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Review

Matching Forces Applied in Underwater Hull Cleaning with Adhesion Strength of Marine Organisms

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Abstract: Biofouling is detrimental to the hydrodynamic performance of ships. In spite of advances in hull coating technology, a ship must usually undergo underwater hull cleaning to remove biofouling during her in-service time. However, some cleaning practices may also lead to decreased lifetime of the fouling-control coating. Therefore, cleaning forces should be minimized, according to the adhesion strength of marine organisms present on the hull. In this article, values of adhesion strength found in available literature are discussed in the light of current knowledge on hull cleaning technology. Finally, the following knowledge gaps are identified: (1) data on adhesion strength of naturally-occurring biofouling communities are practically absent; (2) shear forces imparted by current cleaning devices on low-form fouling (microfouling) and corresponding effects on hull coatings are largely unknown. This knowledge would be valuable for both developers and users of cleaning technology.

Keywords: biofouling; barnacle; adhesion strength; microfouling; macrofouling; ship hull cleaning; ship hull grooming

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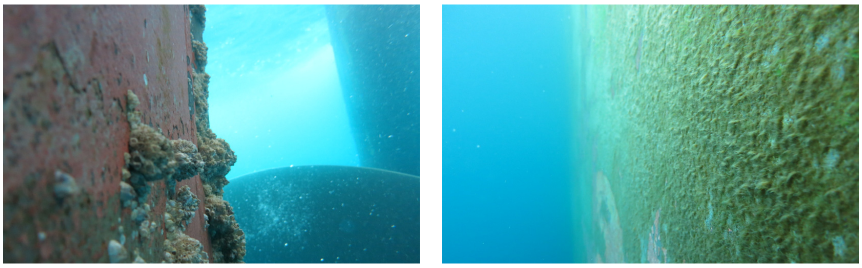
1. Introduction

Biofouling, the colonization of a surface by living organisms (Figure 1), is detrimental to the hydrodynamic performance of ships, through increased roughness of the hull and propeller, meaning higher fuel consumption or lower maximum speed [1]. Furthermore, it is associated with biosecurity concerns, as a mean of transport of non-native invasive species (NIS) [2]. Importantly, coating systems used for reducing or preventing biofouling are associated with high application and maintenance costs, and may cause water pollution through the release of toxic substances [1].

Increased roughness on the ship hull and propeller contributes to increased hull frictional resistance and decreased propeller efficiency, respectively, both translating into increased power consumption, or decreased speed [3]. It is estimated that a thin slime, "just detectable by touch" (microfouling), can lead to an increase in local skin friction of 25% compared to a clean hull [4]. Schultz et al. further compared the condition of a heavily slimed hull to that of a newly-painted hull and estimated an increase of ~9% in the fuel consumption for the US Navy's Arleigh Burke-class destroyer [5]. In broader terms, 9%–12% of global emissions of Greenhouse Gases (GHG) from shipping can be attributed to deterioration of hull and propeller performance, due to both mechanical damage and biofouling [6].



(a) (b)

Figure 1. Biofouling on a ship hull—in spite of fouling-control coatings, underwater hull cleaning is still required: (**a**) hard macrofouling at the stern, consisting of mostly barnacles; (**b**) soft algal fouling and microfouling on the ship's side. Photographs courtesy of Marinvest Shipping AB (Gothenburg, Sweden; reproduced with permission).

As a measure against biofouling, use of fouling-control coatings on the underwater hull can lead to significant operational gains (e.g., [7,8]). Recent estimates suggest that, if each vessel was to shift to its respective "best available" paint technology, the world fleet would benefit from an overall 7%–10% savings in fuel, with a corresponding decrease in air emissions [6]. The two main types of fouling-control coatings correspond to Anti-Fouling (AF) coatings—which rely on biocides for preventing settlement of marine organisms—and Foul-Release (FR) coatings—which rely on surface and bulk mechanical properties to decrease adhesion strength [1]. However, to reduce the impact on non-target marine organisms, the release of toxic substances into the environment should be minimized, at every step from paint application to hull blasting [9–11].

In spite of available fouling-control coatings, ships are still required to undergo underwater cleaning to remove biofouling [12], especially when it comes to algal fouling and microfouling (Figure 1b). Since dry docks have limited availability and dry-docking time represents a loss of revenue for commercial ship operators, underwater cleaning is performed during the typical five-year period between dry-dockings [13]. However, if the underwater cleaning is too aggressive, the fouling-control coating can be damaged, with negative consequences to its effectiveness and lifetime [14]. It is therefore important to know, on one side, the adhesion strength of marine organisms, and, on the other side, the forces imparted by cleaning tools, in order to match cleaning forces to the type and intensity of fouling.

This short review article aims at (1) giving an overview of current underwater cleaning technology; (2) analysing previously published adhesion strength values for different groups of marine organisms on different hull coatings and (3) identifying areas for future research on forces and frequency of underwater cleaning. The current focus is on minimizing cleaning forces for low impact on the fouling-control hull paint, i.e., without affecting its long-term efficacy, and also minimizing the release of toxic substances into the marine environment [11,15]. Other important topics related to underwater hull cleaning, such as the risk of inadvertent release of viable organisms and propagules to the marine environment, are reviewed elsewhere [16].

2. Underwater Hull Cleaning and Hull Grooming

As mentioned above, keeping a ship hull relatively clean between dry-dockings sometimes means resorting to underwater cleaning, typically using aggressive methods such as abrasive pads and brushes. As an alternative to cleaning, "hull grooming" has been suggested, defined as a proactive, frequent and more gentle mechanical maintenance of the hull [5,17]. Except for special cases, in which abrasive conditioning of the coating is desirable (e.g., the so-called "surface treated composites" [18]), forces used during underwater cleaning event should remain as low as possible, in order to maximize the lifetime of the coating [19].

Most common technologies for removing biofouling rely on brushes or water jets [20,21]. Alternative methods that aim at preventing/killing biofouling without removing it are also in use, like for example heat treatment and encapsulation. However, while encapsulation is probably more adequate for recreational vessels and still requires standardisation [22,23], the efficacy of heat treatments on large areas of the hull is still lacking independent evaluation and no recent publications could be found since the last available review from 2010 [20].

Forces imparted by brush systems have been studied for specific types of brushes and reported shear forces are in order of 10 kPa [14,24]. However, these results correspond to specific barnacle geometries (instrumented studs are used, representing barnacles), and no data are yet available on actual forces imparted on other forms of fouling, i.e., macrofoulers other than barnacles, and microfouling. Information on the latter is of particular relevance, considering that proposed brush grooming tools are unable to remove tenacious biofilms (low-form, strongly adhered biofilms) that form under frequent grooming [25]. These biofilms can still have a significant impact on hull hydrodynamic performance, depending on intensity and coverage [26].

It is recognized that brush-systems can erode, or even damage, fouling-control coatings [20,24]. However, reporting on the effects of brushes on hull coatings (e.g., scratching and wear) is limited to a few cleaning devices [14,15,25,27]. In addition, imparted forces are dependent on several factors, such as the type of surface used for cleaning (i.e., carpet, scouring pad or brush), geometrical parameters (for brushes: bristle density, angle and stiffness), standoff distance and wearing of the cleaning surface, e.g., at the tip of bristles in cleaning brushes [24,28]. Comparatively easier to estimate, forces imparted by water jets on the coating are dependent on impact pressure, nozzle diameter and standoff distance [29]. However, the maximum shear force at the wall will still be dependent on the actual roughness of the surface to be cleaned [30], thus varying with surface geometry of the coating/biofouling. To the best of our knowledge, there are currently no studies on forces imparted by water jets on fouled or coated surfaces.

Finally, the above comments apply to easily accessible and relatively flat surfaces of the hull. However, variability in cleaning forces might arise across the hull surface, depending on the cleaning method and the existence of "niche areas" (appendages and sheltered areas), where cleaning devices need to be tailored.

3. Adhesion Strength of Marine Organisms

Adhesion strength can be defined as the force required for removing a marine organism from a given surface, expressed as force per unit area (N/m^2 = Pa). Knowledge of such values is valuable not only for comparing the efficacy of different FR coatings, where low adhesion is targeted, but also as a reference for selecting minimal forces for underwater hull cleaning/grooming [14].

In this section, which is divided into macro- and microfouling, adhesion strength values available in the literature are reviewed, together with an overview of adhesion and failure mechanisms. Emphasis is given here on macroscopic methods of measuring adhesive strength, since we aim at directly translating these results into shear forces necessary for cleaning. Still, microscopic methods are also available, such as Atomic Force Microscopy (AFM), enabling topographical and mechanical characterization of cells and adhesives, for both macrofoulers [31] and microfoulers [32].

3.1. Macrofouling

Barnacles are the most comprehensively studied group of macrofoulers. However, several other relevant groups of macrofoulers must be considered, such as mussels, oysters, tubeworms (polychaetes) and macroalgae. Each group of organisms is associated with its particular adhesion mechanism. Thus, for instance, whereas barnacles, oysters, tubeworms and macroalgae adhere permanently to a surface in their adult stage, adult mussels are still able to move by breaking the byssus threads that keep them anchored to a given location and by growing new threads [33].

Barnacles have different phases of adhesion: temporary adhesion occurs firstly, as the cypris larva explores a surface; secondly, the larva produces a settlement cement; finally, the metamorphosed adult barnacle produces a stronger cement, leading to permanent settlement [33,34]. Adhesion strength is normally tested on adult barnacles using ASTM International Standard D5618-94 [35], which measures shear force necessary to remove barnacles from the surface, using a force gauge (a handheld probe, in most of the cases). Values of adhesion strength obtained using this method are presented in Figure 2. These are reported in the literature for different hull coatings and species of barnacles, as well for other groups of macrofoulers (oysters and tubeworms). Other methods and definitions of adhesion strength have been used, such as measuring pulling forces [31,33,36] and hydrodynamic tests on macrofoulers [37,38], though comparison to the standard shear force method is not always possible.

FR coatings are generally associated with lower adhesion strength compared to epoxy coatings, with values of adhesion strength for barnacles, oysters and tubeworms varying from 0.03 MPa, for a silicone FR coating, to more than 2 MPa, for an epoxy coating (Figure 2). Unfortunately, data are largely absent in the literature for adhesion strength on AF coatings, with only one average value found in available literature ("Ablative", ablative copper AF coating) [14].

Considerable variation is observed within the same species of barnacles, which is mainly attributed to specific formulations of silicone FR coatings, with varying surface chemistry (see Supplementary Materials, Spreadsheet S1 for a more complete description of tested coatings). Other factors may include differences in test conditions, e.g., different growth conditions, different geographical locations and effects of predation (biotic disturbance). The latter are exemplified by the discrepancy between average values for *Amphibalanus eburneus* on Epoxy (Figure 2), where predation leads to higher adhesion strength [39]. In order to avoid biotic disturbances, most studies, from 1998 on, report growing barnacles under the protection of cages [40,41].

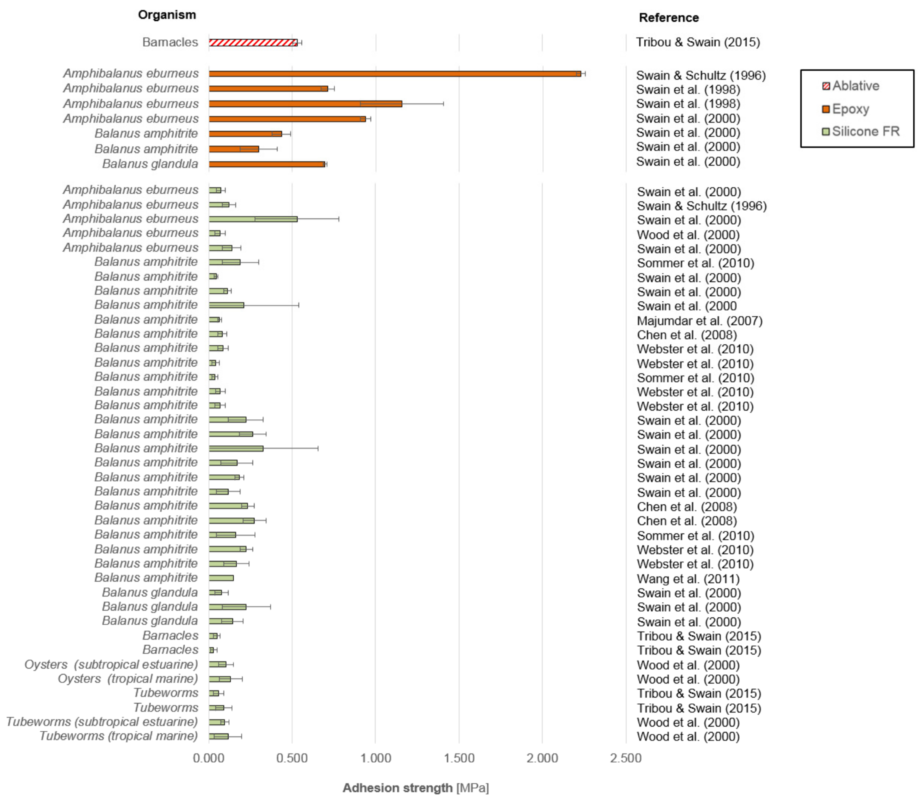


Figure 2. Adhesion strength values for macrofoulers on different types of hull coatings. Legend: "Ablative": biocide-containing anti-fouling coating; "Epoxy": corrosion protection coating; "Silicone FR": silicone Foul-Release coatings (full data in Supplementary Materials). All the tests were reported as using methods based on ASTM International Standard D5618-94 [35]. Error bars correspond to standard deviation of individual measurements obtained using force gauges. Cited articles: Tribou and Swain [14], Swain and Schultz [42], Swain et al. [39], Swain et al. [43], Wood et al. [44], Sommer et al. [45], Majumdar et al. [46], Chen et al. [47], Webster et al. [48] and Wang et al. [49].

For relatively high adhesion strength (e.g., for epoxy coatings), it is not uncommon for cohesive failure to occur, which means that the shell of the organism is broken and measurements do not represent adhesion strength: thus, the force necessary to produce adhesive failure, i.e., complete removal of the shell, is larger than that required for breaking the shell. In the event of cohesive failure, a fraction of the shell remains attached to the surface. Different criteria have been used for dealing with such occurrence: in earlier studies, readings were corrected for the fraction of base plate detached [50,51]; Berglin et al. suggested to quantitatively use the transition from cohesive to adhesive failure as a performance indicator for FR coatings [36]; finally, as standard procedure in ASTM Standard D5618-94, readings are usually considered void if more than 10% of the organism's adhered surface remains on the coating [35]. However, using the latter standard procedure, even if readings with extensive cohesive failure are considered void, the occurrence of cohesive failure may indicate that the actual adhesion strength for that population is underestimated, since cohesive strength sets an upper bound to the measurable adhesion strength. However, very few authors report the rejection percentage (e.g., [47,48]), important information that could indicate underestimation of adhesion strength. Additionally, cohesive failure is a challenge for underwater cleaning, since remaining baseplates contribute to hull/propeller roughness, while possibly decreasing the long-term effectiveness of the fouling-control paint, as discussed below in Section 4.

Finally, values of adhesion strength for oysters and tubeworms on silicone FR coatings are also given at the lower part of Figure 2. These do not seem to differ significantly from those of barnacles, although more data would be needed for a fair comparison. While adhesion mechanisms of barnacles and mussels are well studied, those of oysters and tubeworms have not received so much attention [52]. Again, the incidence of cohesive failure is unknown for available studies on the adhesion strength of oysters and tubeworms.

3.2. Microfouling

The groups of microfoulers that receive most attention in terms of adhesion strength include marine bacteria, benthic diatoms (microalgae) and spores/sporelings of macroalgae. Although the latter spores (i.e., propagules) and sporelings (i.e., young plants) correspond to early development stages of a macroalgae, they are usually considered as microfouling, due to size.

Bacteria and benthic diatoms rely on building up a layer of insoluble Extracellular Polymeric Substances (EPS) in order to adhere to a surface, constituting a biofilm. EPS is mostly composed of carbohydrates [53], but proteins might also play an important role in adhesion, and treatment with proteases has been observed to reduce the adhesion strength of diatom *Navicula perminuta* [54]. After settlement, many benthic diatom species are reported to "glide" on the surface once adhesion takes place, leaving behind a trail of adhesive [53].

Adhesion mechanisms of early stages of macroalgae differ markedly from those of bacterial and diatom biofilms. *Ulva* is the most commonly occurring macroalgae on ship hulls [55]. It produces motile spores (zoospores) that swim by means of flagella and are capable of selective settlement. Thus, once the right environmental and surface cues are offered, a spore will permanently attach by means of secreted adhesive [56].

Values of adhesion strength for different microfouling species and stages of development are given in Figure 3 for more than 80% removal, and Figures 4 and 5 for more than 50% removal and for diatoms and early stages of macroalgae, respectively. All the values correspond to silicone FR coatings.

Due to the reduced size of these organisms, hydrodynamic methods are routinely employed for measuring adhesion strength, replacing the mechanical shear test presented above for macrofoulers [56]. These hydrodynamic methods include the turbulent flow apparatus [57], calibrated water jet apparatus [29] and automated water jet apparatus [58]. The use of different methods may also contribute to some of the variability in the presented data.

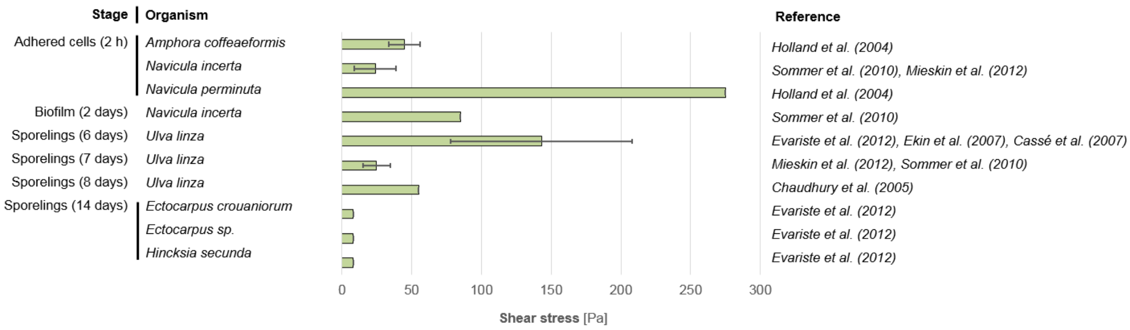


Figure 3. Adhesion strength values for microfoulers (diatoms and early stages of development of macroalgae) on different formulations of silicone Foul-Release (FR) coatings (full data in Supplementary Materials), given as shear stress required for >80% removal. Error bars correspond to the uncertainty estimated by individual studies (when available) or, where more than one study is cited, to standard deviation between different studies. For studies using water jet systems [45,55,59,60], originally reported jet impact pressures were converted to maximum shear stress using the same formula as in [29]. Cited articles: Holland et al. [59], Sommer et al. [45], Mieszkin et al. [61], Evariste et al. [62], Ekin et al. [55], Cassé et al. [58], and Chaudhury et al. [63].

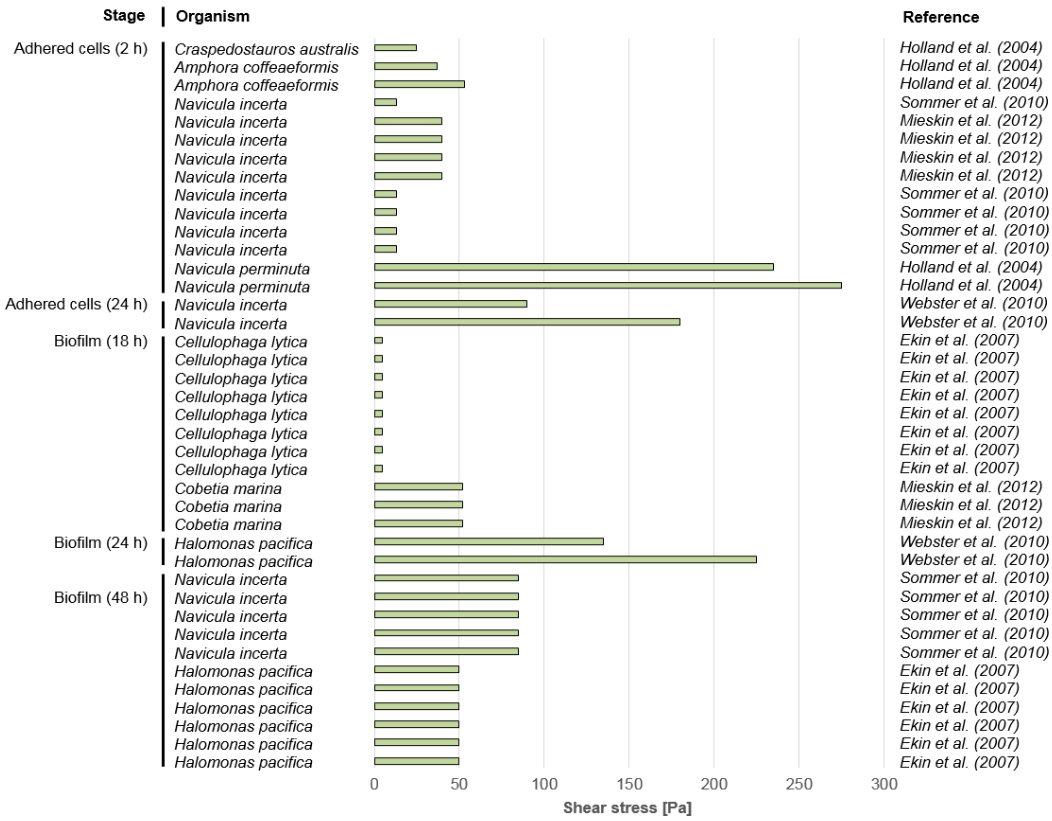


Figure 4. Adhesion strength values for diatoms on different formulations of silicone Foul-Release (FR) coatings (full data in Supplementary Materials), given as shear stress required for >50% removal. For studies using water jet systems [45,55,59,60], originally reported jet impact pressures were converted to maximum shear stress using the same formula as in [29]. Cited articles: Holland et al. [59], Sommer et al. [45], Mieszkin et al. [61], Webster et al. [48] and Ekin et al. [55].

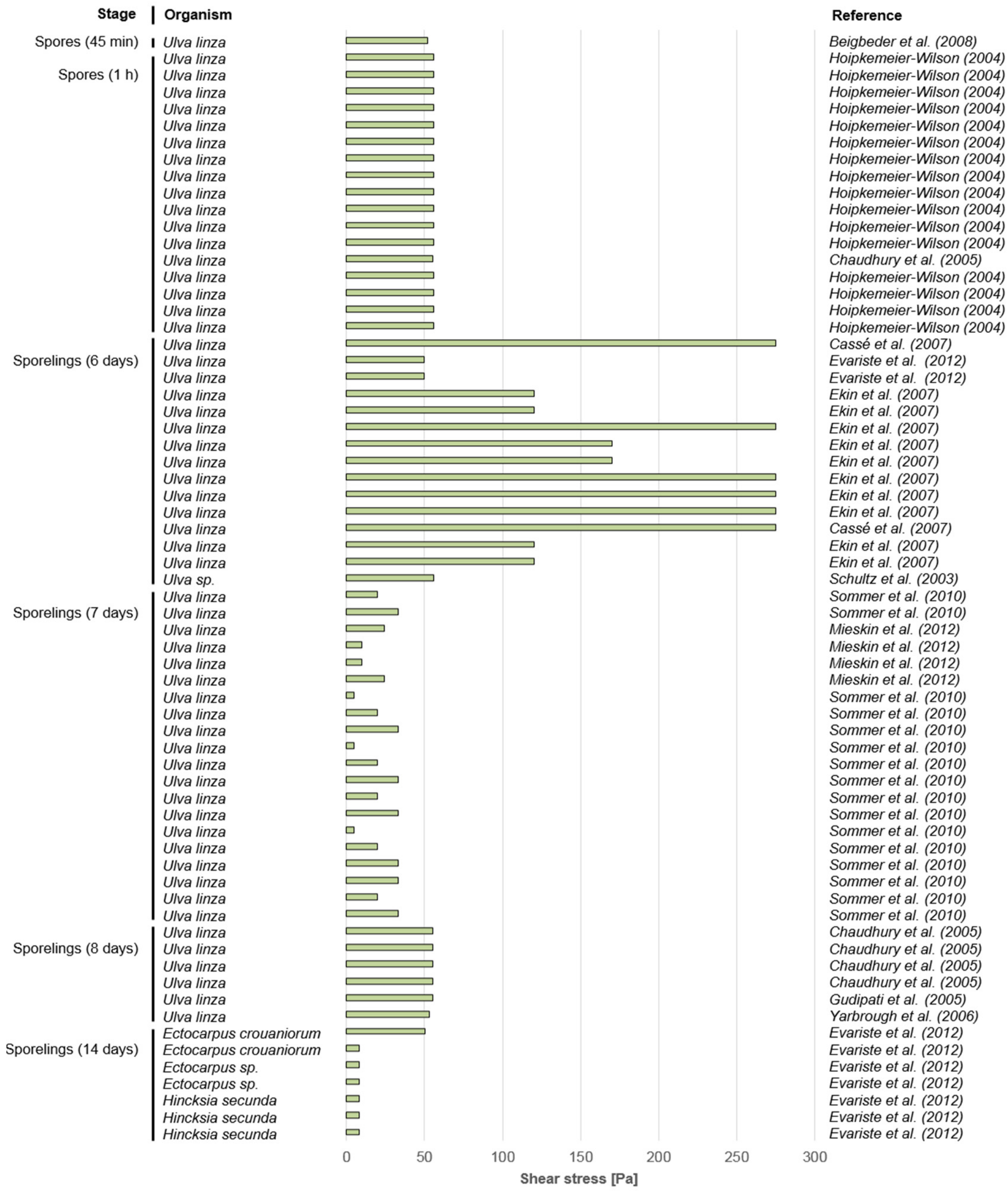


Figure 5. Adhesion strength values for macroalgae (early stages of development) on different formulations of silicone FR coatings (full data in Supplementary Materials), given as shear stress required for >50% removal. For studies using water jet systems [45,55,59,60], originally reported jet impact pressures were converted to maximum shear stress using the same formula as in [29]. Cited articles: Beigbeder et al. [64], Hoipkemeier-Wilson [65], Chaudhury et al. [63], Cassé et al. [58], Evariste et al. [62], Ekin et al. [55], Schultz et al. [66], Sommer et al. [45], Mieszkin et al. [61], Gudipati et al. [67] and Yarbrough et al. [68].

Adhesion strength is given as an applied shear stress, which must be taken together with the corresponding percentage removal and treatment time (usually 5 min for the turbulent flow apparatus [57]). This creates an issue when comparing results from different studies, since at least two values are considered, i.e., the shear stress and percentage removal. As a criterion, shear stress values presented in Figure 3 have been selected for >80% removal, meaning that an initially 100%-fouled surface would have been cleaned by at least 80%. Here, we assume that removal is independent from the initial percentage cover, although it is possible that percentage cover affects removal, considering that it is known to affect wall shear forces [26].

From Figure 3, adhered diatom cells (*Amphora coffeaeformis*, *Navicula incerta* and *Navicula perminuta*), in contact with the surface for 2 h, could be removed by applying shear stresses of ~20 to 275 Pa, whereas a two-day-old biofilm of *Navicula incerta* would require an intermediate shear stress. Sporelings of macroalgae (Figure 3: *Ulva linza*, *Ectocarpus crouaniorum*, *Ectocarpus* sp. and *Hincksia secunda*) are usually tested after growing for six to 14 days, and their adhesion strength on silicone FR coatings varies from ~8 Pa to ~140 Pa. Overall, Figure 3 provides reference values of adhesion strength valuable for deciding on minimum cleaning forces for silicon FR coatings. However, it should be stressed that variability is introduced by differences in surface properties of each FR coating tested within each study (see Supplementary Materials).

Values of adhesion strength corresponding to >50% removal are presented in Figures 4 and 5, for diatoms and early stages of macroalgae, respectively. Here, the minimum reported value corresponds to 5 Pa, for both 18-h-old biofilm of *Cellulophaga lytica* and seven-day-old sporelings of *Ulva linza*. For *Navicula incerta* (Figure 4), adhesion strength is apparently higher when a biofilm is allowed to form, as compared to isolated adhered cells. For macroalgae (Figure 5), it is noted that adhesion strength reaches its maximum values at around one week. As the algae grows, there is usually an increase in reported removal from FR coatings [66]. This is probably due to an increase in the length of the algae filaments (increased protrusion leads to increased drag) rather than lower adhesive properties of older sporelings, at least on FR coatings. This might not be true for all surfaces, since such positive relation between percentage removal and age could not be found on glass [66].

From the above results, at least two species stand out as having higher adhesion strength: these are *Navicula perminuta* and *Ulva linza*. The later is a widely spread macroalgae [56]. Differences between species can be partially attributed to the use of different hydrodynamic methods, for e.g., in Holland et al. [59], but at least one study (Evariste et al.) seems to indicate superior adhesion strength of *Ulva linza,* compared to other macroalgae species [62]. Besides the already mentioned variability in surface properties of different FR coatings, it is not entirely clear, from the literature, to what extent large differences between species (up to one order of magnitude) can be attributed to intrinsic properties of adhesives produced by different species [59] or to different exposure to hydrodynamic stress due to different geometry of cells/sporelings [66].

As noted before for macrofoulers, values of adhesion strength on coatings other than FR are largely missing in the literature. This is possibly due to the focus on the efficacy of FR coatings, rather than forces necessary for cleaning coatings currently in use on the majority of ship hulls. The number of species studied is also limited, whereas results obtained from single species are likely to differ from those obtained using natural communities (multi-species samples). On the latter aspect, a first step has been taken by Mieszkin et al., who studied variations in adhesion strength of *Ulva linza* and *Navicula incerta* on differently pre-conditioned coated surfaces (natural biofilm and *Cobetia marina* biofilm) [61]. Results from the latter study indicate complex relationships between algae and marine biofilms, suggesting that over-generalization should be avoided.

4. Matching Cleaning/Grooming Forces with Adhesion Strength

Thus far, we have discussed how cleaning/grooming is performed and how its forces are measured/estimated (Section 2). Furthermore, we reviewed published results of adhesion strength of marine organisms (Section 3). The remaining question is how well these forces can be matched.

For macrofouling, adhesion strength values of Figure 2 can be directly compared to cleaning forces measured on instrumented studs [14,24]. Thus, for example, the grooming tool suggested by Tribou et al. imparts a shear stress of approx. 0.01 MPa [14], and it would thus be unable to remove an average macrofouler from even a silicone FR coating, since the minimum value in Figure 2 corresponds to 0.03 MPa. However, it can still be effective against minimally adhered macrofoulers [14]. On the other hand, too high a cleaning shear stress means an increased risk of damaging the AF/FR coating, whereas, as pointed out by Bohlander, the amount of paint removal depends also on paint type and age [21]. For an ablative AF paint, Hearin et al. report an area extent of wear (or erosion) of 12% ± 10% of the topcoat after 12-month grooming on a weekly/bi-weekly basis (shear stress ~0.01 MPa), whereas ungroomed control surfaces suffered significantly higher wear, with a 31% ± 20% removal of the topcoat. This difference was attributed to higher forces used in hand-cleaning the ungroomed control surfaces prior to the photographic visual inspection. For an FR coating, Hearin et al. found no wear of the topcoat, but only localised damage, which was attributed to causes other than the grooming itself [27]. In addition, the coating system adheres to the hull with finite strength, which poses an upper limit to forces that can be used during cleaning. Although adhesion of the coating to the hull varies significantly with application quality and exposure conditions [69], the strength of ship hull coatings is normally 2.5–3 MPa [70], which is comparable to adhesion strength values mentioned above for macrofouling on epoxy coatings. Besides wear/damage to the AF/FR coating system, high cleaning shear stress will also increase the frequency of cohesive failure, i.e., shell breakage (Section 3.1), which means an imperfect result from the cleaning, thus contributing to the frictional drag of the vessel. Cohesive failure may also bring about negative consequences for the subsequent long-term effectiveness of the paint, since shell remains could intensify later recruitment by providing chemical cues for settlement [71]. All these factors support the use of hull grooming, targeting early stages of fouling.

Unfortunately, it is not possible to compare adhesion strength values of microfouling (Figures 3–5) to cleaning forces measured on instrumented studs, since imparted forces strongly depend on the geometry of the surface to be cleaned. Although there are data on instrumented barnacles (e.g., [14]), to the best of our knowledge, data are not yet available on shear forces imparted by any brush/pad system on either microfouled surfaces or coated surfaces. Thus, in addition to estimations of shear forces for water jet systems on rough surfaces [30], a collection of values of shear stress from different types of brushes/pads as a function of fouling roughness would enable valid comparisons to be drawn. In turn, this would enable matching cleaning/grooming forces with adhesion strength of microfouling, which is considered the best target for a more coating-friendly underwater hull maintenance.

From the above, recommendations can be summarized as follows, for different stakeholders working with underwater hull cleaning:

- for developers of cleaning technology: (1) shear forces should target microfouling or early stages of macrofouling; (2) forces should be easy to control by the user, with as few adjustable parameters as possible; (3) variability in shear force for each level of cleaning strength should be minimized; and (4) information should be compiled on effects on different types of coatings, microfouled samples and surface roughness;
- for users (e.g., diving companies), ship owners and as tool for various decision makers: (1) underwater cleaning of hulls covered with macrofouling should be avoided, as a rule; (2) the cleaning strength level should be adjusted by taking into account information available from the manufacturer of the cleaning system, as to get a conservatively low first estimate of strength needed for the task, taking into consideration the type and age of coating.

5. Conclusions

In this short review, we discussed the issue of matching forces used in hull cleaning/grooming to the actual fouling condition of the hull, consisting of a multi-species combination of macro- and microfouling. It is apparent that more data will be necessary in order to accomplish this objective. On the one hand, data on adhesion strength of naturally occurring biofouling communities are needed; particularly, data are lacking for adhesion strength of biofouling occurring on AF coatings (biocide-containing coatings). On the other hand, better knowledge is needed on the shear forces imparted by current cleaning devices on low-form fouling (i.e., microfouling), as well as their effects on today's fouling-control coatings. This information would be relevant in designing improved cleaning tools, as practical guidance for divers and ship owners, and as support for decision makers at environmental agencies.

Supplementary Materials: The following are available online at http://www.mdpi.com/2077-1312/4/4/66/s1, Spreadsheet S1: Values of Adhesion Strength from Available Literature.

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Author Contributions: Dinis Oliveira collected the data on adhesion strength from available literature (Spreadsheet S1); Dinis Oliveira and Lena Granhag wrote the paper.

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