstC coatings (Fig. 3). Its porosity was below the detection limit of mercury intrusion porosimetry simultaneously with the oxygen content of 0.2 mass%. These less-oxidized coatings were obtained because this shroud mechanism allows...
the flying particles to avoid encountering the air atmosphere in the longer distance than usual. The significantly low porosity could be seen from the cross-sectional view of the coatings, as shown in Fig. 5. Some gray spots could be found as for the normal HVOF sprayed coatings of SUS316L (Fig. 5a) and HstC (Fig. 5b). These spots correspond to pores and boundaries between the stacked particles. On the other hand, such spots disappeared almost completely as for the on-shroud coating (Fig. 5c). The through-porosity of the on-shroud HVOF sprayed coatings was smaller than that of the normal coating (Fig. 4), although the open porosity of both the coatings was under the detection limit by mercury intrusion porosimetry. This was because the stacking nature was improved by attaching the gas shroud, as explained below. In particular, the dissolution rate of the steel substrate through the on-shroud coatings was close to the reliability limit of this technique over 300 μm in thickness. This indicates that the gas-shroud attachment brought about zero through-porosity coatings.

In the gas shroud system, suppression of oxidation could be explained by the deduction that flying particles were cooled and prevented from meeting oxygen by the inert nitrogen gas. As for the porosity, the in-flight velocity of sprayed particles is a primary factor for controlling the porosity. When SUS316L was used as the feed stock powder, the coating porosity decreases with the in-flight velocity of the particles, as shown in Fig. 6. In particular, in the average in-flight velocity of flying particles over 750 m s\(^{-1}\), the porosity decreased down to 0.1 vol%, i.e. under the detection limit. In this case, their molten fraction was below 40 mass% and molten fraction was not a primary factor for controlling the coating density [3]. Coating by HVOF spraying is a process in which partially molten and semi-molten particles with supersonic speed impinge to the target and pile up. Therefore, we believe that the kinetic energy of the impinged particles controlled the porosity, which depended on the in-flight velocity of the particles rather than their molten fraction, i.e. their temperature. In other words, however, such comparatively low temperature of the sprayed particles contributed to form the less-oxidized coating.

Fig. 5. Optical microscopic images of cross-section of HVOF sprayed coatings, (a) SUS316L with 1.1 vol%, (b) HastelloyC with <0.1 vol% and (c) on-shroud HastelloyC with <0.1 vol%.

Fig. 6. Relation between open-porosity of HVOF sprayed SUS316L coatings and in-flight velocity of sprayed particles.
3.2. Corrosion resistance of HVOF sprayed coatings

3.2.1. Impermeability

In thermal sprayed coatings, existence of boundaries or pores between the deposited particles is generally inevitable because coatings are composed of stacking layers of the small particles. Therefore, corrosion resistance of the coated steels corresponds to that of their entire coating/substrate system. Such pores in the coatings may be connected with each other to form a penetrating path through the coatings to the substrate. In combination of electrochemically noble coating and less noble substrate, the latter has a stronger corrosion tendency than the former because of the galvanic effect. As a result, the substrate corrosion takes place in preference to the coating corrosion. Accordingly, shieldability or impermeability of the coatings determines their protective performance rather than their intrinsic corrosion resistance. This can be seen from the relation between the coating porosity and the polarization resistance of low carbon steels SS400 coated by HVOF sprayed SUS316L and HastelloyC, as shown in Fig. 7. Here the polarization resistance is one of the criteria to estimate corrosion resistance, and its high value corresponds to its high corrosion resistance. The polarization resistance decreases with the porosity because the area of substrate corrosion increases with the amount of the connecting pores through the coatings. This result could be confirmed by the appearance of the specimens after immersion in seawater for 3 days, as shown in Fig. 8. The red-brown corrosion products were observed on the coating surface and they were derived from the steel substrate of SS400. Their number increased with the porosity. As for the on-shroud HVOF sprayed coatings, no corrosion took place on the substrate because it has no porosity, as mentioned above.

Post heat treatment in vacuum was found to improve the corrosion resistance of HVOF spray-coated steels. Firstly, disappearance of some pores increased the coating impermeability and surface oxides of the sprayed particles were gathered and surrounded by the metal particles. Secondly, the rate of corrosion that propagates along the coating/substrate interface was significantly decreased. A model experiment using an artificially provided defect in HVOF sprayed coatings, no corrosion took place on the substrate because it has no porosity, as mentioned above.

Fig. 7. Relation between open-porosity of HVOF sprayed coatings and polarization resistance of HVOF spray-coated SS400 steel. (■: SUS316L and ▲: HastelloyC).

Fig. 8. Photographs of HVOF spray-coated SS400 steels in aerated artificial seawater at 300 K for 3 days, (a: SUS316L with 1.6 vol% porosity, b: SUS316L with 1.1 vol%, and c: HastelloyC with <0.1 vol%).
a coating by drilling a hole through it was performed [13]. It was found that after the heat treatment, the interfacial corrosion rate decreased because the adhesion of coatings was improved and diffusion of some elements at the interface between the coating and the substrate made the interface junction ambiguous. As for the polishing treatment, we found that the corrosion resistance of the coatings was improved by the polishing treatment. This is presumably because the pores were filled with the polishing agent and the fine metal powder formed by abrasion.

3.2.2. Intrinsic corrosion resistance of coatings

If a coating has no penetrating path, i.e. no through-pores, service life of steels protected by the coating depends on the corrosion resistance of the coating itself, in other words, intrinsic corrosion resistance of the coating. Furthermore, the intrinsic corrosion resistance of the coating is expected to be different from that of the corresponding bulk material. Therefore, the intrinsic corrosion resistance of the coating was examined in order to determine and extend the lifetime of the coating [10,11]. In our study, the spray materials were deposited onto the bulk plate of the same material as them in order to minimize the contribution of the substrate.

A degradation reaction similar to crevice corrosion took place on the pores between the particles of the SUS316L coatings, as shown in Fig. 9. This type of corrosion depended on the amount of pores and sensitivity of spray materials to such corrosion reaction. Particularly in HVOF coatings, the top layer of approximately 20–50 μm depth from the coating surface contains more porosity because there is no or little peening effect by the subsequently impinged particles [14]. Inside such pores, the concentration of dissolved oxygen became small as dissolved oxygen was consumed by the cathodic reaction, leading to change of the surrounding metal particles from the passive state to the active state, indicating initiation and propagation of the corrosion reaction. As is the case for SUS316L, pores near the coating surface provided a reaction site susceptible to crevice corrosion. On the other hand, almost all the Hastelloy C coatings did not cause such corrosion. This is because SUS316L is subject to crevice corrosion in seawater whereas Hastelloy C is highly resistant against such reaction. The polishing treatment increased corrosion resistance of the coatings mainly because of removal of the surface layer with more pores appropriate for the starting point of crevice corrosion [10].

Contamination of the coating by oxygen is considered to be another primary reason for decrease in their corrosion resistance because their chemical composition is almost identical to that of the feedstock powder except for the oxygen content. Fig. 10 shows the effect of the oxygen content on the intrinsic corrosion resistance of the Hastelloy C coatings. Containing of excess oxygen in the coatings implies the presence of surface oxides and alloys different from the feedstock powders in terms of chemical composition. The surface oxides are not dense and such an alloy is considered to be less corrosion resistant than the alloy with the original chemical composition. Accordingly, the coating composed of such degraded particles has not as high corrosion resistance as the original metal, e.g. the bulk plate. The heat treatment increased the corrosion resistance because such surface oxides could be removed under an evacuated atmosphere. The polishing treatment also increased the corrosion resistance of the coatings because of removal of the surface oxides. The gas shroud attachment decreased in oxygen content down to 0.2 mass%.

Fig. 11 summarizes the anticorrosion performance of various types of the coating/substrate combination discussed above in terms of corrosion potential and polarization resistance. The corrosion potential of the coatings is
often used as one of the criteria to compare corrosion resistance. There seems to be a positive correlation between the corrosion potential and the polarization resistance. When specimens were low carbon steels coated by HVOF sprayed SUS316L and HastelloyC, some of them had low values of both parameters, near those of the steel plate. From this result, these parameters indicate the total protective performance of the coatings, composed of the impermeability and the intrinsic corrosion resistance of the coatings. The corrosion resistance of the on-shroud coatings of HastelloyC was comparatively high and was comparable to that of the bulk material of HastelloyC. This improvement of the protective performance by the shroud attachment was due to zero through-porosity and due to decrease in oxygen content down to 0.2 mass%. Although the corrosion potential of the on-shroud coating was higher than that of the bulk material, the latest experimental result suggested that the higher value was caused by the existence of surface oxides of the coatings.

3.2.3. Marine exposure tests

Fig. 12 shows appearance of the test pieces after actual marine exposure for 3 months. The top row shows test pieces exposed in the splash zone (assigned by the number 1), the middle in the tidal zone (2) and the bottom in the submerged zones (3), respectively. The test pieces shown in the figure are coatings of SUS316L onto SS400 steels by HVOF spraying (assigned by the capital letter A), HastelloyC (B) and on-shroud HastelloyC (C). As for the coatings of SUS316L in all the zones (A1–A3), severe corrosion damage was observed, as expected from the result of the laboratory corrosion test. Furthermore, the corrosion damage of these test pieces in the 3 months exposure seemed larger at submerged, tidal and least in the splash zone. Especially, the submerged specimen was covered with rust and the coating debonded almost completely from the substrate. This result shows that the corrosion rate of the spray-coated steel with through-pores depends on the contact time of test piece with seawater because permeation of seawater is a critical factor for substrate corrosion in this case. Accordingly, the corrosion rate of the spray-coated steels became higher in the submerged, tidal, and splash zones in that order. Their corrosion rate, however, seemed to be faster than the expected one. This was confirmed by the fact that even HastelloyC coating by the normal HVOF process was corroded in the actual marine environment, especially in the submerged zone (B3) although it performed well in the laboratory test. This is considered to be due to the effect of temperature variation on the corrosion rate and the prevention by seawater flow from closing of the open pores by corrosion products. On the other hand, impermeable HastelloyC coatings formed by the on-shroud spraying kept protection against corrosion attack to both the substrate and the coating in all
zones for 3 months. These coatings had continued to be intact over 10 months as of September 2002.

4. Conclusions

In order to acquire the dense anticorrosion coatings applicable in the marine environment, we used HVOF thermal spray method and obtained in the following results.

1. Fabrication of denser and less-oxidized coatings required higher velocity and lower temperature of sprayed particles. Although these two requirements are not compatible with each other in general, we overcame this problem by using the inert gas shroud attachment. Its objective was to make the flame surrounded by a high flow rate of inert gas. This gave us the particles with in-flight velocity over 750 m s\(^{-1}\) and molten fraction below 40%, succeeding in forming the coatings with zero through-porosity and 0.2 mass% of oxygen content. The remarkably high density and high cleanliness of these coatings brought about high protective performance and high corrosion resistance comparable to the corresponding bulk material, respectively. Post-treatments of coating by polishing and heating was effective to increase corrosion resistance.

2. Thermal energy of in-flight spray particles was revealed by molten fraction of spray particles, determined by quantitative analysis of melted and unmelted particles captured in an agar gel. The through-porosity of the coating with open porosity below 0.1% was determined by using the highly sensitive chemical analysis of dissolved substance from substrate through the penetrating path composed of connecting pores.

3. HastelloyC was a suitable material for HVOF spraying to form corrosion resistant coatings because of its high resistance against thermal oxidation as well as seawater corrosion.

4. In the actual marine environment, corrosion of coated steels proceeded faster than expected from the result of laboratory electrochemical tests. The corrosion rate depended on the contact time of the coated steel and seawater. The HastelloyC coating prepared by HVOF spraying attaching gas shroud system demonstrated the excellent protective performance, i.e. no signs of corrosion damage over 10 months.

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