Preparation methods ant tests of SLIPS against drag

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Slippery-liquid infused porous surfaces (SLIPS) have provided a new research direction in bioinspired materials. These composite materials are done starting from a micro/nanostructured surface, metallic or polymeric, in which an appropriate liquid is infused. The liquid penetrates into the surface pores and it is trapped by the surface morphology. In the present study SLIPS are examined in light of their possible use for drag reduction in naval applications; in fact, the interface with the seawater is mainly due to the infused liquid, inducing a relevant drag reduction. The paper reports a method for the preparation of a SLIPS starting from 1000 series aluminum plates of about 20 cm^2, i.e., in lab scale; then it is reported its characterization in terms of anticorrosion properties by EIS and anti-drag performances by rheometric tests. In addition, the attempt to realize the SLIPS in a bigger scale was done; the specimen was a 3 m2 panel, analyzed to determine its anti-drag performance in a towing tank. In lab scale the SLIPS did not result a protective treatment, but the drag reduction was about 14%. In the towing tank it was possible to discriminate the drag resistance of the SLIPS with respect to a standard aluminum plate, generally used for mega yacht hulls, and a painted steel plate, generally used for ships, but the SLIPS did not reduce the drag as in the lab experiments.

KEYWORDS: SLIPS, EIS, DRAG REDUCTION

INTRODUCTION

The resistance to motion of ships is due to two main effects: friction and wave-making. The relative importance of the two phenomena depends on the hull geometry, the characteristics of the ship motion and the sea state. For a large cargo ship advancing at a relatively low speed on a strait course in still water, frictional effects can exceed 90% of the total resistance, percentage decreasing for higher relative speed, motion complexity and sea roughness. For a few decades empirical formulations have been available to account for hull roughness when scaling experiments carried out on smooth, small scale hull models to rougher full scale technical surfaces in 'as built' conditions. These conditions include the standard surface finishing of rolled plates used in shipbuilding, but also the contribution to roughness from out of planeness of the hull plates, welds or lap joints always present in the hull plating. The same formulations can be adopted to predict the further increase in resistance due to degradation effects like corrosion and wearing or to fouling, all implying an increase of the surface roughness of the hull.

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It is important to note that the direct relation between friction coefficient and surface roughness applies to what could be defined as 'macro-roughness'. Within this range, the leading concept for the control of surface characteristics can be summarized as 'the smoother, the better'. In recent years the controlled presence of micro- or nano-metric protrusions in the wall surfaces seems to offer, on the contrary, new possibilities for drag reduction, superhydrophobic surface. In addition, composite materials done starting from a micro/nanostructured surface (metallic or polymeric) in which an appropriate liquid is infused (the liquid penetrates the surface pores, and it is trapped by the surface morphology) can induce a relevant drag reduction, but also an effective anti-fouling action; slippery liquid infused porous surface, SLIPS [1-4]. In the present work it is reported the method for the preparation of a SLIPS starting from series 1000 aluminum alloy plates of about 20 cm^2, i.e., in the lab scale; then it is reported their characterization in terms of anticorrosion properties by EIS and anti-drag performances by rheometric tests. The novelty of the paper is the attempt to realize the SLIPS in a bigger scale; the specimen was a 3 m^2 panel. The antidrag performances were evaluated in a towing tank.

MATERIALS

The SLIPS for lab scale experiments was obtained starting from high-purity aluminum plates (Al > 99.99%). They were immersed in hydrochloric acid 10 wt.% solution for 30 minutes. The chemical etching produced a micro-step like texture or a labyrinth like structure formed by a network of connected pits (Fig. 1a). This structure is obtained by initial pits that spill over the surface, and progressively interconnect them, producing a homogeneous micro-step like roughness. Then the surface was impregnated with paraffin oil. The excess was removed maintaining the sample in vertical position for 24 hours.

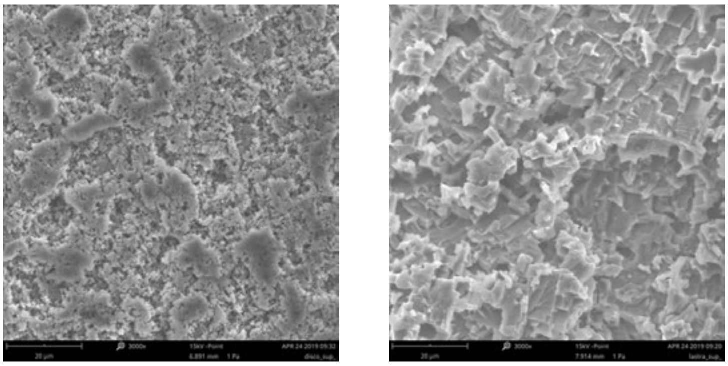


Fig.1 - a) Structure of the etched aluminium plate in: a) lab scale; b) towing tank scale.

The specimen for the towing tank, 3 square meters panel, was an AA1050 H24 alloy; it was immersed for 30 minutes in an opportunely designed tank containing HCl 10%, then it was washed with tap water. The SEM analysis after corrosion showed a microstructure like that of the lab alloy, but the dimensions of the interconnected pits were bigger (Fig. 1b). Despite this difference, the sheet was painted with paraffin oil in the Naples University. The excess of oil was removed keeping the sheet vertical for a night. An AA 5754 H111 alloy was used as reference, being generally used for mega yacht hulls.

METHODS

Laboratory tests

Electrochemical impedance spectra (EIS) were carried out on a computer-controlled electrochemical system (Gamry) in 3% NaCl aqueous solution at room temperature. The tests were carried out in a three-electrode system: a saturated calomel electrode, SCE, was used as reference electrode, a platinum electrode was used as counter electrode and the prepared sample was used as working electrode. The area of the working electrode was 5 cm^2. EIS tests were performed at frequencies ranging from 10^5 Hz to 0.1 Hz at open circuit potential with an amplitude of perturbation voltage of 20 mV.

Rheometric tests were performed using a rheometer Anton Paar MCR 301 equipped with a rotor of 50 mm in diameter and 1.5 mm in thickness (Fig. 2, one layer). In this experimental setup, the rotor was immersed in a rectangular vessel filled with distilled water. The dimensions of the rectangular vessel, the location of the free surface (reference plane), and the dimensions of the disk rotors are given at the following link [3], where the interested reader can access complete details of the geometry. All measurements were performed at a rotor's immersion depth of 40 mm. The contribution of the rotating shaft to the total torque is negligible with respect to that of the disk, and inferior to the error bar in the experimental data.

The Reynolds number Re and the moment coefficient C_m are defined as [5]:

$$Re = \frac{\omega R^2}{\nu} \tag{1}$$

$$C_m = \frac{M}{\frac{1}{2}\rho\omega^2 R^5} \tag{2}$$

where ω is the angular velocity (rad/s), R is the rotor radius (m),ν is the cinematic viscosity of water (m^2/s), M is the measured torque (Nm), and ρ is the density of water (kg/m^3).

The SLIPS was prepared on a separated disk of aluminum with the same rotor's diameter and a thickness equal to 1.5 mm. Subsequently, the SLIPS support was attached to the bottom of the rotor, obtaining a rotating device with a total thickness of 3.3 mm (considering 0.3 mm of silicone gel used for the bonding), named two layers configuration (Fig. 2, two layers), in which only the lower surface was SLIPS, while the lateral and the top surfaces, as well as the rod, were of the same non treated aluminum used as reference. For this reason, the SLIPS sample is not available with the one-layer configuration. Also, a three layers configuration (5.1 mm in thickness), in which a second SLIPS support disk was applied on the top of the rotor was prepared. In this case, only the lateral surface and the rod were not treated (Fig. 2, three layers).

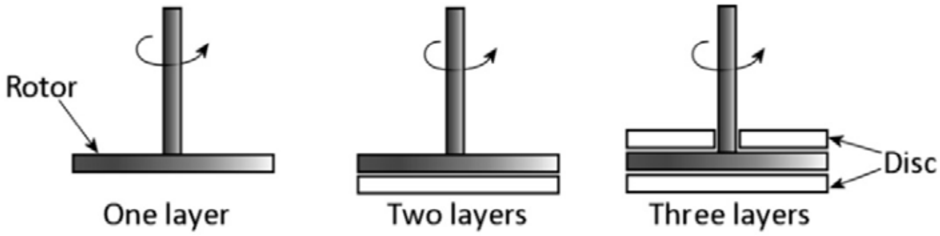


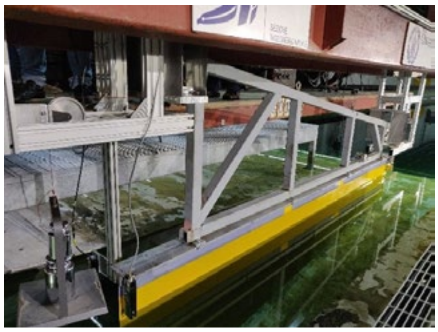
Fig.2 - Different rotors configuration used for the rheological tests in immersion.

In the last two cases the SLIPS results have always been compared to untreated disks of equivalent thickness.

Tests in towing tank

The sheets were tested in the Università degli Studi di Napoli "Federico II" Towing Tank at the Department of Industrial Engineering (Fig. 3a). The tank measurements are length of 136.0 m, width of 9.0 m and depth of 4.5 m, the carriage maximum speed is 10.0 m/s.

a)



b)

Fig.3 - Towing tank of the University of Naples: a) General view; b) the dynamometer connection and a tested plate.

Surveys with towing tank are carried out by means of a carriage moving on rails placed on the longitudinal walls of a rectangular basin.

In resistance tests, the carriage tows the model in uniform and rectilinear motion. The models are constrained to the carriage with load cells that provide the necessary data. For testing the plate, the dynamometer shown in Fig. 3b was designed and built. The device has been designed to obtain optimal alignment of the plate with the direction of motion minimizing the angles of incidence of the flow which would cause additional resistance components. The dimensions of the plates tested in the Towing Tank allow to reach Re close to the typical values of full-scale ships (~10^8). In the specific case, the length of the plates - 3.00 m - and the speed - 5.0 m/s - allowed to reach Re = 1.4×10^7.

RESULTS AND DISCUSSION

Impedance data for the SLIPS prepared in the lab are reported in Fig. 4. Reliability of the results was verified with three replicas of the test.

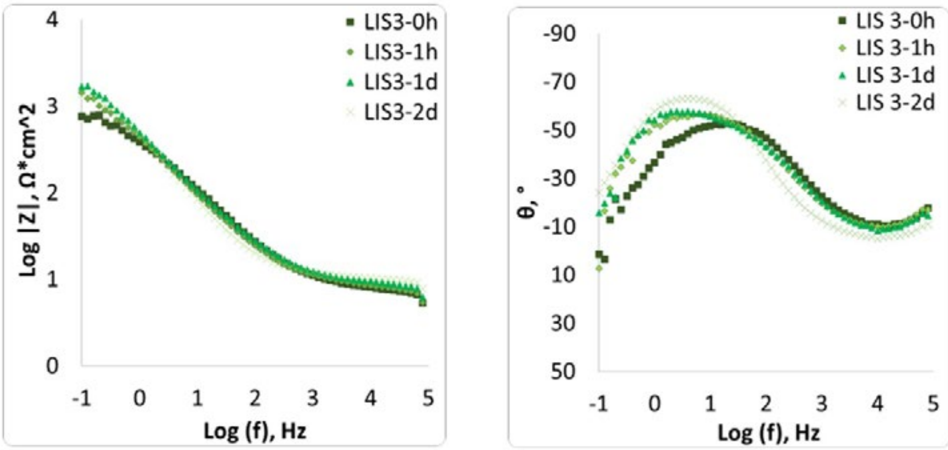


Fig.4 -EIS diagrams (Bode plots) for the SLIPS at 0 hours (LIS3-0h), 1 hour (LIS3-1h), 1 day (LIS3-1d) and 2 days (LIS3-2d) of exposure to the 3% NaCl solution.

The diagrams show that the infusion of paraffin oil does not isolate the metal, but only fills the porosities: the impedance data at 0.1 Hz are about 10^3 ohm cm^2, similar to that of bare aluminum and do not vary during the first two days of immersion. On the other hand, the reproducibility is verified.

Fig. 5 shows the trends of the moment coefficient C_m against the Reynolds number Re for the smooth aluminum disc rotor used as reference. In the figure, the results of three different configurations are depicted, namely, the one-layer configuration (thickness 1.5 mm), the two-layers configuration (thickness 3.3 mm), and the three-layers configuration (thickness 5.1 mm).

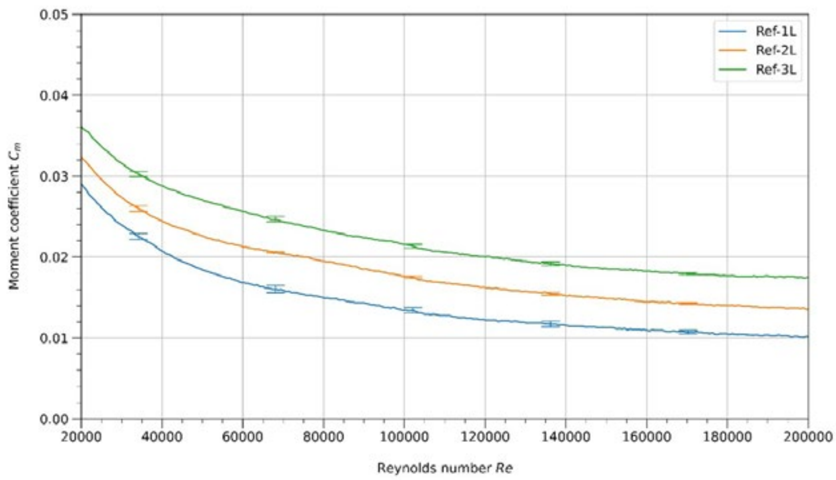


Fig.5 - Comparison of moment coefficient C_m versus Reynolds number Re for smooth aluminum rotors in three different configurations; Ref-1L (one layer), Ref-2L (two layers), and Ref-3L (three layers). The error bars were computed using the standard deviation.

The trends of the moment coefficient C_m as a function of the Reynolds number Re are similar for all disk thicknesses (Fig. 5), and, not unexpectedly, C_m increases monotonically, at each Re, with the thickness of the disk rotor. This is related with the extra drag occurring along the lateral surface of thicker disks.

Fig. 6 shows the moment coefficient C_m against Reynolds number Re for the LIS treatment [1] and the bare aluminum surface corresponding to the two- and three-layer.

The values of moment coefficient C_m are consistently lower than in the reference cases, demonstrating the SLIPS treatment's effect in reducing C_m, and hence drag.

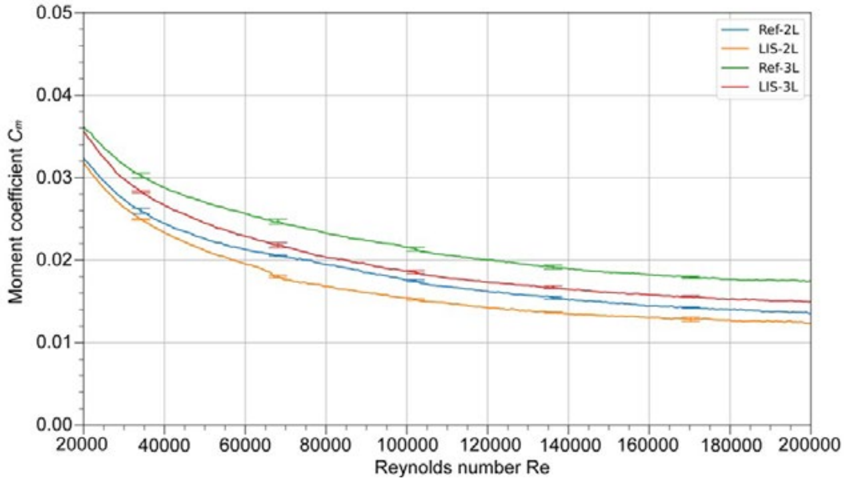


Fig.6 - Moment coefficient, C_m, versus Reynolds number, Re, plots for the reference and SLIPS samples in the two- and three-layer configuration, Ref-2L, LIS-2L, Ref-3L and LIS-3L, respectively.

Defining the efficiency η of the SLIPS as,

$$\eta\ [\%] = \frac{Cm_{ref} - Cm_{LIS}}{Cm_{ref}} \cdot 100 \tag{3}$$

at low Re (from zero to about 10^5), the efficiency is an increasing function of the Reynolds number; beyond Re $=10^5$, η seems to level off, and it slowly decreases for the double layer disk, possibly because the treatment, in this case, has been applied on one side of the disk only. For the three-disk configuration, the efficiency η is approximately constant and equal to about 14%, as shown in Fig. 7.

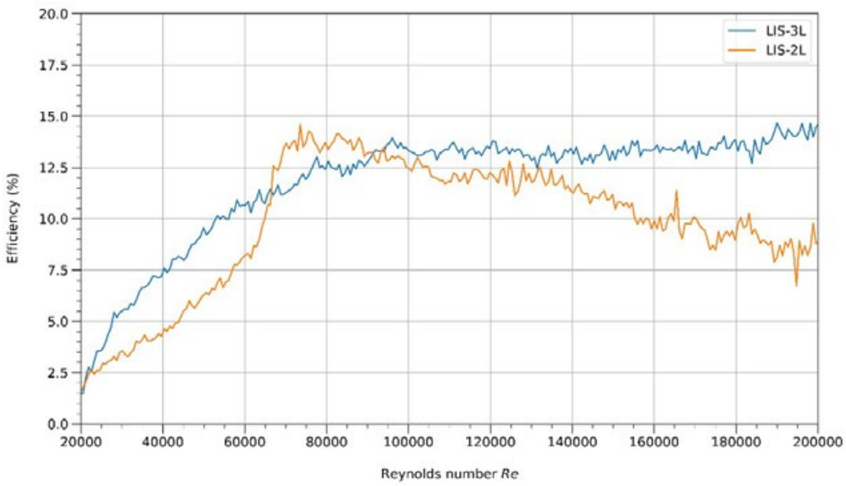


Fig.7 - Efficiency of the SLIPS for the two-layer configuration, LIS-2L (aluminum treated only on the bottom surface), and the three-layers configuration, LIS-3L (aluminum treated on top and bottom surface).

Fig. 8 shows the results of the resistance tests carried out in the towing tank. Tests were performed for Reynolds numbers between 1.7 10^6 and 1.4 10^7, in four different configurations:

1. painted steel (smooth) through standard laboratory procedures, Painted steel,
2. smooth 5754 H111 aluminium, AA 5754 H111
3. AA 1050 H24 aluminium made rough through immersion in acid, free of surface treatment, AA 1050 H24
4. no. 3 painted with vaseline oil subsequently tested after 48 hours of immersion in water, LIS (AA 1050 H24).

Comparing the rough plate, on the other hand, it is noted that the performances are clearly worse. Nonetheless, the effects of the lubrication are evident from the comparison of the plate tested after 48h for which the effect of the lubrication is clearly reduced due to the permanence in the water.

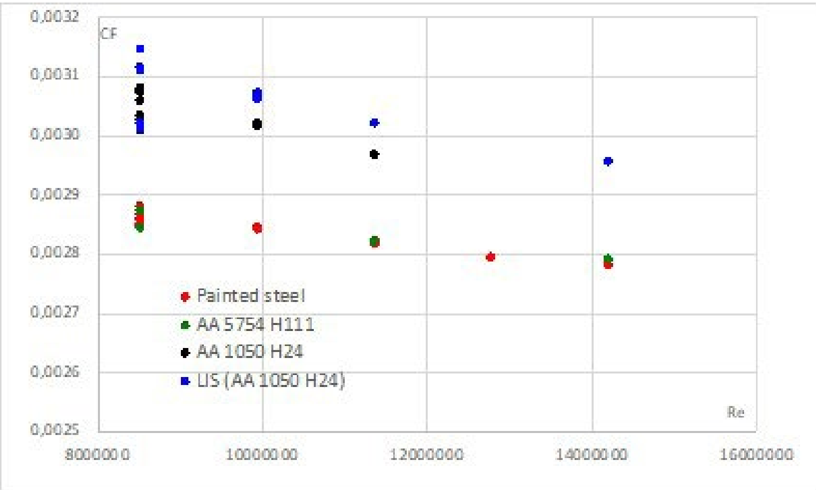


Fig.8 - Comparison of friction coefficient C_F versus Reynolds number Re for the different configurations tested.

CONCLUSIONS

A method able to evaluate the frictional resistance of different surface treatments on lab scale specimens has been described. The advantage of this experimental procedure, based on rotating disk immersed in water, lies mainly in its capacity to assess well even minor differences in the performance of different treatments. Furthermore, this apparatus is designed to attain high shear stresses that, although lower than those of full- scale ships (the maximum Re reached for discs of 11 cm in diameter is 4 105 against 109 for full scale ship), are however beyond the transitional regime. The tested SLIPS showed a 14% drag reduction by this method. On the other hand, the bigger scale SLIPS prepared and tested in the towing tank did not demonstrate the drag reduction found in laboratory experiments, a possible consequence of the difference in base materials and treatments. Nonetheless, the comparison of the behavior of this plate with respect to others demonstrated that the carriage that tows the plates in uniform and rectilinear motion could discriminate well the performance behaviours of samples with only minor differences, rendering this technique ideally suited for further tests.

ACKNOWLEDGEMENTS

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SLIPS per la riduzione d'attrito SLIPS against drag

Le superfici porose infuse di liquido, SLIPS, costituiscono un nuovo campo di ricercar nell'ambito della biomimetica. Questi materiali compositi sono costituiti da una superficie, metallica o polimerica, micro/nano strutturata, in cui è infuso un opportuno liquido. Quest'ultimo penetra attraverso i pori superficiali ed è intrappolato dalla morfologia superficiale. Nel presente lavoro le SLIPSs sono analizzate come possibili trattamenti per la riduzione d'attrito in applicazioni navali; infatti, l'interfaccia con l'acqua di mare è dovuta essenzialmente al liquido infuso, che induce una rilevante riduzione d'attrito. Lo studio riporta, quindi, un metodo per la preparazione di una SLIPS a partire da piastre di alluminio serie 1000 di circa 20 cm2, cioè su scala di laboratorio, la sua caratterizzazione in termini di proprietà anticorrosive tramite misure di impedenza elettrochimica e di resistenza di attrito tramite prove reometriche. Inoltre, è riportato il tentativo di realizzare una SLIPS in una scala maggiore; il campione, costituito da una lastra di circa 3 m2, è stato analizzato in termini di resistenza d'attrito in una vasca navale. Nella scala di laboratorio la SLIPS non ha dimostrato proprietà anticorrosive, ma un abbassamento della resistenza di attrito del 14%. Nella vasca navale è stato possibile discriminare il comportamento, in termini di resistenza al rimorchio della lastra, della SLIPS rispetto a una lastra di alluminio standard, generalmente utilizzato per carene di megayacht, e una lastra d'acciaio rivestita, generalmente utilizzata per carene di navi, ma la SLIPS non ha ridotto la resistenza come nell'esperimento di laboratorio.

PAROLE CHIAVE: SLIPS, EIS, RIDUZIONE D'ATTRITO

TORNA ALL'INDICE >