

Study on New Candidate Coating Materials to Challenge Rudder Cavitation Damage

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Ships' hull is typically protected by a combination of protective coating system and electrical cathodic protection system, which has been an economical and effective measure for ship's hull to date. However, ships' rudder and adjacent hull areas are known to be subjected to premature corrosion damages, which require more frequent coating repair than other hull areas. Conventional organic coating system for ship's hull has been known only to remain intact just for 2~3 months on the rudder and adjacent area, especially for the fast-going ships such as container carriers or naval vessels. In this study, special organic/inorganic coating materials, which are commercially available, were tested in terms of cavitation resistance as an alternative to existing rudder & hull protection system. Both standard ultrasonic tester and in-house developed ultra water jet test method were employed as a means to evaluate their performance against cavitation induced damages. Additionally, the overall cost evaluation and workability at actual shipyard were discussed.

Keywords : ship, rudder, cavitation, corrosion, organic coating

1. Introduction

Marine vessels' outer hull is typically protected by a combination of protective organic coating system and electrical cathodic protection system (including Impressed Cathodic Current System, ICCP, and Sacrificial Anode) which has been an economical and effective measure for ship's hull to date. Coating systems for struts, rudders, and other erosion-prone areas consist of several components. After a surface preparation having a proper surface profile, anti-corrosive primer coats are applied. This is followed by application of a cavitation-resistant coating and a top coat of an anti-fouling paint. However, conventional organic coating system for ship's hull has been known only to remain intact just for 2~3 months or so on the rudder and adjacent area, especially for the fast-going ships such as container carriers or naval vessels. Ships' rudder, rudder stock and adjacent hull areas, thus, are known to be subjected to premature corrosion damages, which require more frequent coating repair than other hull areas.¹⁾ The drastic change of water flow by propeller action has been considered as a source of cavitation bubble, thereby, its implosion may apply a tremendous impact on rudder coating.²⁾ For some cases, as an alternative or reinforce-

ment to the existing hull coating system, noble metal sheathing such as 316L austenitic stainless steel is plated for the cavitation-prone areas. However, it could not be recognized as a perfect solution because of the high-installation cost and other problems such as galvanic corrosion with carbon steel on which the noble metals were welded.

In this study, several types of organic/inorganic coating materials, commercially available, and eligible as new candidates, were tested in a comparison with the standard protection method. To evaluate the cavitation resistance of these new materials, both standard ultrasonic tester and house-devised ultra water jet test method were employed to simulate an actual service condition. Besides that, the overall cost evaluation and workability at actual shipyard were discussed also to provide economically viable solution to the concerned issue. Additionally, the overall cost evaluation and workability at actual shipyard were discussed.

2. Backgrounds and case history

Erosion damage to rudder surface can be resulted from either impact erosion or cavitation erosion. The former is caused by direct impact of fluid jet stream on the rudder surface, whereas the latter is caused by shock wave due to collapse of cavitation induced bubble. From the point

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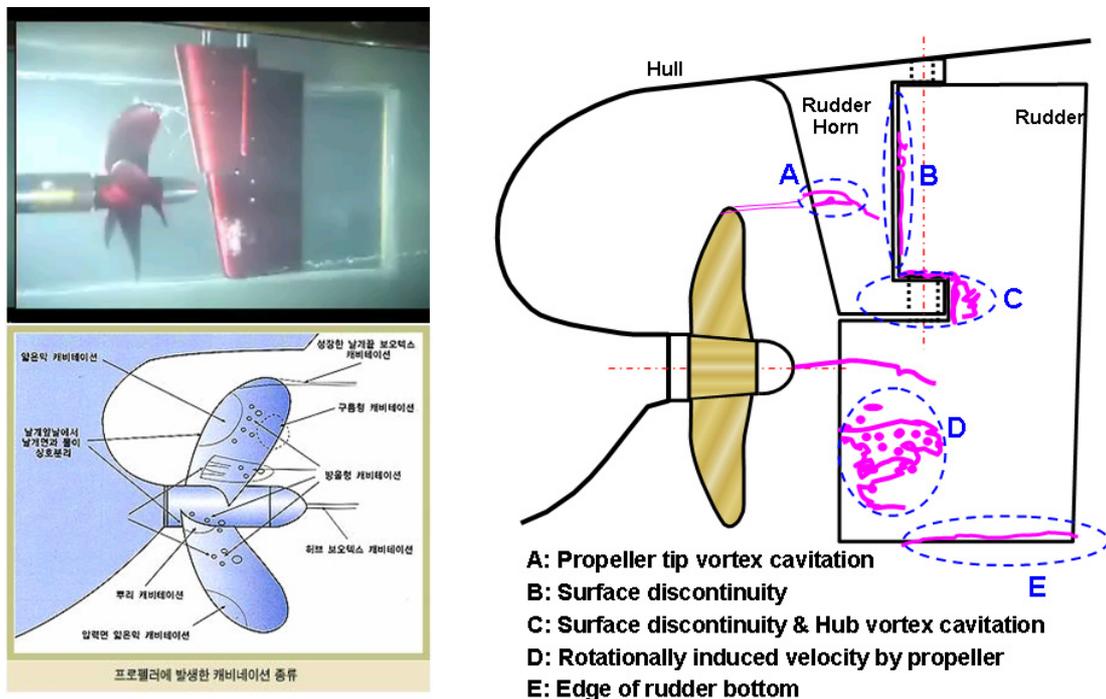


Fig. 1. Schematic diagram of the cavitation erosion part for semi-spade rudder²⁾

of fluid dynamics, cavitation at the rudder surface can be generated either by the local, negative loading or by the vortex at the rudder shoe, as schematically shown in Fig. 1.²⁾ The cavitation generated at the rudder surface will cause vibration and subsequent fatigue fracture of the rudder. As a countermeasure for these phenomena, several attempts have been made to optimize the fluid dynamic shape of the rudder, such as changing propeller design with minimized flow disturbance, elimination of surface discontinuity.

Despite continuous efforts to reduce premature rudder damage for last decades, however, protective organic coating systems currently applied on the fast-going ships such as container carriers or naval vessel's rudders, propeller shaft struts, and other high-stress underwater hull areas often failed within a few months of their installation. Premature corrosion due to failure of these protective coatings in underwater hull areas has been one of several corrosion issues related to high speed marine vessels. Numerous on-site survey of the ships at the dry-dock revealed that the total affected area was typically up to ~40% of the total coated areas, and in most cases the most severe coating loss occurred in a localized area of the out-board sides of both rudders, as shown in Fig. 2.¹⁾

Coating loss resulting in exposed rudder shell plating and subsequent corrosion damage has been significant concerns for ship operators regarding the long-term safety of

the ships. Divers could perform partial coating touch-up and repair in the water, but major refurbishment and maintenance of coating system should be carried out during dry-docking maintenance availabilities. Thus, corrosion damage to exposed rudder shell plating increases maintenance costs and reduce the operation times of the ship, threatening the natural desires to lengthen the dry-docking cycle for improving the ships operational economic efficiency.

U.S. Navy has reported that coatings applied to these areas during both new construction and repair availabilities generally last about a year. According to U. S. Navy's Naval Sea Systems Command (NAVSEA)'s evaluation, typical recoating of rudders, struts, etc. costs the fleet from \$25,000 to well over \$100,000 per occurrence per ship, depending on the surface preparation method used, the coating system selected, and the application process.¹⁾ Since these costs did not include the cost of repairing any damage to the substrate, it could be predicted that loss of the protective coating can allow metal loss and deterioration, increasing repair costs in dry-dock. The struts, rudders, and other erosion-prone areas of ships often require tougher and more resilient coating systems than other underwater hull applications due to the severity of the environment to which they are exposed. The coating system must not only provide protection from the corrosive seawater environment, but also be able to withstand cavitation

and erosion damage that can arise from turbulent seawater flow impinging on surfaces. In order to extend the dry-docking cycle for less down time for ship's operation, several approaches have been made so far either to increase the life expectancy of rudder coatings or to find alternative methods of protecting the rudder from damage between dry-dockings.

These approaches can be either selection of better protective coatings or standardization of the coating application procedure, including surface preparation and inspection. As for the former approach, several materials have been repeatedly proposed and tested both in the laboratory and field condition by several research groups. In these attempts, high hardness organic or inorganic coating materials were applied on the rudder surface with various methods, such as metal spray, ceramic-metal coating.³⁾⁻⁸⁾ The latter approach also has been issued in several cases. For



Fig. 2. Typical cavitation induced corrosion damage of ship's rudder¹⁾

example, the NAVSEA has established the internal rudder coating standard for naval ships, applicable to surface ship preservation, such as NAVSEA Standard Item 009-32, "Cleaning and Painting Requirements." It contains cleanliness, surface preparation, and coating application requirements, along with complete system application instructions for each product (number of coats, coating thickness per coat, etc.) approved for rudder and strut preservation. The leading new shipbuilding companies, such as Hyundai Heavy Industries in Korea, followed the latter track so far mainly due to lack of successful, better coating materials with proven service record.

3. Experimental methods

3.1 Selection of candidate materials

Total seven different types of coating materials were selected for evaluation, which are 316L type austenitic stainless steel, 3 types of metallic alloys for HVOF (High Velocity Oxy Fuel) metal spray applications, and organic coatings of ScotchWeld™ 2216, DuraTough™ DL, Si-type Foul Resistant (FR) paints, as shown in Table 1. Conventional protective coatings system, AC epoxy + AF (EH3250™ + AF795H™), which has been widely used in the new-building shipyards, was also evaluated as a reference.

3.2 Testing of cavitation resistance

Cavitation resistance of each coating sample was evaluated by using both an ultrasonic tester (modified ASTM G-32 method) and in-house built water jet tester. In case of the ultrasonic tester, as shown in Fig. 3(a), samples were placed 0.5 mm below the sonic generator, i.e., vibratory horn, to eliminate vibration induced damage to the coating layer. This arrangement has been known to provide more increased vibration amplitude to the surface to be tested. The actual tester, employed in this test, is shown

Table 1. Selected material for cavitation erosion test

| Classification | Materials / Product Name | Specimen Name | Remark |
|----------------------|----------------------------------------|---------------|--------------|
| Metal Lining | 316L Stainless Steel | STS 316L | - |
| Metal Coating (HVOF) | Stainless Steel 316L (Diamalloy 1104™) | TS_STS316L | AF Exclusion |
| | Self Flux Alloy (Diamalloy 2001™) | TS_Self Flux | AF Exclusion |
| | Amorphous Alloy (Amacor-M™) | TS_Amorphous | AF Exclusion |
| Organic Coating | EH3250™ + AF795H™ | Conventional | AF Inclusion |
| | DuraTough™ DL (Elasto-Ceramic Polymer) | Elastomer | AF Inclusion |
| | ScotchWeld™ 2216 (Epoxy Adhesive) | Special Epoxy | - |
| | Si-Type Anti-Fouling | Silicon AF | - |

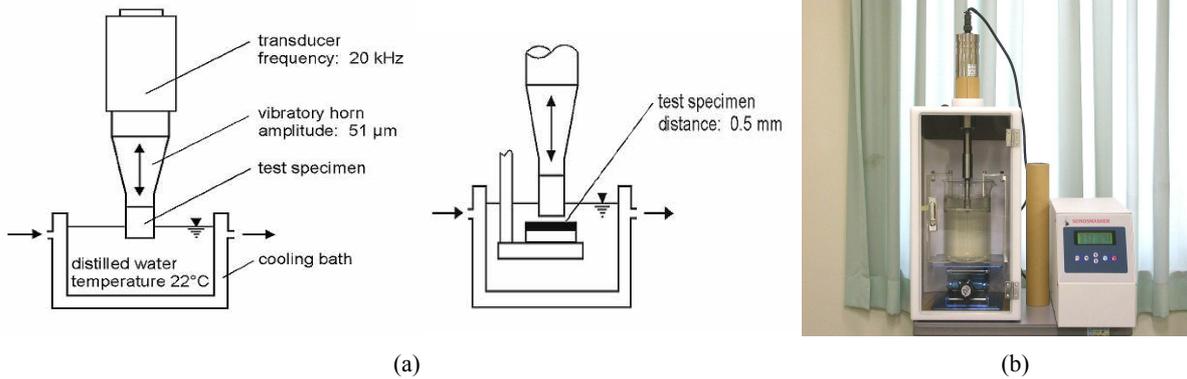


Fig. 3. (a) Schematic diagram, (b) photograph of vibratory cavitation erosion tester



Fig. 4. Water-jet cavitation erosion tester

in Fig. 3(b).

In order to simulate high impact cavitation expected from larger propellers, which were employed in actual ship operation, an in-house built water jet tester was also employed. The tester, as shown in Fig. 4, utilized a high pressure pump to generate high speed water jet impact in a vertical direction to the coating surface. In order to facilitate the erosion observation during the tests, monitoring window was installed directly on the water jet/coating surface contact area.

Cavitation resistance behavior of each coating was evaluated by employing the concept of Cumulative Mean Depth of Erosion (CMDE) and erosion rate, which were taken after the preset testing duration. CMDE can be induced the following equation 1 as follow;

$$CMDE(\mu m) = \sum MDE(\mu m)$$

$$MDE(\mu m) = \Delta W / 10\rho A \quad (1)$$

in which, coating's density $\rho(g/cm^3)$, exposed area $A(cm^2)$ and weight change $\Delta W(mg)$ are used for calculation.

Erosion rate, on the other hand, was evaluated as Mean Depth of Erosion (MDE), which can be induced using the following equation 2;

$$Erosion\ Rate(\mu m/min.) = MDE / \Delta t \quad (2)$$

in which, Δt is the test duration.

Finally, the expectant useful life of each coating against erosion was evaluated by measuring the time required for the CMDE value to reach 100 μm and 200 μm .

3.3 Preparation of coating samples

Testing samples were applied or sprayed on butt end of 316L stainless steel mounting sets, as shown in Fig. 5, following ASTM G 32-02 standard, of which diameter was 15.9 ± 0.05 mm, 10 ± 0.5 mm, for ultra sonic testing and water jet testing, respectively. Before application of each coating, the surface of each mounting set was grit blasted to ISO Sa 2.5 grade and degreased with acetone, then the coatings were sprayed following recommended dry film thickness. In Table 2, the mechanical properties of the selected coatings were summarized.

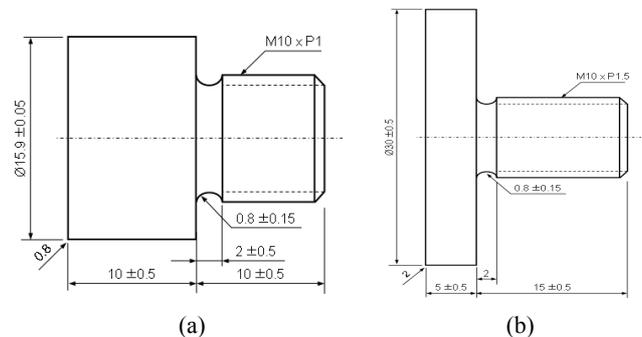


Fig. 5. Dimension of mounting set for cavitation erosion test; (a) ultra sonar, (b) water-jet

Table 2. Mechanical properties of coatings for anti-cavitation erosion test

| Materials Type | Coating Thickness, mm | | Hardness HV0.5 | Density mg/mm ³ |
|----------------|-----------------------|-------------|----------------|----------------------------|
| | Recommendation | Measurement | | |
| STS 316L | - | - | 210~230 | 7.98 |
| TS_STs 316L | 0.4~0.5 | 0.40~0.45 | 230~250 | 7.4706* |
| TS_Self Flux | 0.4~0.5 | 0.45~0.55 | 630~670 | 6.8436** |
| TS_Amorphous | 0.4~0.5 | 0.55~0.60 | 720~780 | 6.3648** |
| Conventional | 0.75~0.85 | 0.65~0.70 | HSA 90 | 1.5 |
| Elastomer | 1.6 | 1.60~1.70 | HSA 80 | 1.13 |
| Special Epoxy | 0.75~0.85 | 0.75~0.80 | HSA 93 | 1.325 |
| Silicon AF | 0.60 | 0.55~0.60 | HSA 84 | 1.6 |

*97% of theoretical density **98% of theoretical density

4. Results and discussions

4.1 Ultra sonar test

Fig. 6 and Fig. 7 shows the ultra sonic test results for each coating after 10 hours of exposure in terms of MDE and erosion rate, respectively. As expected, the conventional organic coating suffered heavy erosion during the initial one hour duration, revealing its poor resistance of the coating layer. Other coatings also showed gradual progress of the erosion during the 10 hour test.

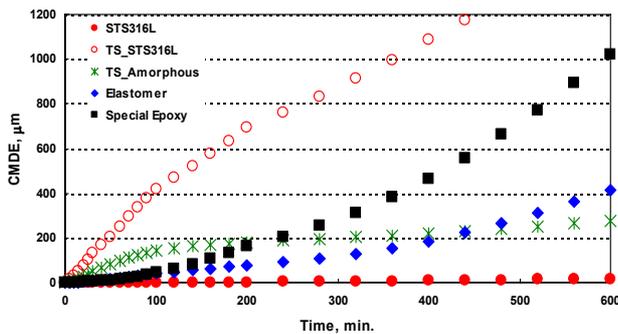


Fig. 6. Cumulative Mean Depth of coatings: ultra sonar test

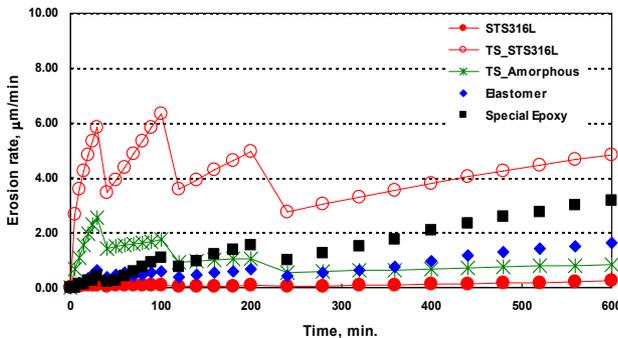


Fig. 7. Erosion rate of coatings: ultra sonar test

Based on the evaluation, it can be concluded that ultra sonar cavitation resistance of the tested coatings is superior in the order of ;

316 stainless steel plate > HVOF amorphous alloy (Amacor-M) > Elasto-ceramic polymer (DuraTough™ DL) > Epoxy adhesive (ScotchWeld™ 2216) > HVOF stainless steel 316L (Diamalloy 1104) > Conventional epoxy paint (EH3250™ + AF795H™).

Considering the hardness of each coating, as shown in the Table 2, also revealed that the degree of hardness did not fully matched with the coatings resistance to the ultra-sonic erosion, suggesting that surface hardness can not be a good screening indicator for coating materials selection against rudder cavitation protection. This might be supported by the empirical opinion from the shipyards that coating's toughness, or the ability to absorb external impact would be simultaneously critical for the candidate materials.

Fig. 8 shows the surface of each coating in the as-sprayed condition and after 10 hour ultra sonar tests. All coating samples showed a sign of erosion damage around their center, and the degree of erosion was different with each coating. As expected, among all coatings, the soft, conventional coatings (EH3250™ + AF795H™) suffered the most severe erosion, exposing more than 20% of bare metal substrate after the test. This partially confirmed that the erosion condition of the current acceleration test is quite intensive in comparison with actual ship's service condition. The 316L stainless steel coating applied by HVOF metal spray (Diamalloy 1104) also experienced a partial loss of coated layer, partially exposing bare metal substrate after the erosion test. On the other hand, only slight erosion was observed for both 316 stainless steel plate and amorphous alloy coating applied by HVOF metal spray (Amacor-M), whereas more intensive erosion on the coating layer were observed for coatings made of an elasto-ceramic polymer (DuraTough™ DL) and an epoxy adhesive (ScotchWeld™ 2216). Partial delamination of coating was also observed for the epoxy adhesive coating.

The expectant useful life of each coating against erosion, as calculated by measuring the time required for the CMDE value to reach 100 µm and 200 µm, revealed the similar result in terms of each coating's erosion resistance characteristics. The soft, conventional coatings (EH3250™ + AF795H™) reached to 100 µm CMDE value only in 4 minutes, and other coatings took longer time to reach that depth in the following order; 316L stainless steel by HVOF metal spray (24 min.) < Amorphous alloy coating by HVOF metal spray (63 min.) < Epoxy adhesive (155 min.) < Elasto-ceramic polymer (264 min.) < 316 stainless

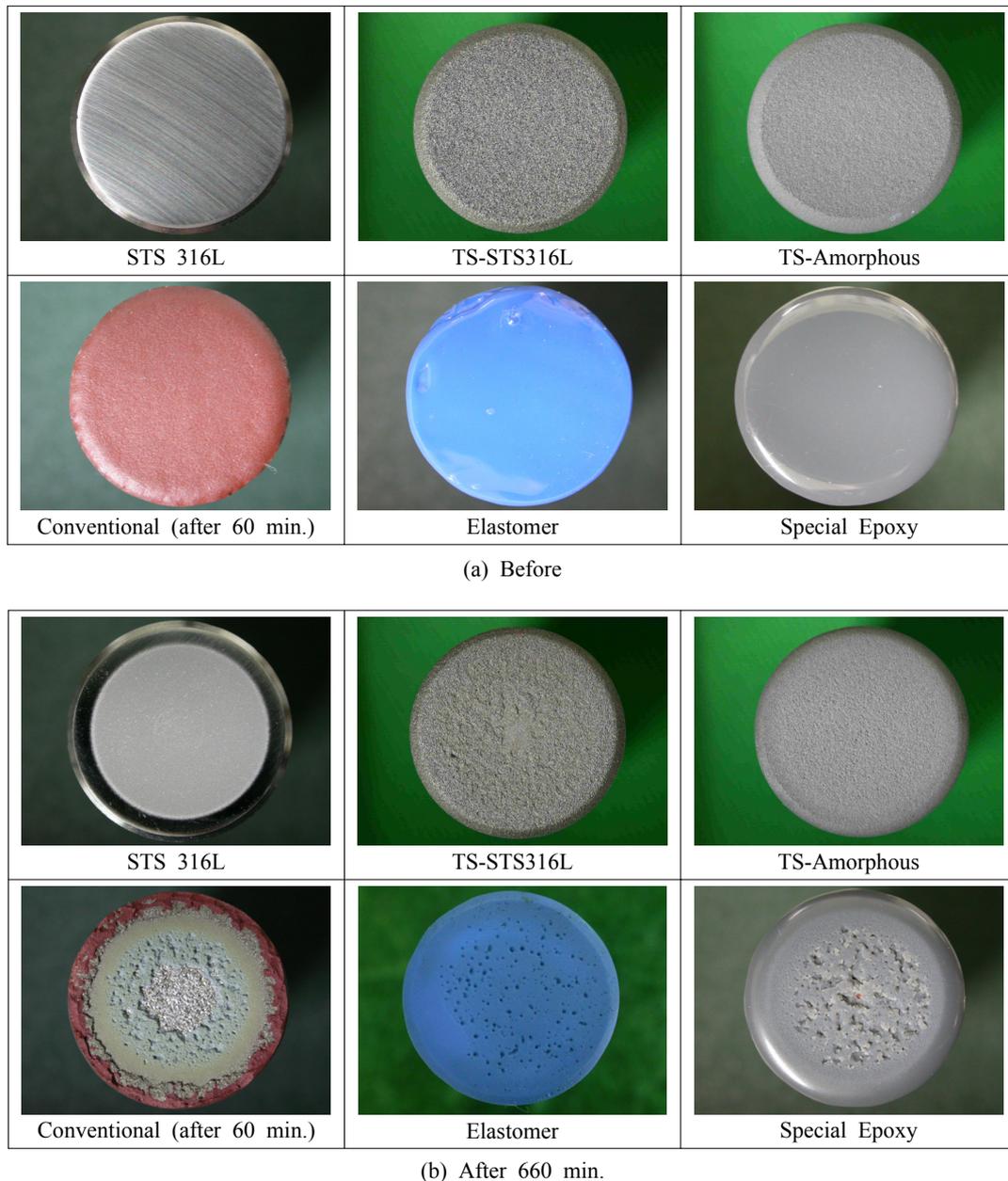


Fig. 8. Appearance of coatings before and after vibratory erosion test

steel plate (3,968 min.).

To reach 200 μm of the CMDE value, it took a little longer for each coating, but the trend was only slightly different; Conventional coatings (6 min.) < 316L stainless steel by HVOF metal spray (307 min.) < Epoxy adhesive (236 min.) < Amorphous alloy coating by HVOF metal spray (155 min.) < Elasto-ceramic polymer (415 min.) < 316 stainless steel plate (7,906 min.).

4.2 Water jet test

In the water jet test, high impact water jet was propelled

from 22 kg/cm^2 capacity high pressure pump operated by a 5.5 kW/7.5 HP motor. The water jet, formed in the water reservoir maintained at the temperature range of $25\pm 3^\circ\text{C}$, would vertically impact on the coating surface at the speed of ~ 60 knots through 6 mm diameter nozzle, in which the samples were located 150 mm apart from the nozzle's end.

Fig. 9 and Fig. 10 shows cumulative Mean Depth of Erosion (MDE) and erosion rate of each coated sample measured from weight loss ΔW , after 11 hours of water jet test. The basic trend was quite similar to that already

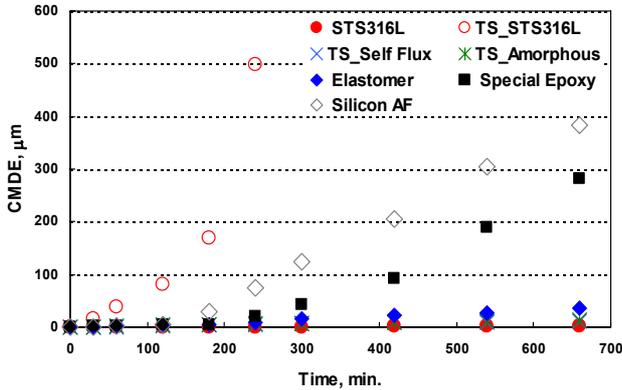


Fig. 9. Cumulative mean depth of coatings: water-jet test

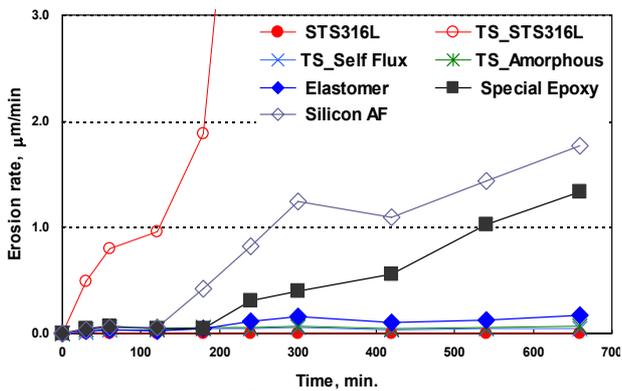


Fig. 10. Erosion rate of coatings: water-jet test

observed in the ultra sonar test, even though the time scale to reach to the severe erosion stage is somewhat different due to the difference in delivery mechanism of the me-

chanical impact.

The expectant useful life of each coating against erosion, as calculated by measuring the time required for the CMDE value to reach 100 µm and 200 µm, confirmed the similar result in terms of each coating erosion resistant characteristics. The soft, conventional coatings (EH3250TM + AF795HTM) reached to 100 µm CMDE value in 4 minutes, and other coatings took longer time to reach that depth in the following order; 316L stainless steel by HVOF metal spray (166 min.) < Si-AF coating (271 min.) < Epoxy adhesive (430 min.) < Elasto-ceramic polymer (1,814 min.) < Amorphous alloy coating by HVOF metal spray (4,920 min.) < TS self flux alloy coating by HVOF metal spray (5,782 min.) < 316 stainless steel plate (29,438 min.).

To reach 200 µm of the CMDE value, it took a little longer for each coating, but the trend was only slightly different; Conventional coatings (7 min.) < 316L stainless steel by HVOF metal spray (186 min.) < Si-AF coating (413 min.) < Epoxy adhesive (552 min.) < Elasto-ceramic polymer (3,587 min.) < Amorphous alloy coating by HVOF metal spray (9,895 min.) < TS self flux alloy coating by HVOF metal spray (11,596 min.) < 316 stainless steel plate (58,850 min.).

4.3 Economic viability of coating materials

For optimal selection of cavitation resistant coating materials, another two significant criteria are economical feasibility and working condition. In the selection procedure, the total cost and easiness in application and maintenance in field condition, such as surface preparation requirement,

Table 3. Cost estimation of selected coating materials

| | Product | Cost(₩/m ²) | Application method | Thickness | Working Time (270m ²) | Remark |
|----------------------------|------------------------------------|-------------------------|--------------------|-------------|-----------------------------------|--------------------|
| Metal Spray Coating (HVOF) | STS316L (Diamalloy 1003) | 600,000 | HVOF* | 0.4~0.5mm | < 7 day | AF Excluded |
| | Self flux alloy (Diamalloy 2001) | 1,300,000 | HVOF | 0.4~0.5mm | < 7 day | AF Excluded |
| | Amorphous alloy (Amacor-M) | 1,200,000 | HVOF | 0.4~0.5mm | < 7 day | AF Excluded |
| Organic Coating | Conventional (AC+SPCAF) | 100,000 | Spray | 0.8~0.9mm | < 7 day | - |
| | Elastomer (Elasto-ceramic polymer) | 1,300,000 | Brush lining | 1.6(2.4)mm | < 7 day | AF Included |
| | Special Epoxy | 200,000 | Spray | 0.75~0.8mm | < 7 day | AF Included |
| | Silicon AF (AC+Si-AF) | 150,000 ~200,000 | Spray | 0.55~0.65mm | < 7 day | - |
| Metal Lining | STS316L | 1,000,000 ~1,300,000 | Weld lining | 5mm | > 7 day(70m ²) | Galvanic corrosion |

Table 4. Workability comparison of selected coating materials

| | Product | Application method | Thickness Control | Work Accessibility | Dust control Set-up | Repair | Others |
|----------------------------|------------------------------------|--------------------------------------|-------------------|---------------------------------|---------------------|-----------|-----------------------------------------------|
| Metal Spray Coating (HVOF) | STS316L (Diamalloy 1003) | High Velocity Oxy-Fuel Thermal Spray | Uniform | Extra Boom Lift (Mobile Lifter) | None | Easy | -Noise cutoff needed -Field work difficult |
| | Self flux alloy (Diamalloy 2001) | | | | | | |
| | Amorphous alloy (Amacor-M) | | | | | | |
| Organic Coating | Conventional (AC+SPCAF) | Spray | Uniform | Boom Lift (Mobile Lifter) | None | Easy | - |
| | Elastomer (Elasto-ceramic polymer) | Brush Lining (Hand Spread) | Brush lining | Full Scaffolding | Mandatory | Difficult | - |
| | Special Epoxy | Spray or Roller | Uniform | Boom Lift (Mobile Lifter) | None | Easy | - |
| | Silicon AF (AC+Si-AF) | Spray | Uniform | Boom Lift (Mobile Lifter) | None | Difficult | - |
| Metal Lining | STS316L | Weld Lining | - | - | - | - | - |

application equipment as well as environmental condition, should be thoroughly reviewed. In Table 3 and Table 4, the estimated total cost of each candidate materials and their workability are summarized, respectively.

The 316L stainless steel plate, which showed the best erosion resistance in the acceleration test, has been known to be quite expensive material compared to other coatings. In terms of the installation method, additional, extensive cost and time required for special welding for 316L stainless steel, are another disadvantage to other methods. All other coatings cover in this study, on the other hand, can be sprayed in a rather short period.

The HVOF spray coating procedure, however, also retain another disadvantage due to the special equipment requirement, which is generally heavy and lacks mobility in the actual field condition. Moreover, generally ship yard's dry dock is known to be a less ideal environment for such rather complicated work. High cost for the HVOF powders is another difficulty for wider use of this technology for rudder protection.

The organic coatings showed much better flexibility in terms of cost and workability. Especially, the epoxy adhesive, such as ScotchWeld™ 2216, which showed much better erosion resistance than the conventional coating, can be a proper choice, since it can be sprayed in shipyard dry docks with a single component airless pump, and repair of the coatings can be done with less difficulty. The total cost of the epoxy adhesive will be another advantage against other candidates. However, it still needs finer evaluation regarding their long term cavitation resistance in-

cluding actual field test, which is the foremost, intrinsic requirement for this purpose.

5. Conclusions

As an alternative to existing rudder & hull protection system, several organic/inorganic coating materials, which are commercially available, were tested in terms of cavitation resistance. Both standard ultrasonic tester and in-house developed ultra water jet test method were employed as a means to evaluate their performance against cavitation induced damages. In terms of cavitation resistance, the performance was increased in the following order;

Conventional organic coatings < 316L stainless steel by HVOF metal spray < Si-AF coating < Epoxy adhesive < Elasto-ceramic polymer < Amorphous alloy coating by HVOF metal spray < TS self flux alloy coating by HVOF metal spray < 316 stainless steel plate (58,850 min.).

In the consideration of overall cost and workability in the ship yard dry dock, the epoxy adhesive having better erosion resistance than the conventional coating, exhibited good sprayability with a single component airless pump at relatively lower total cost.

References

1. <http://www.nstcenter.com/>: Coating Systems for Struts, Rudders, and Other Erosion-Prone Areas.
2. J. M. Han, D. S. Kong, I. M. Song, and C. S. Lee, Proc. Cavitation 2001, p.1-8, Session B9.005 (2001).

3. J. H. Boy, A. Kumar, P. March, P. Willis, and H. Herman, Construction Productivity Advancement Research Program, USACERL TR-97/118 (1997).
4. "Rudder Coating Failures on Navy Ships", SSPC 2003
5. R. A. Bardsley, D. A. Fayocavitz, and S. Kado, Rudder Investigation of DDG 51 Class, Mega Rust 2005.
6. K. Sugiyama, S. Nakahama, S. Hattori and K. Nakano, *Jr. Wear*, **258**, 768 (2005).
7. V. A. Pugsley and C. Allen, *Jr. Wear*, **233**, 93 (1999).
8. M. M. Lima, C. Godoy, P. J. Modenesi, J. C. Avelar-Batista, A. Davison, and A. Matthews, *Surface and Coatings Technology*, **177**, 489 (2004).