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Fouling-release of barnacles from a boat hull with comparison to laboratory data of attachment strength

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ABSTRACT

Fouling-release of various life stages of barnacles was measured from two silicone-based products and a reference Plexiglas (PMMA) surface on a boat hull. From a standard PDMS polymer and a commercial fouling-release coating (Veridian®), removal of permanently attached cyprids was efficient whereas removal of newly metamorphosed barnacles was low. The PDMS polymer also demonstrated very low release of juvenile barnacles, indicating significant adhesion to this product. In comparison, Veridian® showed higher release of juveniles but similar low release of newly metamorphosed barnacles. Thus, we suggest that coating performance is best evaluated using newly metamorphosed barnacles. The efficiency of fouling-release coatings is commonly tested in a laboratory environment. For barnacles, the adhesive strength can be tested by mechanically shearing or pulling the organisms off the surface. The link between such mechanical testing and the coatings actual performance on a ship hull is however poorly investigated. We calculated the stresses imposed on barnacles by flow and the release data from the present study were compared to earlier measured tensile adhesion strength of barnacles on PMMA and PDMS. The release of permanently attached cyprids was much higher than expected from the tensile strength tests. One likely explanation is that the difference in applied force angle in the laboratory and on the boat hull result in different detachment failure modes. For newly metamorphosed and juvenile barnacles the results from the hull release experiment and the tensile strength measurements were more compatible. We also evaluate and conclude that the imposed forces calculated from mean velocities in the boundary layer better explain detachment of barnacles than forces resulting from instantaneous high velocity sweeps.

1. Introduction

Among environmentally benign approaches to prevent fouling, we find systems termed non-stick surfaces or fouling-release coatings. The general idea is to minimize the adhesion between the organisms and the surface, so that hydrodynamic stress imposed by a ship moving through the water or for slow moving vessels a simple mechanical cleaning is sufficient to remove the fouling. The efforts have been concentrated on two families of materials, fluoropolymers and silicones (Brady, 1999; Yebra et al., 2004). The mechanisms to prevent fouling differ between these materials (Brady, 2001). The fluoropolymers with its minimal surface free energy (tendency to interact with other molecules) discourage the initial bounding strength of organisms, and the interface formed is sharp and easily snapped by shear (Brady, 2001). Silicone or poly(dimethylsiloxane) (PDMS) coatings generally have somewhat higher values of surface energy and these materials likely form slightly stronger bonds with fouling organisms. But due to the low modulus of the material the application of a force to a foulant deforms the silicone and a failure mode similar to peeling occurs, a process which requires less energy than detachment by shear or tension (Brady, 2001; Gay, 2003). Today's commercially available products are almost exclusively based on PDMS elastomers, which has been found to be the more efficient alternative. However, recent research efforts to combine the advantages from both silicones and fluoropolymers show promising results (e.g. Marabotti et al., 2009).

In order to predict the performance of a fouling-release coating, we need knowledge about the hydrodynamic forces organisms are exposed to in relation to the adhesive strength of the organisms to the substrate. The prediction of hydrodynamic forces imposed on foulants on a ship hull is not trivial. The boundary layer thickness will increase with the distance from the bow leading to decreased mean velocities and forces acting on the fouling organisms closer to the stern. Turbulent boundary layers are also very dynamic with instantaneous high velocity sweeps reaching far down into the velocity gradient (Johansson and Alfredsson, 1982; Denny 1988;

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Koehl, 2007). Organisms therefore risk experiencing instantaneous forces of far greater magnitude than time-averaged means. An additional complication is that dense fouling will alter the flow so that forces on individual organisms may be affected by sheltering and wake interactions (Vogel, 1994; Schultz et al., 1999). A straightforward way of testing a material's fouling-release performance is, of course, to expose fouling organisms to increasing flow velocities and determine the critical velocity or wall shear stress leading to detachment. Relevant flow speeds (>5 m s^{-1}) may either be generated by applying test surfaces to a ship hull or a towed foil (Schultz et al., 1999), or by use of a flow channel capable of high flow speeds (Schultz et al., 2000; Zardus et al., 2008). In addition, two types of water-jet apparatuses have been developed to measure the adhesion strength of spores and sporelings of the macroalga *Ulva* (Finlay et al., 2002; Cassé et al., 2007). None of these methods are, however, trivial. Boats or ship hulls need substantial modifications to carry test surfaces without disrupting local flow regime. Laboratory flumes that can accommodate living macrofoulers in flow speeds in excess of 10 m s^{-1} are very bulky and costly. An alternative strategy is to predict fouling-release efficiency from measurements of material-specific adhesion strength and model the flow-induced forces acting on a fouler attached to the hull surface. The strength of adhesion can be measured by mechanically pulling or shearing the settled organism off the surface using a tensiometer (e.g. Yule and Walker, 1984; Swain et al., 1992; Berglin et al., 2001; Holm et al., 2006; Robson et al., 2009). The force imposed on an organism by flow can be divided into a lift and a drag component, which both are functions of the flow velocity and the size and shape of the organism (Denny, 1988). Lift and drag coefficients for use in modeling of the forces can be derived using a force balance or transducer (Denny et al, 1985; Schultz et al., 1999). Schultz et al. (1999) measured the forces imposed on barnacles by flow and made a predictive model of the maximum shear and tensile adhesion strength that would allow self-cleaning to occur at operational speeds. However, the link between laboratory measurements of adhesion strength and actual fouling-release performance on a ship hull is still poorly investigated.

In the present study, we measured fouling-release of permanently attached cyprids, newly metamorphosed barnacles and juvenile barnacles of the species *Balanus improvisus* (Darwin) from a boat hull. Removal of the various life stages of barnacles was measured from poly(methylmethacrylate) (PMMA, control surface) and from two silicone formulations, a standard poly(dimethylsiloxane) (PDMS) and the silicone-based fouling-release coating Veridian®. In a previous laboratory study (Berglin et al., 2001) we measured the tensile forces required to remove these different life stages of barnacles from PMMA and PDMS surfaces. In the present study, we try to evaluate if mechanical adhesion strength measurements of *B. improvisus* on the same materials coupled to a hydrodynamic model can be used to predict fouling-release on a boat hull. The hydrodynamic model is based on measurements of local flow velocities close to a boat hull and validated against the measurements of fouling-release for the three different stages of barnacles. We also assess the significance of using instantaneous high velocity sweeps rather than mean velocities in the boundary layer when predicting organism detachment. Results are discussed in terms of boundary layer properties and fracture mechanics.

2. Materials and methods

2.1. Fouling-release of barnacles

Three materials were tested in the study of fouling-release. Test panels of poly(methylmethacrylate) (PMMA) and two silicone formulations, a standard poly(dimethylsiloxane) (PDMS) and the silicone-based fouling-release coating Veridian® were prepared. The test panels, 84 × 48 mm, were glued onto 110 × 48 mm PMMA supporting panels using a silicone adhesive (Sikasil C®, Flexo Ltd., New Zealand). The PDMS substrate tested was a 2-component room temperature vulcanizing (RTV) system, Sylgard-184, delivered by Dow Corning, USA. The silicone elastomer was mixed according to the producer's instructions and poured into flat moulds to a depth of 2–3 mm and were left to cure for 8–12 h in 50 °C. The casts were then cut into test panel size. Substrates of Veridian® fouling-release coating (International Paints Ltd.) were prepared by applying one layer of primer and two layers of top-coat onto PMMA panels resulting in a minimum coating thickness of 250 µm, which according to the manufacturer is sufficient for maximum efficiency. The PMMA test surfaces were prepared by simply gluing a panel to the supporting panel. The 2 mm thick PMMA plates of medical grade were purchased from Plastic Produkter AB, Sweden. After preparation, all panels were cleaned using hot water and a detergent. The panels were then placed in running seawater for two days prior to barnacle larvae settlement.

Cypris larvae of *Balanus improvisus*, reared in the laboratory according to Berntsson et al. (2000), were allowed to settle on test panels during 2–3 days. About 10 panels of each of the materials were placed vertically in a container (200 × 400 × 100 mm) with filtered seawater and approximately 1000 cyprids from a mixture of larval batches were added. The settlement of larvae was conducted in 18–20 °C. Settlement and subsequent flow exposure on a boat hull was repeated on several occasions during a 2 month period. Panels were exposed to flow by the use of a 4.55 m long plastic boat (HavsBris R455) equipped with a 20 cm diameter tube through the hull, situated ca 80 cm from the stern and 23 cm from the center of the boat. Test panels were mounted onto an inner tube fitting precisely into the hull tube and joining flush the boat hull exterior. Two panels of the same substrate were mounted side by side in a quadratic depression on the bottom of the tube (Fig. 1). Since the thickness of the test panels varied between 4 and 5 mm, plates of different thicknesses were placed under the test panels ensuring that the panels were mounted flush with the boat hull. The boat was equipped with a 30-hp outboard motor and a maximum speed of 11.3 m s^{-1} (22 knots) was reached. The boat speed was verified using a GPS.

The fouling-release properties of the three substrates were tested both using panels with newly settled barnacles and panels with juvenile barnacles (base plate area 3–34 mm^2). The fouling-release test was performed by running the test boat in a sequence of 7.7, 9.8 and 11.3 m s^{-1} (15, 19 and 22 knots) during 30 s at each speed, noting the number of barnacles released after each 30 s run. Panels with newly settled barnacles had a mixture of permanently attached

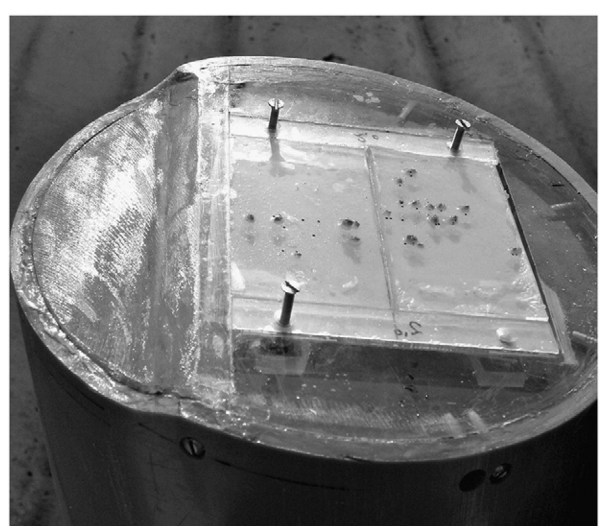

Fig. 1. Mounting of test panels fouled by juvenile barnacles. The tube bottom was adjusted flush with the boat hull prior to flow exposure.