Friction Increase due to Roughness of Ship Hull Paint

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IMO adopted a revision of MARPOL Annex VI to establish the Energy Efficiency Design Index (EEDI) for new build ships in July 2011. The target EEDI will be tightened incrementally until 2025. The ship hull roughness is one of the most important factors that affect ship resistance and efficiency. In this study, friction measurements of cylinders painted with antifouling paint were conducted using double rotating cylinder equipment. Some antifouling paints showed lower Rz and higher RSm values, thus resulting in lower Friction Increasing Ratios (FIR) of currently available antifouling paints. Actual ship hull surface roughness is measured using a roughness analyzer that can measure only Rz at a standard length of 50mm. However, the Rz value alone does not provide enough information to predict friction. Therefore, the replicate method was developed in order to analyze the hull roughness parameters. Roughness analysis using both roughness amplitude and wave length parameters is shown to be very useful for predicting more accurately the ships' friction resistance.

1. Introduction

Global warming resulting from greenhouse gas (GHG) emission and depletion of fossil fuel resources are global concerns. These environmental issues are major concerns for the shipping industries as well. An investigation by IMO reports that the carbon dioxide emissions from global shipping activities to be 2.7% of the world-wide CO2 emission. As a result IMO adopted a revision of the MARPOL treaty annex VI to introduce the EEDI (energy efficiency design index) in July 2011. The EEDI is calculated in the vessels design phase, and confirmed during the sea trials. The EEDI requirement baseline will be tightened until 2025 after the treaty entered into force on January 1st 2013. Hence every shipbuilder is facing with the requirement to improve the energy efficiency by all possible means such as optimizing the ship’s shape or improvement of the additional facilities such as propellers. Friction resistance is responsible for 60 - 80 % of the remaining resistance after the vessel's shape has been optimized for long time. Hence reduction of the friction resistance is the method to effectively further improve a ship's fuel economy. Air lubrication systems and the Toms effect have been introduced as the technologies used to reduce the frictional resistance of vessels. Those technologies are promising method, because lower friction forces than a smooth surface can be obtained from them. As of today the former technology has only been applied on a very limited number of vessels and the latter is only in the phase of experimental research. On the other hand, antifouling paints have been applied in an attempt to prevent the attachment of marine organisms to the ship's hull aiming to limit the increase of fuel consumption by those extraneous causes. These paints are already significantly contributing to energy saving operation resulting in limiting the emission of greenhouse gas. It is important to create a surface structure that will cause as little drag as possible by management of the paint application and by using an antifouling paint that will create a smooth surface because they are applied on the bottom of the hull which directly contact with sea water. Preventing the increase of the surface roughness by management of the paint application and using smooth surface antifouling paints can play a major role in the reduction of the greenhouse gas emission. Nevertheless, the information regarding surface roughness profile of vessels and the increase of friction due to surface roughness is very limited. In this technical information, the progress of surface roughness measurements and friction research by the authors and collaborative study members will be discussed. It is Chugoku Marine Paints’ challenge to reduce the hull resistance and to develop a new generation low friction, fuel saving self-polishing antifouling paints. The "SEAFLO NEO" will also be introduced.

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2. Paint surface roughness and hull resistance

Drag worked on a vessel during in service can be divided into three categories: wave making resistance, form resistance and friction resistance. Hence, a non-dimensional coefficient of the total resistance resulting from drag force, speed, immersed surface and mass density of the fluid is defined by the following equation.

\[ C_t = C_w + (1+K)C_f + \Delta C_f \]

where, 
- \( C_t \): Total resistance
- \( C_w \): Wave making resistance
- \( (1+K)C_f \): friction resistance + form resistance
- \( \Delta C_f \): correction term (roughness).

\( \Delta C_f \) is a correction value that is calculated from the difference between the power curve from sea trial results and the design power curve calculated from towing test results of a model of the vessel. \( \Delta C_f \) includes all kinds of effects like welding beads, design error, hull surface roughness. The major part of the \( \Delta C_f \) is regarded as friction increase that caused by hull surface roughness. Hence reduction \( \Delta C_f \) by minimizing the paint surface roughness directly corresponds to the fuel economy of the vessel. Irregularly flowing turbulent water flow will always be present on the surface of fast steaming vessels. And a layer near the hull body is called “turbulent boundary layer”. There is a very thin layer called the “viscous sub-layer” at the bottom of the turbulent boundary layer. When the hull roughness is smaller than the thickness of the viscous sub-layer the surface is called a “hydraulically smooth surface” and there is no change in friction resistance. However when the hull roughness is greater than the thickness of the viscous sub-layer, this layer is unable to hide the peaks and roughness will influence friction. The thickness of the viscous sub-layer depends on the speed of the vessel. With greater speed it is thinner than with lower speed. The thickness of the viscous sub-layer varies with speed the practical value for ships and allowable roughness is verified to be approximately 10 to 30 micrometer. \( \Delta C_f \) or Brake Horse Power (BHP) prediction methods have been proposed using a calculated average hull roughness (AHR) that is generated from large number of measurement data from every hull area using this instrument. On the other hand, the inaccuracy of predictions of the roughness effects on friction only using the roughness height parameter has already been pointed out in literature. For example, the relation between the friction coefficient (Cf) in a vertical axis and the Reynolds number in a horizontal axis are shown in Figures 1 and 2. In the case of sand-roughness (extreme short wavelength roughness) the friction coefficient becomes constant with increasing speed as shown in Figure 1. The characteristic of friction increase arise by vortex in the vicinity at the tip of roughness. However the friction increase is

3. Hull roughness measurement and friction resistance

The prediction of a vessel's resistance from hull paint roughness data has been attempted for a long time. The "BSRA HULL ROUGHNESS ANALIZER" a hull roughness measuring instrument has been used as the standard roughness measuring method in the ship-building industry from decades ago. This instrument only measures the gap between maximum peak and trough in a given length of 50 mm. \( \Delta C_f \) or Brake Horse Power (BHP) prediction methods have been proposed using a calculated average hull roughness (AHR) that is generated from large number of measurement data from every hull area using this instrument. On the other hand, the inaccuracy of predictions of the roughness effects on friction only using the roughness height parameter has already been pointed out in literature. For example, the relation between the friction coefficient (Cf) in a vertical axis and the Reynolds number in a horizontal axis are shown in Figures 1 and 2. In the case of sand-roughness (extreme short wavelength roughness) the friction coefficient becomes constant with increasing speed as shown in Figure 1. The characteristic of friction increase arise by vortex in the vicinity at the tip of roughness. However the friction increase is

![Figure 1 Friction increase due to sand-roughness.](4)

![Figure 2 Friction increase due to wavy-roughness.](4)
parallel to the friction coefficient of smooth surface due to increase of speed, in the case of longer wavelength of roughness (wavy-roughness) as shown Figure 2. Furthermore, it has been reported that the degree of resistance increase depending upon the inclination of wavy roughness differs. In this literature, results of recent studies by the authors and collaborative study members regarding this friction increase due to wavelength and height parameters of wavy-type roughness are introduced. Dynamic numerical simulation (DNS) has been performed on sinusoidal walls that possessing several wavelength and amplitude ratios by Tokyo University of Agriculture and Technology to explain friction increase phenomena on that wavy-roughness. From this simulation it became clear that the friction force on roughness turned out to be the total sum of wall shear stress and local pressure resistance on the roughness. The integral of wall shear stress variation became zero, and the friction increase due to roughness was mainly caused by pressure resistance on the roughness when the ratio of wavelength and amplitude was greater than ten. Tokyo University of Science conducted the double rotating cylinder test with two-dimentional geometrical roughness. Friction increasing ratio was observed to vary depending upon roughness pitch and height. Afterward they tried to divide the friction factors into wall share stress and pressure resistance by roughness height and pitch, and verified result by using flow speed distribution analysis with LDV (Laser Doppler Velosimetry). The authors also have been conducting similar friction tests using artificial wavy-roughness and three-dimensional artificial roughness. As the artificial roughness's wavelength became shorter and roughness height became higher, the friction tends to increase (Unpublished results). Super high precision parallel plate towing tank test were conducted by the National Maritime Research Institute with variation in roughness height and pitch two-dimensional geometrical roughness formed on a flat plate. The friction increase ratio was also varied by changing wavelength and height of the roughness. By using parameters of wavelength, amplitude, and viscous sub layer thickness, the resistance increase was estimated, and it was verified that the actual towing tank results is in agreement with estimated results. On the comparison test between painted surface and on a blasted surface undertaken with the parallel plates mentioned earlier, the differences in friction increase property between “Sand-roughness” and “Wavy-roughness” have also been confirmed. These evaluation results suggest that it is highly important to have parameters include wavelength and height for roughness and viscous sub layer’s thickness of actual vessels. Furthermore, evaluating the each parameter to find out how they affect the fluids on wall shear stress and pressure resistance vicinity of roughness is necessary. Finally, evaluation of these parameters effect for friction resistance on actual vessels is important.

4. Measurement of the surface roughness and analysis of the roughness parameters and visualization.

The patterns and size of surface roughness are significantly different as a result of the mechanisms by which the roughness is formed. The roughness measurement method must be chosen in accordance with size and hardness of the tested surface. For example, roughness patterns formed by mechanical processing or blasting are decided by the edge and shape of the blade and processing interval or the shape of blasting media (sand, grid or steel shots). Such roughness patterns formed by mechanical processing tend to have short wavelength. In the case of high resolution equipment with a thin contact needle or non-contact laser displacement meter (especially roughness measurement for soft surface) is suitable. In the case of smaller or nano-order scale structures such as paint pigment roughness or biomicrosopic-surfaces, confocal laser scanning microscopy or Atomic Force Microscope (AFM) is suitable, because these methods have extremely high resolution. In this section, the roughness analyzer of which the authors use for measuring the roughness of paint film, and the analysis cases of surface roughness are introduced. Roughness pattern of the paint film also varies depending on the factors with the way the roughness is formed. The painted surfaces tend to have longer wavelengths and larger profiles than those of mechanically processed surfaces. Hence, the measurement in narrow given length is not suitable. Thereupon, authors developed the equipment capable of measuring cross-sectional profile of surface roughness by scanning the area of 30 mm x 30 mm (with 121 points at 250 micron meter x 121 line), where the test plate was set to the laser displacement meter attached to X-Y stage. By the use of this equipment a three dimensional profile was created and roughness parameters such as Rz, Rzjis, Rc, Ra, Rq, Rsk and Rku (JIS B 0601) in a given length of 30 mm were calculated at the same time. The evaluation conducted with this equipment is highly convenient, because it is possible to identify the surface pattern by a three-dimensional visual image and numerical parameters. An example measurement of a number of surface roughness patterns are shown in Figure 3. The maximum height (Rz) of current antifouling paints and dry spray roughness exceeds 100 micrometer, whereas Rz of "SEAFLO NEO" and "Silicone foul release coatings" are 50-60 micrometer. Also, Wavelength parameter (RSm) tend to become longer as 1871 micrometer for...
"Dry spray", 3454 micrometer for current self-polishing antifouling paint, 5255 micrometer for "SEAFLO NEO" and 6703 micrometer for silicone foul release coating. The extremely short wavelength "Dry spray" is understood to belong to the group of "sand roughness", and the ones with long wavelength "Silicone foul release coating" and "SEAFLO NEO" are understood to belong to a small slope in the group of "wavy-roughness". It is understood that the measurement with this equipment obtains the difference of paint film surface relatively accurately, therefore setting of evaluation length, measurement pitch and resolution is being set appropriately. Shortening of the measurement pitch is required only when Dry Spray is to be measured as it has extremely short wave length. The evaluation length of 50 mm is suitable in order to grasp the characteristics of surface roughness appropriately, and this is one of the reasons for the setting of measurement length of conventional BSRA roughness analyzer.

5. Roughness and friction evaluation using double rotating cylinder equipment

The authors use double rotating cylinder equipment to evaluate the friction resistance of coating roughness. This equipment filled with deionized water of which the temperature is being maintained to be 23 Celsius degrees by thermo controller, in a stainless steel rotating cylindrical water tank with internal diameter of 320 mm. Antifouling paints is applied on the test cylinder of poly vinyl chloride with the external diameter of 310 mm processed by lathe, and it was immersed into the rotating water tank. On the upper support shaft of the inner cylinder a torque meter was installed to measure the torque resulting from the rotating movement of the outer cylinder. For these experiments the outer cylinder is rotated at 1000 rpm. With this equipment the chance of installation error is extremely low, and constant rotation condition can be maintained at all the time, therefore the reproducibility of measurement is quite high. Furthermore, the viscosity of the hydraulic fluid is able to be maintained constant as the temperature is controllable. By carrying out the reproducibility test for one year by using unpainted cylinder with diameter of 310 mm, the deviation of each measurement was

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found to be in a range from -0.5% to +0.5% from 6.48 Nm at 1000 rpm speed. In this set-up the gap between inner cylinder and outer cylinder is only 5 mm, hence an effect of film thickness on the measurements cannot be avoided. Experiments were conducted to estimate the effect of film thickness using a 309 mm and a 311 mm diameter smooth cylinder. The 311 mm cylinder acts as +0.5 mm film thickness and the 309 mm cylinder as a -0.5 mm film thickness. The cylinders were prepared by lathe processing. The torque for the 309 mm cylinder is 6.30 Nm, the torque for the 311 mm cylinder is 6.84 Nm (see Figure 4). The torque increase with increasing diameter is obvious. This can be explained by a thinner boundary layer because of the shorter distance between the inner and the outer cylinder. Hence a film thickness correction is necessary for evaluation of the friction caused by painted inner cylinders. Because exact determination of the paint film thickness or the diameter of the painted cylinder is impossible the film thickness of a single coat of paint is assumed to be 125 micrometer. A double coat is assumed to be 250 micrometer. The torque of a smooth cylinder at those diameters is read from Figure 4 as 6.55 Nm for the single coat and 6.63 Nm for the double coat. The resistance increase generated by this equipment is understood that it is mainly due to the friction resistance caused at outer wall of painted cylinder. Therefore, the increase ratio from corrected mirrored torque by film thickness when outer cylinder is rotated at 1000 rpm, is defined as the Friction Increase Ratio (FIR). FIR is defined by following equation (1).

$$FIR(\%) = \frac{T - T_0}{T_0} \times 100(\%) \quad \text{(equation 1)}$$

where, $T =$ torque (Nm) on a painted inner cylinder

$T_0 =$ torque (Nm) on a smooth surface inner cylinder at (corrected for film thickness).

The friction speed $u^*$ was calculated from shear stress using equation (2). Wall shear stress $\tau_w$ was calculated from the measured torque for the 310 mm smooth cylinder at a rotating speed of 1000 (rpm). The thickness of the viscous sub-layer is estimated as twelve micrometer from non-dimensional distance $y^+ = 5$ using wall row (9). The viscous sub-layer therefore is thin enough for evaluating the effect of the roughness of an actual vessel. In the case of lower speed tank test we have found significant lower friction increase values for same patterns of roughness than higher speed test (unpublished results). Those results indicate that the reproduction of thin viscous sub-layer without changing roughness scale equivalent to actual vessels’ is highly important.

$$u^* = \sqrt{\frac{\tau_w}{\rho}} \quad \text{when} \ 0 < u^*y/v < 5 \ * \ \text{viscous sub-layer} \quad \text{(equation 2)}$$

where, $u^*$: friction speed

$\rho$: density of water (23 degree of Celsius)

$\tau_w$: wall shear stress

$y$: distance from the wall

$v$: dynamic coefficient of viscosity (23 degree of Celsius).

This experiment was conducted to confirm the effect of surface roughness on friction. Therefore various antifouling paints were sprayed on 310 mm diameter cylinders reproducing the painting conditions suitable for painting vessels in the dry dock. Changes in friction due to the different cylinder surfaces were evaluated. The following method was used to measure the surface roughness of the painted cylinders. The test cylinder was rotated at about 0.5 rpm and displacement from the rotating cylinder was measured using a confocal laser displacement meter that was fixed on the equipment. Forty thousand data points were generated for one round (one meter length). In this way the sampling pitch is 250 micrometer, which is same as when using the desktop roughness analyzer explained in paragraph 4. Measurement is done on 10 lines starting at 50 mm from the bottom to the top and spacing of each measurement line is set at 25 mm. Each measurement line is divided into 20 sections of 50 mm. Surface roughness parameters $R_z$, $R_{zj}$, $R_c$, $R_a$, $R_q$, $R_{sk}$, $R_{ku}$ and $R_{Sm}$ (JIS 0601) in these 50 mm evaluation sections are calculated. Averages of the parameters at 200 points are calculated to obtain representative parameters for each cylinder.

### 6. Friction and roughness evaluation results from the double rotating cylinder test

The result of this test has been already reported in the conference proceedings of the Japan Society of Naval Architects and
The evaluation was undertaken by using maximum height (Rz) in a given length of 50 mm and the average length of the factors (RSm) as representative parameter for height, since (Rz) is easily be compared with currently available roughness measurement data. Figure 5 indicates FIR in vertical axis and Rz in horizontal axis gathered from table 1. On the graph, it indicates that the higher the roughness is the more the resistance increases, however it was also verified that the high and low resistance are mixed even at the same Rz value. On Figure 6, it indicates RSm in horizontal axis and FIR in vertical axis. It is verified it tends to have higher FIR when wavelength is short. Furthermore, Figure 7 indicates the square of roughness height divided by wavelength as being reported value. On Figure 6, it indicates RSm in horizontal axis and FIR in vertical axis. Relatively good correlation is indicated with the exception of dry spray shown as DS (delta plot) in Figure 7. From the above fact, it is understood that the friction resistance increase against mirror surface can be estimated easily by using the following equation (3) when Rz and RSm are measured, with the exception of short wavelength and high roughness of Dry Sprays. With the speed range of this study, the influence of viscous sub layers thickness was not considered because it was sufficiently thin, however, it is necessary to take viscous sub layers thickness into consideration when evaluating friction increase of the slow speed areas.

Table 1 Roughness parameters and FIR of cylinders. (10)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rz (µm)</th>
<th>Rzjis (µm)</th>
<th>Rc (µm)</th>
<th>Ra (µm)</th>
<th>Rq (µm)</th>
<th>Rk (µm)</th>
<th>Rku (µm)</th>
<th>RSm (µm)</th>
<th>FIR (%)</th>
</tr>
</thead>
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<td>N_SPC</td>
<td>31.8</td>
<td>21.5</td>
<td>22.5</td>
<td>8.5</td>
<td>10.7</td>
<td>0.3</td>
<td>5.1</td>
<td>1094</td>
<td>0.80</td>
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<td>11.1</td>
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<td>3.2</td>
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<td>0.1</td>
<td>2.8</td>
<td>9907</td>
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<td>27.4</td>
<td>9.7</td>
<td>12.1</td>
<td>0.2</td>
<td>2.8</td>
<td>8986</td>
<td>1.21</td>
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<td>36.5</td>
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<td>9.6</td>
<td>12.1</td>
<td>0.3</td>
<td>5.4</td>
<td>6904</td>
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<td>9.8</td>
<td>12.7</td>
<td>0.7</td>
<td>5.9</td>
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<td>1.37</td>
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<td>2.9</td>
<td>4225</td>
<td>1.79</td>
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<td>C_SPC</td>
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<td>42.9</td>
<td>15.5</td>
<td>19.5</td>
<td>0.3</td>
<td>5.2</td>
<td>3527</td>
<td>5.99</td>
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<td>0.6</td>
<td>3.6</td>
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<td>11.2</td>
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<td>116</td>
<td>65.4</td>
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<td>29.1</td>
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<td>72.5</td>
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<td>3.0</td>
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Table 2 Correlation analysis between the surface parameters. (10)

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<tr>
<th>Parameter</th>
<th>Rz</th>
<th>Rzjis</th>
<th>Rc</th>
<th>Ra</th>
<th>Rq</th>
<th>Rk</th>
<th>Rku</th>
<th>RSm</th>
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<tr>
<td>FIR (%)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>Rzjis</td>
<td>0.99</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rc</td>
<td>0.99</td>
<td>0.98</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Ra</td>
<td>0.99</td>
<td>0.98</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Rq</td>
<td>1.00</td>
<td>0.98</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rk</td>
<td>0.55</td>
<td>0.50</td>
<td>0.52</td>
<td>0.51</td>
<td>0.54</td>
<td>1.00</td>
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<td>RSm</td>
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<td>-0.43</td>
<td>1.00</td>
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Figure 5 Relation between Rz and FIR (10)

Figure 6 Relation between RSm and FIR (10)

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\[
E_{-FIR} = 2.62 \times \frac{R_{z}^2}{RSm} \quad \text{(equation 3)}
\]

The resistance increase of Dry Spray greatly deviated from the correlation, compared to the resistance increase of other specimens. One possibility as a reason of above mentioned matter is that the wavelength shorter than 1000 micron meter was not appropriately measured as the roughness measurement interval of this study was 250 micron meter. Another possibility is that the resistance increase was large because it was in the form of sand roughness of which generates peel-off at the tip of roughness due to large roughness slope as explained in paragraph 3.

Three types of antifouling paints have been tested, Current self-polishing paints as C_SPC (diamond symbols in Figures 5, 6 and 7), "SEAFLO NEO" as N_SPC (circle symbols) and “Silicone foul release coating” as FRC (square symbols). Observed Rz for current self-polishing coating are between 21.0 and 161 micrometer, RSm are between 3096 and 4225 micrometer, and the resulting FIR are between 3.8 and 21.6%. FIR is calculated as 5-10% for the Rz range of 75 -125 micrometer. This range is considered as standard for new building vessels. The Rz value of "SEAFLO NEO" ranged between 18.4 and 66.2 micrometer and RSm ranged between 4400 and 6694 micrometer. These roughness profiles are of lower height and longer wavelength than that of C_SPC, and the FIR range was 0.8 - 1.6%. For “Silicone foul release coatings” Rz ranged between 54.3 and 55.0 micrometer and RSm ranged between 8321 and 8506 micrometer. This is the longest wavelength in this investigation. The resulting FIR values ranged between 1.21 and 1.44%. Although the viscous sub-layer is extremely thin, the friction increase ratios for Silicone antifouling paints and for "SEAFLO NEO" are still less than 2%. If those extremely smooth surfaces are reproduced on actual vessels, the friction increase due to roughness will be extremely low. "SEAFLO NEO" is based on a newly developed low viscosity self-polishing polymer to make low VOC (Volatile Organic Compound) content possible. Rheology control is undertaken through choosing the optimal additives for improving new polymer’s leveling properties to achieve smooth surface. Other development targets of this product were an increased efficiency of paint transfer from the spray gun to the surface to be painted and a reduction of the average time necessary for application. Those were to be achieved by increasing the volume solids of the paint. The National Maritime Research Institute has carried out tests to establish the spraying properties of the paint under different wind and spray gun distances. These tests were carried out in a wind tunnel. Results showed that even in very adverse conditions of high winds combined with high gun distance both transfer efficiency and dust dispersion were improved. (11) As already introduced in this article, an extreme increase in friction is observed at extremely short wave length that are typical for "Dry spray" roughness. It is important to avoid the formation of spray dust in the paint application process. The dust formation prevention property of “SEAFLO NEO” proves greatly effective to avoid "Dust spray" type surface roughness. The VOC (volatile organic compounds) content of "SEAFLO NEO" is very low. This contributes to the reduction of VOC emission and therefore to control of air pollution. The low odor of the product contributes to the improvement of operation environment. The high volume solids combined with the improved paint transfer efficiency results in a reduction of the paint consumption and therefore in a reduction of the number of paint containers required and application cost. Reduction of CO₂ and VOC emission, reduction of waste, reduction of paint consumption and reduction of the cost of application are advantages of this antifouling paint. The Industry-academia-government cooperation that led to the development of “SEAFLO NEO” has received credit. The National Maritime Research Institute, Hitachi Chemical Company Ltd. and Chugoku Marine Paints Ltd. were awarded the Minister of Land, Infrastructure, Transport and Tourism Prize at the 10th Industry-Academia-Government Collaboration Contribution Awards in September 2012. For further improvement it is necessary to improve the entire paint system. Chugoku Marine Paints have started to sell new ultra low roughness anticorrosive paints (BANNOH 1500 series). Improvements are based on the same theory as above. Fuel savings by reduction of the roughness of the outer shell of vessels, VOC reduction and reduction of paint consumption will continually be promoted.

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7. Roughness analysis on actual vessels

Past literature and this study indicate there is an effect of roughness height and wavelength parameters on friction. However there is very little information on the roughness parameters for actual vessels. To run a roughness parameter analysis on actual vessels, replicate samples were collected from four new building vessels that were being built in the same shipyard. A thermo plastic resin was used to replicate the hull roughness. This plastic resin is easily softened by heating it to around 60 degree of Celsius. Replicates were made by pressing the warm material firmly to the paint surface. The replicate shape was settled after cooling and samples can easily be removed from the hull without any damage to paint surface. Hence roughness sampling using this replicate method can easily be conducted on actual ships. From a total of nine to fifteen points on each vessel a replicate sample was collected. In principle five samples (1: fore part 2: fore erection part 3: middle part 4: after erection part 5: after part) were taken from both sides of the vertical bottom and of the flat bottom. Due to the building schedule, sampling was not able to be carried out on some erection parts of vessels no.3 and no.4. Roughness analysis was conducted using the laser roughness analyzer after the replicate samples were brought back to laboratory. Rz and RSm distribution analysis result are shown in three-dimensional bar graph in Figure 8.

Average Rz and RSm values of Ship No.1 which was painted with “SEAFLO NEO” were 60.7 micrometer and 4909 micrometer respectively. Compared with the other vessels that were painted with “Current SPC” Ship No.1 tends to have lower roughness and longer wavelength profiles. Estimated FIR (E_FIR) calculated by equation (3) for Ship No.1 is 2.0 %. Average Rz and RSm of Ship No.2 is 80.1 micrometer and 3481 micrometer respectively. Calculated E_FIR for Ship No.2 was 4.8 %. Average Rz and RSm of Ship No.3 is 87.3 micrometer and 3711 micrometer respectively. Calculated E_FIR for Ship No.3 is 5.4 %. Average Rz and RSm of Ship No.4 are 79.7 micrometer and 4417 micrometer respectively. Calculated E_FIR for Ship No.4 is 3.8 %. The values are listed in Table 3. The minimum Rz value for each vessel is lower than the 75 - 125 micrometer range that typically results from the tests using the BSRA analyzer. Apparently in this shipyard the hull roughness control is very good, 1.8 - 3.4 % of friction difference between “SEAFLO NEO” painted vessel, and “Current Antifouling paint” painted vessels is estimated. According to 80 % of friction resistance for large blunt hull vessels, 1.4 - 2.4 % of fuel efficiency improvement is estimated for this vessel. Because the conditions under which the sea trials were carried out vary considerably because the influence of small deviations from the design can rather significantly influence fuel efficiency.

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consumption, direct comparison is very difficult. However in general a 1 - 4 % reduction in fuel consumption is observed for vessels painted with "SEAFLO NEO". The prediction of 1.4 - 2.4 % reduction in fuel consumption seems to be a reasonable result.

Table 3 Rz, RSm and estimated FIR value on actual vessels (10)

<table>
<thead>
<tr>
<th>Ship</th>
<th>Coating</th>
<th>Rz range (micrometer)</th>
<th>RSm range (micrometer)</th>
<th>Rz average</th>
<th>RSm average</th>
<th>E_FIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td>N_SPC</td>
<td>25 – 100</td>
<td>4500 – 6000</td>
<td>60.7</td>
<td>4909</td>
<td>2.0</td>
</tr>
<tr>
<td>No.2</td>
<td>C_SPC</td>
<td>50 – 125</td>
<td>3000 – 5000</td>
<td>80.1</td>
<td>3481</td>
<td>4.8</td>
</tr>
<tr>
<td>No.3</td>
<td>C_SPC</td>
<td>50 – 125</td>
<td>3500 – 5000</td>
<td>87.3</td>
<td>3711</td>
<td>5.4</td>
</tr>
<tr>
<td>No.4</td>
<td>C_SPC</td>
<td>50 – 125</td>
<td>3000 – 8000</td>
<td>79.7</td>
<td>4417</td>
<td>3.8</td>
</tr>
</tbody>
</table>

8. Conclusions

For further improvement of the vessel fuel economy, we consider accurate roughness analysis and friction testing under conditions similar to those of sailing vessels essential. In this project high precision roughness analysis and double rotating cylinder tests to measure resistance have been conducted and the following results have been obtained.

1) The thickness of the viscous sub-layer in the double rotary cylinder test has been calculated as twelve micrometer using “wall-low”. The double rotary cylinder method is considered to be an effective evaluation methodology for friction due to surface roughness.

2) The Friction Increase Ratio of dry spray is typically between 29.1 % and 36.2 %. Dry spray roughness has a very short wavelength. At the building site care has to be taken to prevent this kind of roughness.

3) Roughness of silicone foul release coatings and next generation self-polishing paints such as “SEAFLO NEO” tends to have a lower height and longer wavelength profile. The resulting Friction Increase Ratios are lower than those of current antifouling paints. Improvement of leveling performance is considered as an effective tool for further friction reduction.

4) With higher roughness and shorter wavelengths an increase in friction is observed. FIR can be estimated using equation 3.

\[ E_{FIR} = 2.62 \times \frac{Rz^2}{RSm} \] (equation 3)

5) Actual hull roughness analysis that includes height and wavelength parameters was conducted in this study using the replicate method. "SEAFLO NEO" is shown to have lower roughness and longer wavelength than “current” products. A maximum 50 point roughness analysis for one vessel has been carried out. This method is one of the promising methods to analyze actual hull roughness.

Goals for further research are as follows. Friction increase property evaluation under lower rotary speed condition will be conducted for evaluating the effect of variation of the viscous sub layer thickness, because this time only friction increasing causing by thin viscous sub layer under high speed condition was evaluated. The roughness resulting from dry spray has been shown to cause an increase of friction that cannot be accommodated by the current correction formulae. Hence, the necessity of higher resolution roughness measurements has been suggested. Further optimization of roughness measurements can be achieved by close examination using higher pitch roughness measurements. More accurate hull quality control can be achieved if an onsite three-dimensional roughness profiler that can measure roughness height and wavelength with calculating the estimated FIR value at the same time is developed. The results of this experiment will be utilized for further improvement of anticorrosive paints, antifouling paints and paint application methods. Finally all those improvements will contribute to more efficient vessel fuel economy.

Acknowledgement

This research is conducted as part of a collaborative study with Dr. Y. Kawaguchi at Tokyo University of Science, Dr. K. Iwamoto at Tokyo University of Agriculture and Technology, and National Maritime Research Institute. Dr. H. Tanaka of Japan Marine United Corporation advised the relation between friction and roughness height square over wavelength. We would like to express our appreciation on their cooperation and valuable advice.

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