Hull coating roughness and the impact on fuel efficiency

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Abstract

In this paper, the roughness contribution of Fouling Control coatings on ship hulls is addressed. The two generic coating types, silicone-based and self-polishing antifouling coatings are compared under lab-scale and real-life application scenarios. It is concluded that silicone-based coatings give the lowest surface roughness irrespective of application and substrate conditions. It is also noted, however, that the surface roughness of coatings is orders of magnitude lower than that of biofouling organisms. Therefore it is a prerequisite that the coatings effectively hinder biofouling accumulation for the hull coating roughness to have a long-term impact on the fuel-performance.

Introduction

Roughness of the hull is one of the most important parameters when it comes to efficient operation of modern commercial ships (Ref e.g. DNV-GL). It is well established that roughness leads to friction, and friction leads to increased fuel consumption or lower speeds (Schultz, 2007; Townsin, 1979; Hinson, 1999; Lindholdt, 2015

; Walker et al., undated), however, a good model describing the correlation between roughness and friction has not yet been identified. This is partly due to the complexity of a rough surface and the difficulties connected to characterise it in sufficient details despite many attempts (Townsin, 1979, Candries 2001).

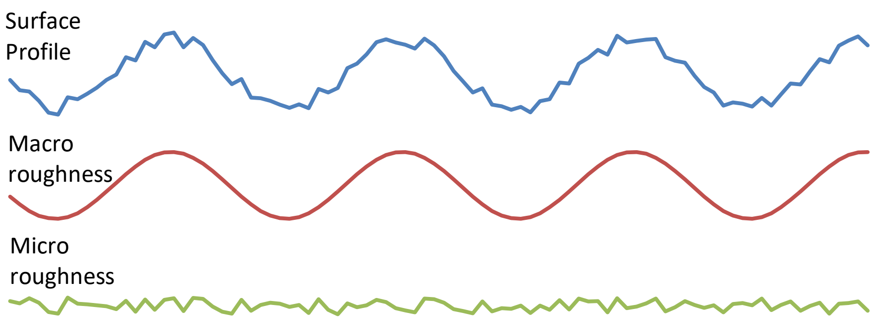
Computational fluid dynamics (CFD) may be used in the search for a robust model of roughness-induced drag increase. A recent study using CFD modelling of 4 different antifouling coatings, found “fairly good agreement “ between the experimental data and the data obtained from the CFD model. However, the same study concludes that “further study into the correlation between roughness and drag are a necessity for the development of accurate CFD prediction methods” (Demirel 2014).

To aid ship owners and operators in the focus of keeping low roughness, this paper aims at comparing the two predominant paint technologies available for fouling control purposes when it comes to the roughness they impose on a ship hull. The two technologies are here grouped as erodible antifouling, and silicone-based coatings. The former covers antifouling coatings based on the continuous release of biocides into the seawater by polishing mechanisms, and the latter covers conventional biocide free Fouling Release as well as biocide containing Fouling Defence coatings (Sørensen 2015).

It is the aim of this paper to identify the smoothest most fuel-efficient coating in its pristine conditions so, as such, the development of fouling on the coating will not be considered in the benchmarking. Where possible, the comparisons have been performed from samples applied under real-life conditions, or conditions mimicking those of paint applied in commercial yards.

Roughness

Surface roughness is the measure used to characterise the finely spaced surface irregularities occurring on all surfaces. It is commonly used to describe the random irregularities, whereas 'lay' and 'waviness' describes the repeating compositions of the surface texture. As such, roughness is the most relevant texture-parameter to consider in connection to the surface of spray applied hull coatings. Roughness is often divided into micro- and macro-roughness as illustrated in . Figure 1. Very often macro-roughness will be confused for the waviness of a surface.



. Figure 1: A surface profile (blue) divided into macro roughness (red) and micro roughness (green).

The macro roughness is defined as the distance between the highest and the lowest point in the surface profile (MacKenzie, 2008) and is illustrated as the red line in Figure 1. Macro roughness of a hull coating can be characterised as the average hull roughness (AHR) using e.g. a TQC roughness analyser where the distance between the highest and lowest recorded point over a surface profile of 50 mm is reported. The micro roughness is defined based on a given cut-off value (i.e. the roughness size reported when disregarding roughness over a certain value). It is illustrated as the minor peaks on the surface profiles when subtracting the macro roughness (cf. Figure 1). Normally finer analytical tools are required to record the micro roughness of a surface. Optical profilometry is commonly used as characterisation tool and will record the macro roughness simultaneously. However due to the instrumentation, it is rarely used in the field.

Characterisation of roughness

Due to the complexity of surface roughness, there are a vast number of parameters to describe surface roughness. Amplitude parameters (notated R) are used to characterise the surface based on vertical deviations of a surface profile from its (smooth) mean. One of the most widely used roughness parameters is the arithmetic average (Ra) of the surface. Areal roughness parameters (notated S) works similarly to the amplitude parameters, but are calculated over an area. Slope parameters describes the slope of the profile, and spacing parameters defines frequency of the roughness profile. As indicated, the number and complexity of roughness parameters is very high. The definition of said parameters lies beyond the scope of this paper, the reader is referred elsewhere for more in depths explanation.

Causes to hull (coating) roughness

All surface treatments generate texture in the form of lay, waviness or roughness. For hull coatings, there are three determining factors for the roughness resulting from application of a hull coating (Hinson, 1999), these are:

1. Condition of the substrate
2. Quality of the coating application
3. Type of coating technology
4.

After undocking of a vessel, the roughness will furthermore be determined by the following two factors:

1. Fouling accumulation
2. Coating dissolution and/or erosion
3. Damages and coating deterioration

Substrate conditions account for the type of substrate used and how well it is prepared, such as spot or full blasting, but also welding seems from the construction of the ship contributes to the overall roughness of the hull. The quality of the coating application can depend on the equipment utilised, as well as the skill of the painter. However, external factors such as weather conditions during the application also affects the final roughness of the system.

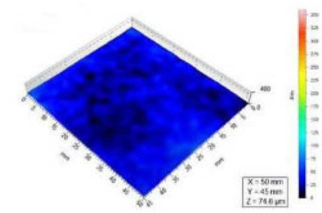
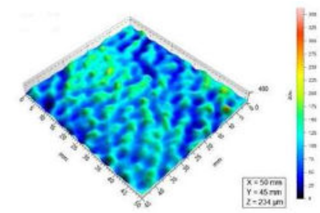
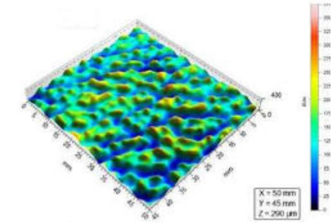
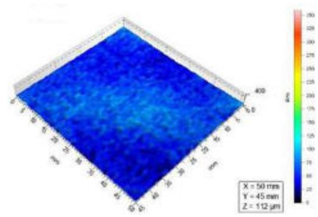
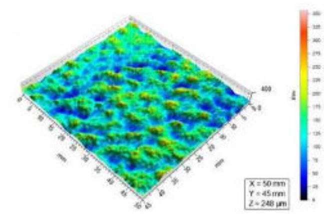
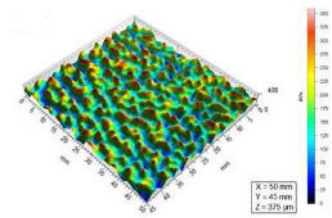
The type of coating technology used has a great impact on the final hull roughness. Today in the market two generic technologies account for the vast majority of applications. These are copper-based antifouling coatings, and silicone-based fouling release (or Fouling Defence coatings). Whereas the former are based on the controlled release of biocide, from a polishing mechanism, the latter technology is predominantly composed of the silicone binder-system giving rise to non-stick properties. In the following a conventional self polishing (SPC) antifouling coating will be compared to a silicone-based system under conditions mimicking those of paint application done in a maintenance yard. The aim is to quantify the resulting roughness of these two technologies.

Condition of the substrate

To investigate how the substrate roughness influences the final coated surface roughness, a silicone based coating and a SPC antifouling have been applied on three substrates with different initial roughness (smooth plate (< 10 µm), 211 µm, and 322 µm). These roughness numbers correspond to a surface that is smoother than a newly build ship, a ship that have been through 3-4 dry dockings, and a ship that is at the end of its lifetime without any intermediate full abrasive blasting, respectively. After application, the AHR is measured and images from optical profilometry is generated on the different coated surfaces to evaluate the differences in macro roughness. All results are listed in Table 1.

Table 1:. The AHR (µm) values measured on three different substrates using a TQC roughness analyser. The substrate have been coated with a silicone based and a SPC coating. Hereafter AHR values are generated again. In addition, the macro roughness of the surfaces has been characterised by optical profilometry (Lindholdt 2015).

Substrate conditions	Ideal	Good	Poor
Corresponds to	Smoother than a ship from new building	Ship that have been through 3-4 dry dockings	Ship at the end of its lifetime
AHR of the substrate	Smooth plate (< 10 µm)	211 µm	322 µm
	41 µm	134 µm	209 µm

Silicone based coating			
	64 µm	161 µm	267 µm
Top tier SPC antifouling			

From Table 1, it is seen that the (macro) roughness of the substrate has a significant impact on the final roughness after application of the final coat. Looking at the data, there are several interesting conclusions to draw; Firstly, it is clear that under all the roughness scenarios, the silicone-based top-coat result in a smoother finish than the conventional SPC antifouling. This effect seems to become more pronounced with increasing substrate roughness. Secondly, it can be seen that the top-coat and its application dictates the final roughness only when applying on a smooth plate (i.e. the final roughness is higher than the substrate roughness). This means, that for a substrate roughness less than approximately 40 – 60 µms, the final macroroughness will be determined by the coating roughness. Above this threshold, the substrate will be the predominating contributor to the final roughness. However, always with the silicone top-coat providing the lowest final roughness and friction (Lindholdt 2015).

Quality of the coating application

To analyse the influence of the substrate preparation and application conditions on the final coating roughness, AHR values have been collected using a TQC roughness analyser on actual ship hulls after application of a SPC top-coat or a silicone top-coat. The results are reported in Figure 2. The ship-types under investigation includes crude oil tankers, container ships, bulk carriers, etc. Vessel-age and surface preparation varies between the different measurements, but is evenly distributed between the two coating-types.

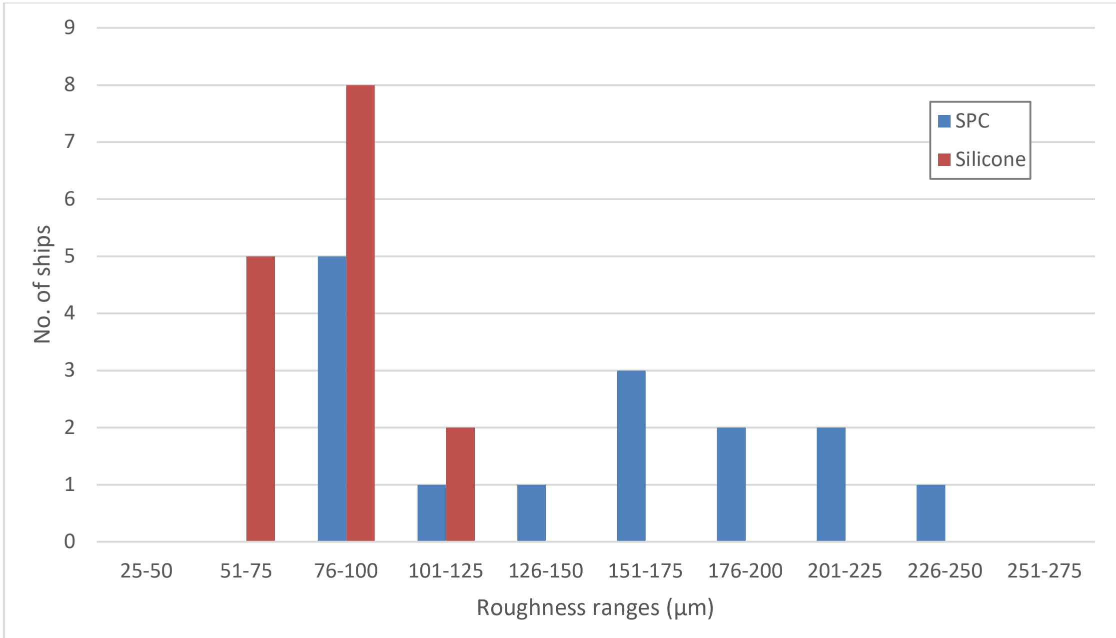


Figure 2: AHR values (µm) measured using a TQC roughness analyser on different ship types such as crude oil tankers, containers and bulk carriers and different vessel age. The measurements have been carried out for both silicone coated ships (red) and ships coated with SPC antifouling (blue). Whether the surface is full blasted or spot blasted during preparation, it is equally distributed between the ships coated with silicone or those coated with SPC.

From the results of final roughness measurements reported in Figure 2, it can be seen that there is a significant difference between the data sets of the hulls applied with silicone top-coat and the hulls applied with conventional antifouling (SPC). The improved surface condition from applying silicone-coatings also holds true in real-life coating applications. This means that irrespective of coating conditions (climatic, painter skills etc.), the silicone coatings ultimately end up smoother than the antifouling counterparts.

Type of coating technology

It is evident from the above, that, application of a silicone-based top-coat will result in a smoother hull compared to applying a conventional antifouling system. This is due to the distinct different coating technologies, whereas SPCs are generally formulated with high pigment volume concentration and organic binders, silicone coatings contain very little pigment and the silicone binder has a very low surface energy. To investigate how the surface roughness develops during service, surfaces of a silicone based and a conventional SPC coating have been measured by laser profilometry when freshly applied and after having been dynamically exposed to 30°C sea water for 7 weeks and at 12 knots. The resulting surface profiles are shown in Figure 3.

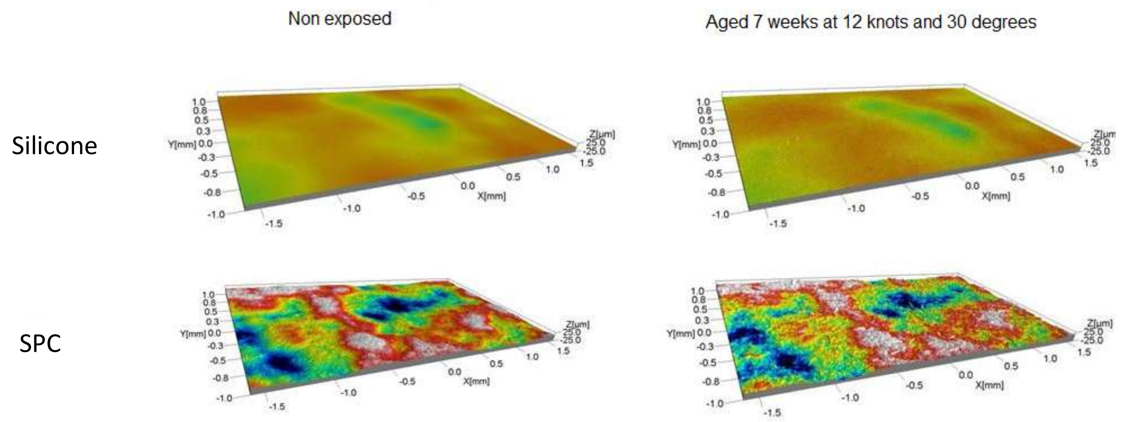


Figure 3: Surfaces displaying micro roughness of a silicone based coating and a conventional antifouling measured by laser profilometry when freshly applied and after being exposed to sea water at 30°C for 7 weeks, at 12 knots.

The images before exposure correlates very well with the results reported above (cf. Table 1 and Figure 2). It is seen from Figure 3 that the differences persists, also after seawater-exposure. In fact, the difference between the silicone surface and the antifouling surface becomes larger during dynamic seawater exposure. This is because the silicone coating stays smooth while the roughness of the SPC increases when exposed to sea water. These studies have been performed on a biocide-containing commercial silicone coating, and it can be seen from the results that biocide diffusion out of the silicone based coating do not leave cavities in the coating after the exposure in sea water. This is due to the limited amount of biocides that goes into these coatings (Ref naval architect), and the properties of the silicone binder.

Impact of coating deterioration on surface roughness

From the above, it is clear that hull roughness depends highly on the type of coating system used, as well as application condition and choice of surface preparation. As stated above, over the course of a docking period, other factors contribute to the roughness of the hull. Mechanical damages from impact of floating debris, groundings, and ship operation (e.g. tug-boats and fenders), will roughen the coating. The roughness contribution from mechanical deterioration of the coating system can be very difficult to assess, as it rely on the type of operation, and random occurrences). However, it has been reported that coating deterioration induces roughness with a factor of two (Schultz 2007). Another study reports the continuous roughness increase over the course of the docking period, due to the mechanical damages from anchor chains, tugs, grounding berthing, etc. These mechanical damages can, furthermore, lead to blistering, cracking, corrosion, and detachments, which will result in an even higher surface roughness. According to this study, the roughness of a silicone coating system increases in average 5 µm pr. year whereas the surface roughness of a SPC antifouling increases approximately

20 µm pr. year in service (International, 2003). In Table 2 below, the impact of such roughness increase from mechanical damages on fuel consumption and speed reduction have been estimated.

Table 2: Influence of roughness increase on fuel consumption and speed loss over a 5 year period. These are calculated for both a silicone based coating and a conventional SPC antifouling.

	Roughness increase (µm/year)*	Fuel increase (5 year period) (%)**	Speed loss (5 year period) (%)***
Silicone based	5	2.5	0.8
SPC antifouling	20	10.0	3.3

*(International, 2003).

**Calculation based on Townsin's rule of thumb, that a 10 µm increase in roughness will result in a 1% increase in fuel consumption (Townsin, 1979).

***Calculation based on the assumption that fuel increase can be converted to power loss 1:1 and power loss can generally be converted into speed loss in the ratio 3:1.

Impact of biofouling on roughness

In addition to the mechanical roughness, biofouling on the ship hull also contributes to the overall roughness. If biofouling settlement starts to dominate the hull surface, the impact of the roughness will be significantly increased. The magnitude depends on the amount and type of fouling (Schultz, 2007). It should be noted that whereas the roughness of a coating system will fall in the range of 50 – 250 µms, Slime will normally contribute with 2 to 3 time the roughness, small animals and weed fouling will be an order of magnitude higher than the paint roughness, and large animal fouling will be yet another order of magnitude higher (Schultz 2004). By assuming that the fouling is equally distributed over the entire hull, Schultz (2007) predicted that light slime results in up to 11% increase in needed shaft power to retain speed (for a navy vessel (FFG-7 frigate)l sailing with a speed of 15 knots).However, calcareous fouling were reported to increase required shaft power up to 86%. The data as reported by Schultz (2007) has been summarised in Table 3.

Table 3: Roughness and resistance data for a naval FFG-7 frigate. The table has been modified from Schultz (2007).

	Roughness data from Schulz 2004 Rt 50 (µm)	Increase in total resistance for a FFG-7 frigate at a speed of 15 knots
Hydraulically smooth surface	0	0
Typically as applied AF coating	150	2%

Deteroriatated coating or light slime	300	11%
Heavy slime	600	20%
Small calcareous fouling or weed	1000	34%
Medium calcareous fouling	3000	52%
Heavy calcareaous fouling	10000	80%

Considering both the roughness impact and the impact on overall ship resistance as summarised in Table 3, it is clear that the contribution from the various paint systems (see Figure 2) is insignificant if fouling is not effectively prevented.

Conclusion

From the results presented in this study, it is clear that silicone-based technologies offer a smoother surface than conventional antifouling counterparts. This effect is independent of the substrate conditions. In fact, it is shown here that the higher the initial roughness, the greater an effect of choosing silicone-based systems over conventional antifouling paints. The results presented here also documents that the surface roughness of silicone-based coatings is unchanged during dynamic seawater immersion, irrespective of the silicone contains soluble biocides.

Whereas the coating induced roughness do contribute measurably to the friction of the hull, it is negligible compared to the roughness and subsequent friction induction induced by biofouling. It is therefore important to not only consider the final roughness of the coating system, but also consider the long-term protection against fouling that a given coating system offers, when selecting hull coating solutions. In summary, if the hull coating needs to be smooth, a silicone system should be chosen, and if the hull in general needs to stay smooth, said silicone system should offer long term protection against the settlement of biofouling organisms.

References

Candries M. (2001*) Drag, boundary-layer and roughness characteristics of marine surfaces coated with antifoulings* PhD thesis. Univ. Newcastle upon Tyne.

Demirel Y. K., Khorasanchi M. Turan I. Incecik A. Schultz M. P.n (2014). *A CFD model for the frictional resistance prediction of antifouling coatings. Ocean Engineering*. 89 Pp 21 - 31

Hinson E. D. (1999) Analyzing underwater hull coating system wear for surface combatants, Naval Postgraduate School.

International (2003) *Propeller*, Issue 16, August 2003, Marine Coatings, Akzo Nobel.

Lindholdt A. (2015) *Fuel efficiency and fouling control coatings in maritime transport*, PhD thesis, Technical University of Denmark.

MacKenzie D. (2008) Surface Texture Measurement Fundamentals, Mahr Federal Inc.

Schultz M. P. (2007) Effects of coating roughness and biofouling on ship resistance and powering, Biofouling, 23(5), p. 331-341.

Sørensen K. F., Hillerup D., Blom A., Olsen S. M., Yebra D. M. (2015) *Keeping your guard up.* Naval Architect. Pp 39 – 44.

Townsin, R. L. (1979) The economic consequences of fouling and roughness,

Marine Fouling Seminar, London.

Walker J. M., Flack K. A., Lust E. E., Schultz M. P., Luznik L. (2013) *The Effects of Blade Roughness and Fouling on Marine Current Turbine Performance*, 10th European Wave and tidal energy conference series, Aalborg, Denmark.