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An experimental investigation of the composite coating for marine propellers on cavitation characteristics and fouling release property

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An experimental investigation of the composite coating for marine propellers on cavitation characteristics and fouling release property

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Abstract. Marine propellers with complex shaped surface could not satisfy hydrodynamics and have complex flow-structure interactions during running. While cavitation and marine organisms are two obstacles when ship propellers keep propulsion efficiency, many of them have been coated with fouling release coating to maintain propeller propulsion efficiency. In this paper, the introduction of the composite coating to marine propellers can not only effectively resist to cavitation erosion, but also be free from marine organisms. In the above context, tests for the cavitation characteristics of the composite coating were carried out. Composite coatings on the tool head for 40 h or hedging for 100 h had slightly loss of light with the cumulative weight loss less than 5 mg. Open water tests showed the composite coating did not significantly affect thrust and torque characteristics of model propeller. After the use on ship propellers for a period of 16 months, composite coating matched well only with minor damage on the leading edge, but none diffusion under the coating layer. And also marine organisms on blades of propeller could be washed away easily with high pressure water.

1. Introduction

A propeller is a type of fan that transmits power by converting rotational motion into thrust, which is the power unit of a ship. As the pressure difference is produced between the forward and rear surfaces of the airfoil-shaped blade, and water is accelerated behind the blade [1]. High performance of propellers should conquer cavitation erosion [2-3] and fouling [4-5], both of them contributing to speed declining and fuel consumption increasing [6-7].

The propellers operated at high rotational speed or under heavy load accelerate poop flow rate, coupled with the high-speed flow around. Water is too late to fill the front of the blades after thrown around; the pressure on the upstream surface of the blade can drop below the vapor pressure of the water, and result in the formation of a vapor pocket. Inception cavitation [8-9] occurs in the region of boundary layer, and also propeller blades roughness stimulates transition of the boundary layer from laminar to turbulent flow. The harm [10] of cavitations results mainly in threefold: cavitation bubbles form at the area of low pressure, and then flow to blades of rudder or propeller at the area of high pressure, causing the vapor pocket closed explosion. The collapse of cavitation bubbles create shock wave and hence cavitation noise; Cavitation bubbles on propeller blades will change the flow, cut



down propeller efficiency and reduce sailing speed; blades of propeller and rudder suffering from long-term cavitation would give different size of pits on their surface which accelerate the erosion and fouling phenomenon. The French "Charles de Gaulle" nuclear-powered aircraft carrier [11] sent huge cavitation noise when following sea trials in 1999, which affected the sleep of sailors. One year later, four propellers were cavitated seriously; three of them lost operation completely.

Marine fouling [12] ranges from micro-fouling (bacterium, algae, slime etc) to macro-fouling (microalgae, soft bodied and hard shelled). Attachment of marine fouling organisms is a very complex process [13], which beginning with slime, and finally to macro-fouling. Copper alloy substrate of propeller immerse in the water, give the surface of black oxide film which providing breeding grounds for the attachment of marine organisms. In the process seaweed, sea squirts, barnacles and other marine creatures gradually adhere to the surface of propeller in large quantity which contribute to weight and roughness of ship hulls which reducing their propulsive efficiency. Unpredictable fuel consumption was made up for a loss of marine organisms. As reported in British Ship Research association, surface area of propeller is not big, but it is very huge in energy loss that cavitations and fouling brought [14]. For example, to a container ship of around 3000TEU traveling with a speed about 23 kn, the energy loss caused by corrosion for propeller reached to 6%, almost one-third of the total loss [15]. Also fouling on propellers of blades gives uneven blade with different weight which increasing drag torque. All of these bring enormous economic and security risks.

To date, the most effective method is self-polishing co-polymer technology with various toxic compounds, but the shipping community is forced to review their anti-fouling policies to meet the tougher environmental regulations. So a completely environmental friendly antifouling technology (silicone coating known as "fouling release" property) [16] was introduced in the early 1990s. It is through hydrodynamic shear forces to control the attachment of marine organisms rather than killing them in various ways. After that, many different fouling release coating has been developed which result in more and more applications for ship hulls and propellers. Within the above context, the experimental study in this paper developed a cavitation resistance fouling release composite coating containing high adhesion epoxy primer, buffer epoxy coating, and silicon tie-coat and fouling release top-coat. The four-layer coating showed good matched property and certain elastic deformation [17] which transforming impact energy the collapse of cavitation bubbles brought to heat with subsequent diffusion. And the fouling release top-coat possesses the necessary properties for fouling release when hydrodynamic shear forces [18] are sufficiently robust. Also, the test for ship propeller with four-layer composite coating was conducted for 16 months. The composite coating can effectively solve the cavitation corrosion and fouling problems for our ship propeller.

2. Experimental method and materials

A four-layer composite coating including high adhesion epoxy primer, buffer epoxy coating, silicon tie-coat and fouling release top-coat were prepared by Marine Chemical Research Institute Co. Ltd., Table 1 showed a summary of the composite coating system.

Table 1. Summary of the composite coating system.

Abbreviation	Type	Color	Dry film thickness/ μm
EP512	epoxy primer	dull red	50
EP525	buffer epoxy coating	black	50
FR-01	silicon tie-coat	pink	100
FR-02	fouling release top-coat	red	200

Epoxy primer had good surface wetting and penetration resistance, high wear resistance also extra tough behavior. Aluminium powders enhanced waterproof property and corrosion resistance. And epoxy primer possessed excellent adhesion more than 10 MPa. Buffer epoxy coating served as the transition between epoxy primer and silicone systems. While silicon tie-coat connected buffer epoxy

coating with fouling release coating. Buffer epoxy coating and silicone tie-coat both were elastomer which reducing the pulse energy when the cavitation bubbles collapsed. And fouling release top-coat adopted low surface energy silicone system which offering the release of marine organisms. Fouling release top-coat with low surface energy obtained poor wettability to marine organisms. Loose attachment of them to fouling release top-coat was easily removed through hydrodynamic shear. In the following sub-sections, the details of each group of the tests were presented separately.

2.1. Cavitation resistance tests

The test columns were rinsed for removing oil and debris from their surfaces and dried to constant weight at 105 °C for 1 hour before and after cavitation tests. Cavitation [19] was induced by longitudinal oscillations at 20 kHz with amplitude of 25 µm and the hedge distance of 2 mm in freshwater; the testing temperature of the medium was 25 °C. They were carried out comparing cumulative weight loss before and after a period of cavitation using XOQS-2500 intelligent temperature control material cavitation testing machine and also photographic recording surface topography of the samples were got. The experiment acted in the samples by high-power ultrasonic, simulated generation and collapse of cavitation bubbles and gave a rapid evaluation of cavitation resistance of tested samples. As we know, marine propeller is made from copper alloy. The column blank gave a detail of the destructive effects of cavitation to copper alloy through hedging for 600 min, and morphologies of eroded surface was obtained.

2.2. Open water tests

Open water tests [20] were performed according to the International Towing Tank Conference (ITTC) procedure for open water tests (ITTC, 2005). In the tests, torque and thrust values of model propeller from an existing submarine were measured. The experiments were carried out to cover the advance coefficient (J) ranging from 0.42-0.84; water speed in the tunnel was stayed at 3.5 m/s under the atmospheric condition. The advance coefficients were got by adjusting the rotational speed of the propeller (n). Uncoated and coated propellers were used to undergo open water tests. Each case was repeated 3 times for accurate results.

2.3. Model propeller tests

The propeller used for the test was a model (300 mm diameter) with the 1:8 ratios to an active duty submarine. And it was coated with the composite coating after surface treatment. A 600 L cylinder was filled with seawater and gravel, model propeller was moving at 500 rpm in the cylinder. Surface topography was recorded regularly. The equipment was simulating the impact of the seawater mixed with silt to propeller and its blades and mechanical property and cavitation resistance of the composite coating were evaluated.

2.4. Drag reduction tests

Skin friction from drag on propeller is of great importance to the performance of marine vehicles. And the drag reduction tests were carried out by using rotating disks [21-23]. The disks were fabricated from 304 stainless steel sheet stock and measured 22.86 cm in diameter and 0.3 cm in thickness. After sanding and rinsing the disks, they were coated with composite coating and biocide-based AF coating using air spray. Rotating disks were mounted to a variable speed electric motor equipped with a torque sensor. The torques generated during spinning of the disks which were used to calculate moment coefficients C_m . Before drag reduction tests, surface characterization measurements were performed using a probe type profiler (KLA-Tencor) to compare roughness and texture characteristic of composite coating and biocide-based AF coating. The specimens were examined at a scanning speed of 50 µm/s, with the signal sampling frequency 200 Hz and pressure 2 mg. After that, roughness of two coating was calculated by probe type profiler.

2.5. Seawater exposure methods

Test panels of copper alloy substrate (350 mm×250 mm×3 mm) were applied with composite coating system as table 1. And they were immersed in shallow submergence [24-25] at a depth of one meter in Qingdao Port after the top-coat was hard-dry. The gulf of Qingdao port has mature biomes and vigorous marine life, with the seawater flow less than 2 m/s. Scratches (1×40 mm) to primer and substrate were applied by cutting the coatings with a knife; the composite coats have been subjected to the salt spray test performed on scratched panels. Also the corrosion protective effect of epoxy primer could be found out. Regular observation by photographing should be carried out to investigate antifouling properties of the top-coat.

2.6. Real-ship application tests

Ship propeller was coated during docking. Surface of propeller and its blades was full of marine organisms, especially hard fouling. After removing them, propeller with copper alloy substrate was undertook surface treatment. When propeller surface was dry, garnets were used for lightly sweep sand. Propeller and its blade could get higher surface area; improve the interface adhesion with primer. And then roughness of the substrate reached to 50~75 μm . And then, surface was wiped by dilute to remove debris and dust in the process of sweep sand. Air spray was employed for the composite coating successively. And tie-coat and top coat should be a paint film once without repair. Track record usage of composite coating timely should be carried out during dock repair again.

3. Results and discussion

3.1. Weight loss for columns in two types of cavitation

As contrast to composite coating, blank column of copper alloy was eroded by cavitation, the morphology of its surface was showed in figure 1. The cavitation damage was severe and cavities appeared everywhere, and after 600 min, cumulative weight loss reached about 40 mg.



Figure 1. Eroded surface of copper alloy.

Cavitation can be achieved in two ways: one method was putting composite coating on tool head for 40 h and the other was hedging for 100 h. Weightlessness curves of test columns were obtained after a period of time in figure 2.

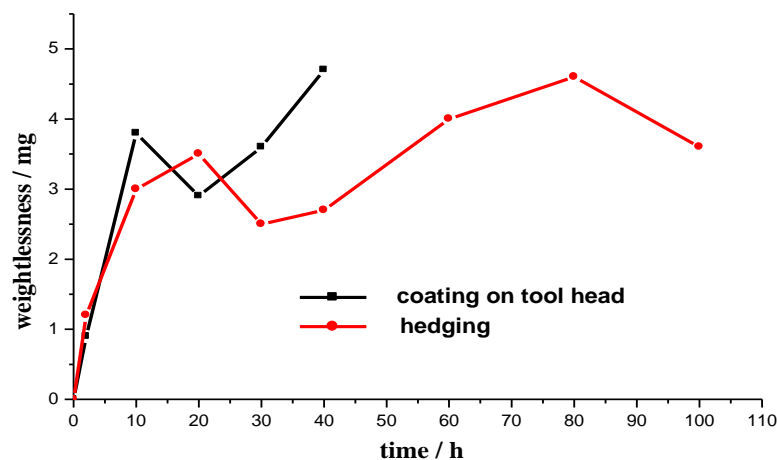


Figure 2. Weightlessness curves of test columns over time.

We could see that the composite coating had obvious weight loss within the first 10 hours from figure 2. Tested column for hedging received moderate growth from 10 to 20 hours and from 30 to 80 hours. After 10 hours, the composite coating kept relatively stable cavitation resistance property, for buffer epoxy coating, silicon tie-coat and fouling release top-coat were all elastomers. Three types of matching coat contributed to reduce the impact generated by cavitation bubble collapse, which establish a barrier from the propeller substrate. While the composite coating tested on tool head had slowly increased between 20 to 40 hours. The uncertainty analysis caused weight increase in both of them. In general, cumulative weight loss of tested columns was all less than 5mg on tool head for 40 h and hedging for 100 h. Also the surface characterizations of composite coating were got before and after the cavitation resistance tests from figure 3.

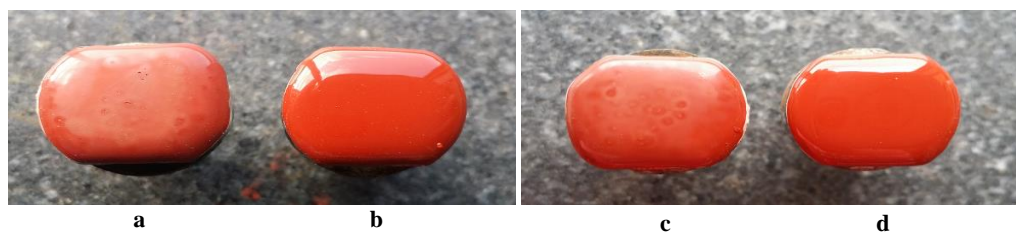


Figure 3. Surface characterizations of composite coating before and after cavitation tests: (a) coating on tool head for 40 h; (b) newly painted columns; (c) Hedging for 100 h; (d) newly painted columns.

The composite coating on tool head for 40 hours received some empty pits, only existed a few tiny breakages, but merely to top-coat. Also it was obvious in the presence of the light loss. For the other tested column hedging for 100 hours, less empty pits were appearing on the surface with no damage and coating film remained relatively intact with slightly loss of light. The visco-elastic fouling release composite coating acted as a damper absorbing the energy of cavitation noise and shock wave as collapse of cavitation bubbles, hence reducing damage of noise level.

3.2. Effects of propulsion and torque performance for the composite coating

Results of open water test were shown in figure 4 to compare the performance of the propeller blades with the uncoated and coated composite coating. In this figure propeller advance coefficient J , thrust

coefficient K_T , torque coefficient K_Q is defined as:

$$J = \frac{v}{nD} \quad K_T = \frac{T}{\rho n^2 D^4} \quad K_Q = \frac{Q}{\rho n^2 D^5} \quad (1)$$

Where v is the water velocity (m/s), n is the rotational speed of the propeller (r/min), D is propeller diameter (m), T is thrust (N), ρ is the density of water (kg/m^3) and Q is the torque (Nm).

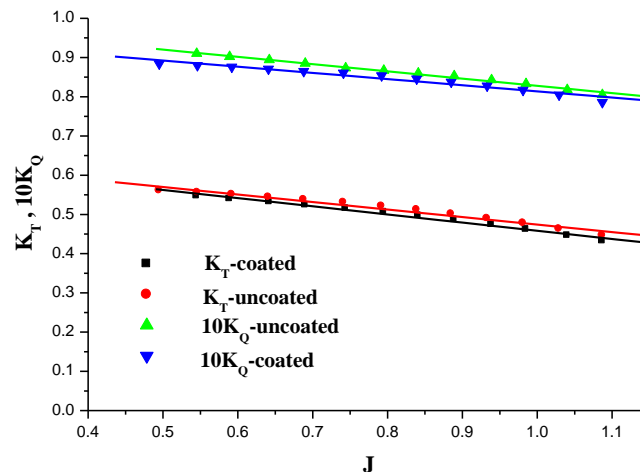


Figure 4. Comparison of open water test results for coated and uncoated cases.

Thrust coefficients of the blades without the composite coating were slightly higher than the coated blades by an average of 0.9%. This was also valid for the torque coefficient, as the blades with composite coating gave an average reduction of 1.6% compared to those uncoated blades. Based on the previous experiment results and present measurements we could conclude that the composite coating does not significantly affect thrust and torque property of the model propeller.

3.3. Flow erosion simulation

Four blades of the model propeller were coated different matching coating as table 2.

Table 2. Matching coating of four blades.

Blade A, B	Blade C, D
EP512	EP512
/	EP525
FR-01	FR-01
FR-02	FR-02

Blade A and blade B employed three layers without buffer epoxy coating compared to other two blades. Model propeller was rotating at the speed of 500 rpm after 300 hours. Seawater and gravel mixed in the cylinder simulated the severe marine environment, collided matching coating to accelerate wear behavior of coatings. Also cavitation performed to destroy matching coating during rotation. Characteristic photography of blade surface was obtained after 300 hours showed in figure 5.

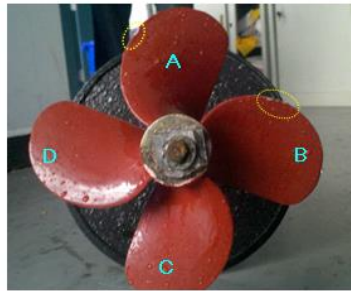


Figure 5. Photography of blade surface for 300 h.

We could see the leading edge of blade A and blade B appear small areas damaged, but matching coating of blade C and blade D kept relatively intact from figure 5. This phenomenon showed 4-layer coating system was matching better with good mechanical behavior and cavitation resistance.

3.4. Drag reduction performance comparing propeller coating to self-polishing coating

Drag reduction tests were carried out by comparing moment coefficients C_m between Zinc acrylate self-polishing coating (SPC Zinc) and the composite coating for propeller (propeller coating). And composition of two tested coating system were showed in table 3.

Table 3. Composition of the tested coating systems.

	SPC Zinc	Propeller coating
Anti-corrosive coat	EP501	EP512
Sealer	/	EP525
Tie-coat	EP507	FR-01
Top-coat	YF02	FR-02

Note: both of the tested coatings were prepared by Marine Chemical Research Institute Co. Ltd., The anti-corrosive coating of SPC Zinc comprised two layers, with a target dry film thickness of 100 μm while one layer and 50 μm to propeller coating; the target thickness for sealer coating was 50 μm to propeller coating; thickness of the tie-coat was 50 μm to SPC Zinc while 100 μm to propeller coating; top-coat consisted of three coats, with a target thickness of 200 μm while two coat to propeller coating with a target thickness of 200 μm .

In the tests, the friction disk machine was employed for the analytical tools necessary to characterize the roughness and drag, which also can be used to predict the skin friction for a flat plate with similar surface properties. The torques generated during spinning of the disks were used to calculate moment coefficients C_m ,

$$C_m = \frac{2Q'}{\rho\omega^2 r^5 \Phi^2} \quad (2)$$

Where Q' is the measured torque (Nm), ω is the angular velocity (rad/s), and r is the radius of the disk (m). Φ is the swirl factor, $\Phi=0.854$ [26] for the friction disk machine. The rotational Reynolds number Re for each moment coefficient was calculated from equation (3), as follows:

$$Re = \frac{\omega r^2 \Phi}{\gamma} \quad (3)$$

Where γ is the kinematic viscosity (m^2/s). The results of the drag reduction tests for the coated surfaces in the unfouled condition were given in figure 6. Variation of moment coefficients C_m with rotational Reynolds number Re between SPC Zinc and Propeller coating were presented for

comparison in figure 6.

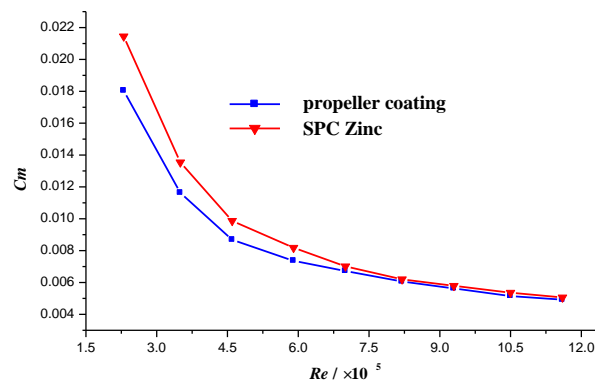


Figure 6. Smooth plate line for 300 h moment coefficients and rotational Reynolds number.

At the lowest Reynolds number, the SPC Zinc coating showed rapid growth in C_m compared to propeller coating. Moment coefficients gradually decreased with the rotational Reynolds numbers grew larger. Moment coefficients gave a rapid decline in the low Reynolds number region while mild fall in high Reynolds number area. Both coatings presented similar downtrend in the second half of the experiment, which was attributed to Reynolds number effect. For the bigger Reynolds number, the weaker viscous effects and the smaller the coefficient of friction. Generally speaking, propeller coating expressed relatively low moment coefficients in all process of the tests compared to SPC Zinc coating and showed obvious drag reduction performance especially in the low Reynolds number region.

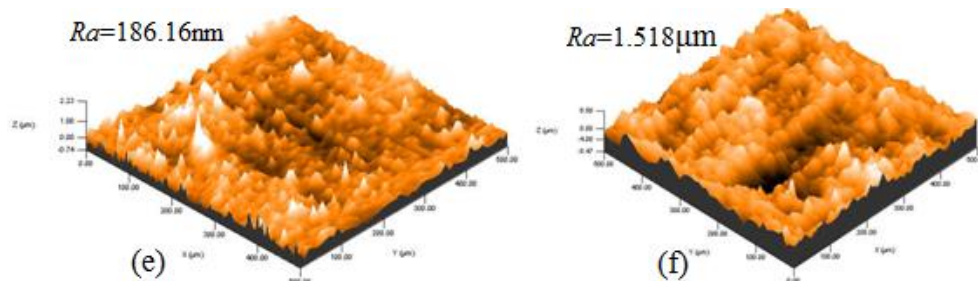


Figure 7. Surface profile of propeller coating (e) and SPC Zinc coating (f).

The main difference between propeller coating and SPC Zinc coating lay in characteristics, as shown in figure 7 for two typical roughness profilograms. The SPC Zinc coating surface gave a spiky closed texture (e, $R_a=1.518 \mu\text{m}$) whereas the fouling release propeller coating (f, $R_a=186.16 \text{ nm}$) displayed a small proportion of short-wavelength roughness. It was thought the rheology of coating is significantly different for fouling release propeller coating and SPC Zinc coating. Today, the growth of the boundary layer contributed the most to cavitation, while roughness of blades accelerated boundary layer transition from laminar to turbulent flow and caused cavitation generating. Smooth surface of fouling release propeller coating not only could reinforce cavitation resistance but also reduce mucus wetting area to coating, at the same time it can effectively reduce the frictional resistance to seawater with excellent drag reduction.

3.5. Fouling release property by seawater exposure methods

Seawater exposure methods were carried out lasting 34 months from June 29th, 2012 to April 15th, 2015. Three years later, test boards with fouling release propeller coating were taken out of the

seawater. And photos were taken about growth of marine organisms on testing boards from Figure 8. Large coverage by soft fouling such as sponges was investigated. Some algae occupied half of the third board from Figure 8 (g) Only a few sea squirts were caught in the middle of first two boards in Figure 8 (g). Only two barnacles at the edge of the third block within 20mm should be overlooked for edge effect, while the wooden frames which were used to fasten samples were densely occupied by barnacles.

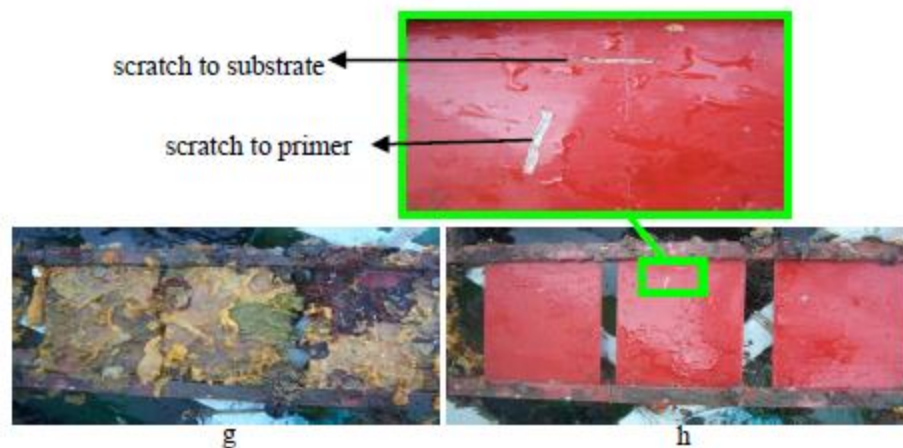


Figure 8. Photos of matching coating for seawater exposure(g: initial state after 34 months; h: test boards after scouring).

Fouling on test board was easily removed through the scour of seawater; propeller coating was free from adhesion of marine organisms and expressed release from fouling. Water on coating surface gathered to some layers which showed low surface energy properties. Also scratches damage to substrate and primer obtained to investigate anticorrosive property to primer without diffusion phenomenon under matching coating appeared in the enlarged picture.

3.6. Fouling release property for seagoing vessel

Propeller blades were contaminated with many species of marine organisms at dock as figure 9. after a period of time in service. From the picture, it had been difficult to find out the propeller surface which was full of mature barnacles like craters and white tube worms. Test boards had dense growth of tubeworms with barnacles and calcareous shells brown in color in fouling ratings in the level of 90 [27].



Figure 9. Biofouling on blades of propeller at docking site.

Biofouling contributed to a sharp increase in fuel consumption and a remarkable reduction in propulsion efficiency. Also, adhering of marine organisms led to uneven weight blades which arousing unsafety and accidents. During maintenance and repair, all the marine organisms were removed away; also surface treated was carried out to propeller base. After that, cavitation resistance fouling release propeller coating was applied to propeller.

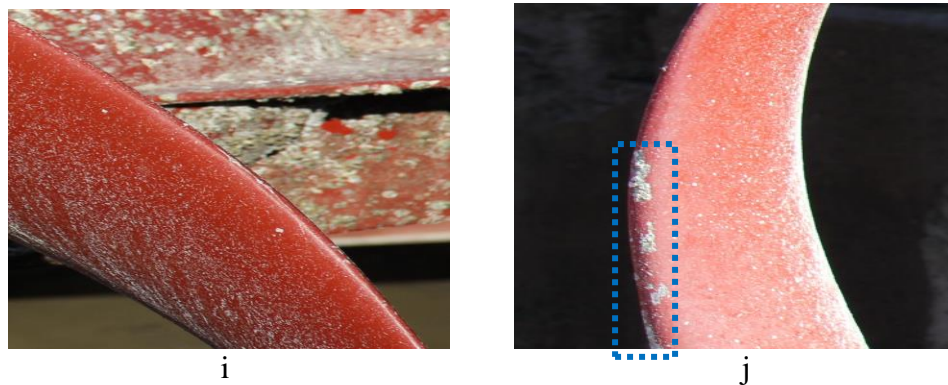


Figure 10. Surface after six months service.

After operating for 6 months, we found matching coating showed integrity overall from the left picture of figure 10. merely small areas damaged in the leading edge (blue dashed box) with no diffusion under the composite coating.



Figure 11. Appearance of the whole blade after sixteen months service.

Characteristics of the whole blade were shown in figure11. After 16 months navigation, some calcarina were adhering on the inside of the blade, while very few were on the central axis of the blade. After washing, the blade was free from any marine organisms. Also detail image on top of the blade after 16 months was given in figure 12. Calcarina was gathering on top of the blade.



Figure 12. Detail image on top of the blade.

Drop of water like sphere did not spread after washing which exhibit low surface energy. From the

detail, it presented a small regional breakage at the leading edge with water meeting. Also, property of composite coating was keeping track of investigation.

4. Conclusions

The experimental study and practical application were carried out to investigate the property of fouling release coating on the performance, cavitation resistance and antifouling to marine propeller. And try to correlate surface characterization with nature of composite propeller coating. Some conclusions drawn from the study are as follows:

Cavitation resistance tests were undertaken to study withstanding cavitation shock of composite propeller coating. Weightlessness curves of test columns demonstrated weight loss within 5 mg for two methods; Thrust coefficient and torque coefficient of the composite propeller coating had no influence in hydrodynamic performance; Model propeller kept intact and matched better with good mechanical behavior and cavitation resistance after rotating for 300 h; Characteristics of propeller coating expressed much flatter to SPC Zinc coating which delaying boundary layer transition from laminar to turbulent flow and cavitation bubbles generation. Seawater exposure tests last nearly 3 years; soft fouling such as sponges was easily removed after washing, also, fouling release propeller coating was effective to hard fouling. Generally speaking, cavitation resistance fouling release propeller coating had no toxic anti-fouling compounds and was safe to health of construction workers and marine environment. Also, obvious properties in cavitation resistance and antifouling were given, including remarkable drag reduction. All of these were essential to present high efficiency and extend the service life for propellers.

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