FIELD TESTS ON THE CATHODIC PROTECTION OF A SHIP PROPELLER SYSTEM

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The efficiency of the cathodic protection of a propeller system, installed in a large-medium sized ship, was investigated. This system is constituted by a 17 4PH propeller shaft, concentrically mounted in an AISI 304 stern tube. Sea water is usually pumped in the interspace between these two metallic parts for cooling the propeller system during navigation, but in the main part of the year it remains stagnant because the ship is berthed in the harbour. Considering that such conditions determined critical localized corrosion phenomena on the propeller system, in this work the efficiency of the cathodic protection, performed by plain steel anodes, was tested. A real propeller system (about 3 m in length) was slightly modified for monitoring the potential in different points by the use of local probes. Even the protection current was suitably monitored. The tests were performed both with stagnant and with moving sea water up to a flow rate of 40 L/min, in order to find the same conditions of the ship during navigation. From the experimental results, the efficiency of the cathodic protection was good even if the circulating water with the higher flow rate represents a critical condition.

INTRODUCTION

The selection of the stainless steel alloys destined to marine applications is a crucial step of the industrial design process, where not only their mechanical properties must be considered but also their localized corrosion performances, taking into account the high aggressiveness of sea water [1,2]. 17 4PH, a precipitation hardened stainless steel, is good for both these characteristics [3-7]. It is a martensitic stainless steel with a 3 wt% of copper which determines, together with chromium, the alloy hardening thanks to the precipitation of these two metals reach phases [7,8], during an ageing process carried out at 480-600 °C [3,4]. The precipitation process is commonly carried out after a solubilization at about 1000 °C.
From a previous work [9], in some propeller shafts, crevice and pitting corrosion were found in a relatively short time. In particular, pitting on the metallic parts subject to mechanical stress can determine the cracks initiation with the subsequent failure. Considering the examined cases, pitting corrosion was observed in the whole surface of the shaft while crevice corrosion was found in correspondence of rubber bearings, used for the installation of the shaft concentrically inside the stern tube.
Some authors reported in the literature [10] similar corrosion phenomena on AISI 316 propeller shafts. Both this material and 17 4PH stainless steel are suitable for

naval industry but the possibility of localized corrosion has to be considered in any case.
17 4PH stainless steel is particularly prone to stress corrosion cracking, both in those conditions where hydrogen is generated (therefore, determining hydrogen embrittlement like most high resistance steel) and in sea water where the shaft failure was taken into consideration [8]. Special attention must be paid to the selection of the sacrificial anodes in cathodic protection, which must bring a given metallic structure in protection conditions, without reaching negative potentials sufficient to determine hydrogen evolution. However, even when such negative potentials are not reached, bringing 17 4PH to lower potentials with respect to its corrosion potential could produce a reduction of its mechanical performances [11].
In this work, the efficiency of cathodic protection performed with plain carbon steel anodes was examined. This was the strategy considered for eliminating the localized corrosion phenomena found in the 17 4PH propeller shafts, excluding the possibility of hydrogen evolution as well. For this aim, the experimentation was performed in Ancona harbour on a real propeller shaft-stern tube system, with a length a little bit more than 3 m and constituted respectively by 17 4PH and AISI 304 stainless steels. The protection currents and the localized potentials were monitored using suitable probes and a workstation. Sea water was collected directly from the harbour mole by means of a pump.

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EXPERIMENTAL PROCEDURE

A 17 4PH propeller shaft (φ = 115 mm and length 4 m) concentrically mounted in an AISI 304 stern tube (φ = 163
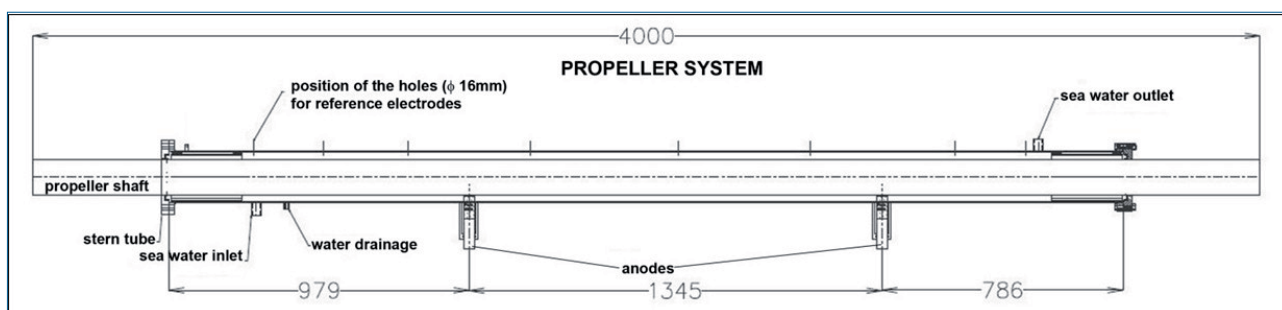
Fig. 1 - Scheme of the propeller system, modified for the installation of the suitable reference electrodes (in the φ 16 mm holes) and with the two plain steel anodes on the walls of the stern tube. Furthermore, sea water inlet and outlet are shown. All measure numbers are in mm.

Fig. 1 - Illustrazione schematica del sistema asse e astuccio, con le modifiche per l'inserimento di opportuni elettrodi di riferimento (nella serie di fori da 16 mm) e con i due anodi di acciaio comune opportunamente supportati sulla parete dell'astuccio. Sono inoltre indicati i punti di ingresso e di uscita dell'acqua di mare. Tutte le misure sono in mm

mm and length 3.11 m) were both used for the present experimentation as schematically shown in Fig. 1.

Along the whole stern tube length, 8 holes were made (φ = 16 mm; they are visible in the upper side of Fig. 1) in order to insert 7 Ag/AgCl/KCl sat. reference electrodes (E = -35 ± -45 vs. SCE) and a SCE electrode (+0.241 V vs NHE), all suitably built in laboratory for continuous monitoring of the potentials at different points of the system. All potentials measured in this work are reported with respect to SCE. The local potential measurements, performed by these probes, allowed the verification of cathodic protection efficiency along the whole interspace.

In the diametrically opposite side, the seats for two plain steel anodes, cylindrically shaped (φ = 35 mm, length 70 mm), were obtained (Fig. 1). Initially, their position was defined with respect to stern tube ends so as to have the same distance from each of them and corresponding to 1/4 of stern tube length; in this way, the cathodic protection current can be distributed homogeneously in the whole interspace between the two metallic parts. However, due to ship specific design reasons, the anodes were placed as shown in Fig. 1.

At the stern tube ends, two sluice valves were installed respectively for water inlet and outlet. They gave the possibility either to have a circulating water at a defined flow rate or to maintain water in stagnant conditions. Adriatic sea water (salinity 39 g L^{-1} and oxygen concentration 7-8 ppm [1,2]) has been collected by means of a pump directly from the harbour mole. Thanks to the valves, the flow rate for this experimentation was set at 20 L/min, 30 L/min and 40 L/min. This highest flow rate corresponds approximately to that of the circulating water in the propeller system during navigation.

During the assembly of the whole system, the shaft, the stern tube and the anodes were electrically insulated. They were connected electrically with a control board which allowed the measure of the partial currents supplied by the anodes with respect to both metallic parts to be protected. A simplified electrical scheme of the circuit is represented in Fig. 2, where also the reference electrodes

are shown. Finally, the shunt resistors (1 Ω), visible in Fig. 2, were used for continuous monitoring of partial currents in all experimental conditions. The switches allowed the direct observation of polarization effects during the tests. The continuous monitoring of currents and potentials were carried out by means of a Data Switch Unit Agilent Technology Mod. 34970A where two multiplexer modules 34901A were inserted: the first one for potential measurements while the second one for partial current measurements. The Unit was connected to a PC by a RS-232 port for data storage at defined intervals of time.

At the beginning, for all test sessions, all switches of Fig. 2 were OFF for recording the free corrosion potentials of all metallic parts of the studied system (Fig. 1). Subsequently, they were sequentially switched ON in order to observe the polarization effects produced by the anodes and then to test the initial efficiency of the cathodic protection.

RESULTS AND DISCUSSION

Firstly, the tests were performed with circulating water in the interspace between the shaft and the stern tube and subsequently in stagnant water.

When the sea water flow rate was 20 L/min, the potential trends corresponding to the different metallic parts, are shown in Fig. 3. The polarization effect is pretty clear at the activation of cathodic protection in correspondence of the sudden variation of the shaft, the stern tube and the anode potentials (see left side of Fig. 3). Gradually, the system potential reached stationary values around -0.350 V vs SCE, which corresponds to perfect passivity conditions [9].

Fig. 4 shows the trend of the total cathodic protection current with an initial peak of 0.065 A and with a subsequent achievement of a stationary value around 0.045 A. Both anodes supplied more or less the same amount of current, as can be observed from the partial current curves, while between the shaft and the stern tube, the first adsorbs less current than the second one. This can be explained by

Fig. 2 - Scheme of the circuit used for cathodic protection tests. The symbols mean: PS = propeller shaft; ST= stern tube; ANi= anode, i=1,2; Agi = Ag/AgCl reference electrode, i=1,...,7; SCE = saturated calomel reference electrode; SW = switch.
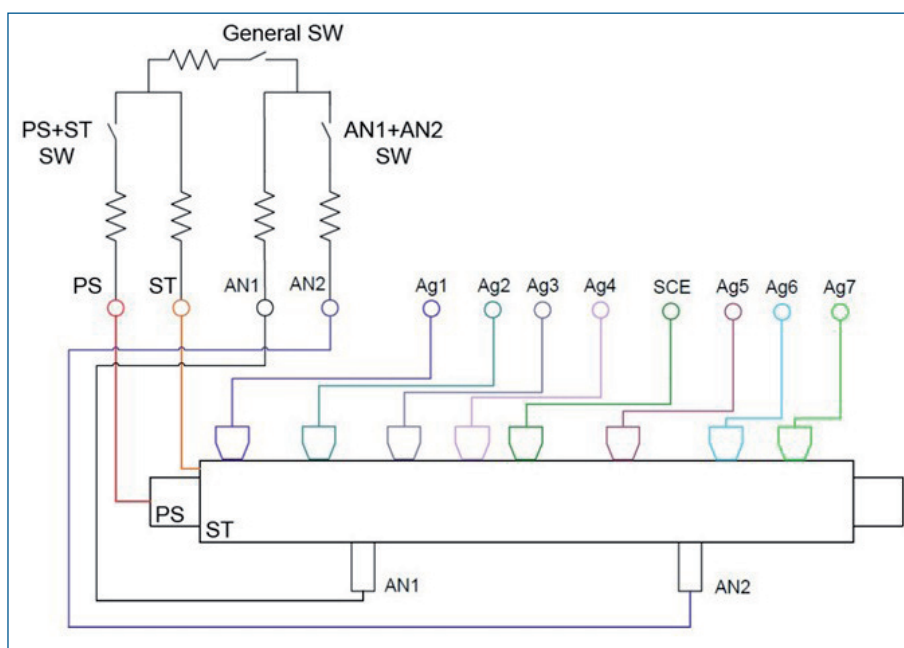
Fig. 2 - Schema del circuito utilizzato per la protezione catodica. I simboli riportati significano: PS = asse; ST = astuccio; ANi = anodo, i=1,2; Agi = elettrodo di riferimento Ag/ AgCl, i=1,...,7; SCE = elettrodo di riferimento a calomelano saturo; SW = interruttore
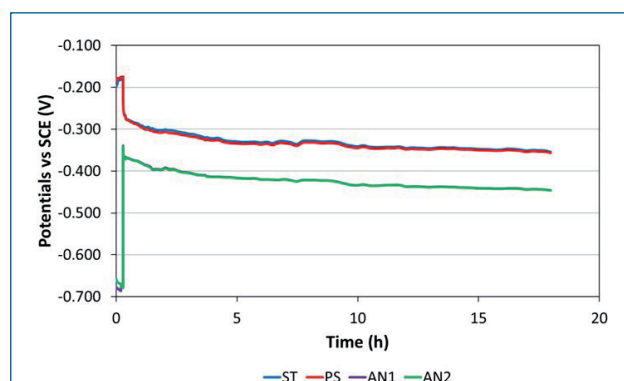

Fig. 3 - Potential trends in cathodic protection conditions with circulating water at 20 L/min.

Fig. 3 - Variazione dei potenziali in condizioni di protezione catodica con acqua circolante a 20 L/min.
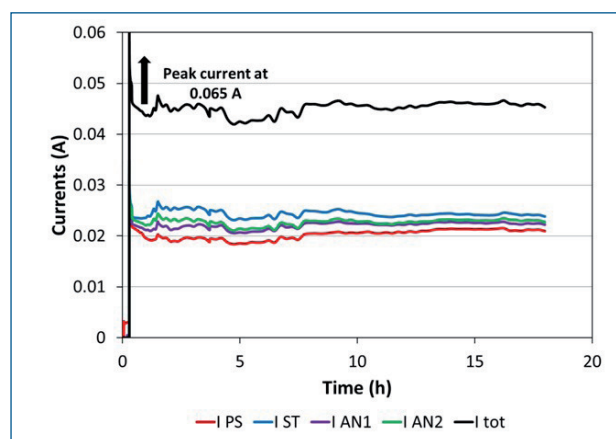

Fig. 4 - Partial current trends (absolute values) in cathodic protection conditions with circulating water at 20 L/min.

Fig. 4 - Variazione delle correnti parziali (in valore assoluto) in condizioni di protezione catodica con acqua circolante a 20 L/min.
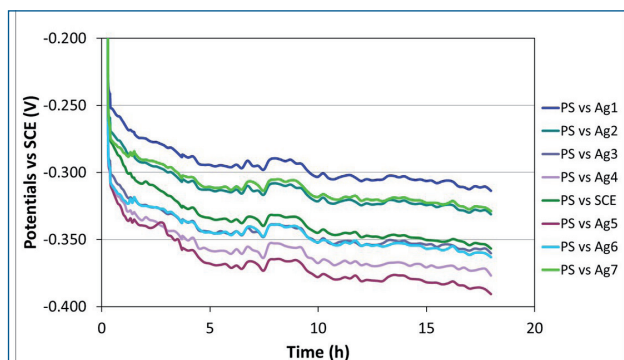

Fig. 5 - Trends of the local potentials on the basis of reference electrode positions (Fig. 2) in the case of the test with circulating water at 20 L/min.

Fig. 5 - Variazione dei potenziali locali secondo la disposizione degli elettrodi mostrata in Fig. 2. Prova di protezione catodica con acqua circolante a 20 L/min.

the higher active surface of the stern tube with respect to that of the shaft (1.58 m^2 vs. 1.12 m^2).

Fig. 5 shows the potentials recorded by all reference electrodes schematically illustrated in Fig. 2: from this diagram, it is possible to conclude that the system is in the perfect passivity condition in all parts, showing in this way the efficiency of cathodic protection determined by both anodes. Furthermore, the possible overprotection with the consequent hydrogen evolution, which can determine the 17 4PH embrittlement, can be excluded. In despite of the low differences between each potential trend, more negative values were measured from the reference electrodes installed in the zones near to the anodes, where polarization effect is higher, while more positive values were recorded in the zones far from them (Ag1 and Ag7; see Fig. 2 and Fig. 5).

Significant differences between the previous case and the case of circulating water at 30 L/min were not

observed. Therefore, for the sake of brevity, the currents and potentials relative to this case are not reported here. However, the cathodic protection was guaranteed from both anodes.

On the contrary, the case of the circulating water at 40 L/min was significantly different, because it determines a turbulent water flow with the clear presence of air bubbles in the fluid running in the interspace of the propeller system. This determines the presence of a high concentration of oxygen on the surface of metallic parts which contributes to increase their potentials both with and without cathodic protection (Fig. 6). However, such an increase of the corrosion potential could mainly be attributed to the formation of biofilms on the metal surface [12], which is quite normal in sea water exposure as that observed in this work. The increase of the stainless steel corrosion potential determines an increase in its own susceptibility to localized corrosion. In fact, in these conditions, the risk of pitting corrosion of 17 4PH stainless steel is present, due to the achievement of potential values above the pitting potential of this material with circulating sea water (E_{pit} = 0,074 V vs SCE [9]). Therefore, cathodic protection is essential in this situation.

Switching on the cathodic protection, the potential of the shaft reached values in the range -0,040 and +0,030 V vs SCE, where higher values correspond to the zones far from the anodes (measured by Ag1, Ag2 and Ag7 reference electrodes; their trends are not reported here). Therefore, in these conditions, the cathodic protection is essential to avoid the risk of localized corrosion process in the propeller system.

Concerning the total current trend, after the initial peak determined by the protection switching on event, it reaches values quite high in comparison with those reached in the cases of circulating water at 20 and 30 L/min. In fact, with flow rate at 40 L/min, the quasi-stationary conditions are reached at 0.095 A. The higher current measured in this case with respect to those measured previously is determined by the significant increase of the stern tube and shaft corrosion potentials with respect to the anode corrosion potentials (compare Fig. 3 in the left side and inset of the Fig. 6). This produces an increase of electromotive forces of the galvanic couple plain steel-stainless steel with the consequent increase of the protection current.

In conclusion, in the case of the system with stagnant water, potential and current trends were rather different from those recorded with circulating water. In fact, without sea water renewal, oxygen consumption determined by cathodic protection produces the decrease of its concentration. As a consequence, a gradual decrease of the total protection current is observed with the achievement of very low values close to 0 A, after 40-50 hours (Fig. 7). This behaviour is not surprising taking into account that the protection current is strictly related to the limit diffusion current of oxygen, whose value is influenced by its concentration in the water, by the water temperature, flow rate and turbulence [1]. Considering that the water is stagnant and the oxygen is consumed by the metallic
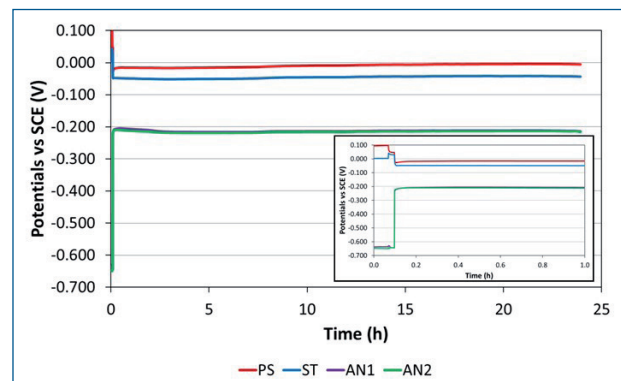

Fig. 6 - Potential trends in condition of the circulating water at 40 L/min. Inset: magnification of the diagram at early time periods.

Fig. 6 - Variazione dei potenziali in condizioni di protezione catodica con acqua circolante a 40 L/min. Inserto: ingrandimento del grafico a valori bassi di tempo.

parts of the propeller system during cathodic protection, its concentration tends to decrease and as a consequence its limit diffusion current tends to decrease.

Of course, even the potentials measured with stagnant water were different, if compared to those recorded with circulating water (the diagram is not reported for a sake of brevity); they tends to decrease contemporarily for all metallic parts up to the achievement of -0.650 V vs SCE, which corresponds to the perfect passivity condition. Furthermore, at these potential values, there is neither the evolution of hydrogen nor the consequent risk of stainless steel embrittlement.

The current supplied by plain steel anodes and measured after experimental tests can be used to calculate their durability and to program their substitution.

The consumption of an anode can be determined considering the current supplied in quasi-stationary conditions using the following equation:

$$M_{Fe} = \eta * \frac{I*24*3600}{2*96500} * 55,8 \tag{1}$$

where M_{Fe} represents the anode consumption in g/day, I represents the quasi-stationary current supplied and η represents the anode dissolution efficiency.

Considering the average of the stationary current supplied by both anodes, more or less in equal amounts, and considering η =1, from equation (1), the average consumption of an anode can be calculated obtaining the values showed in Table 1.

In conclusion, taking into account the consumption data of the previous Table 1 and the anode dimensions (Ø35x70 mm), its theoretical life time can be obtained as shown in Table 2.

Considering that the propeller system studied in this work is relative to yachts, a hypothesis of their use during a
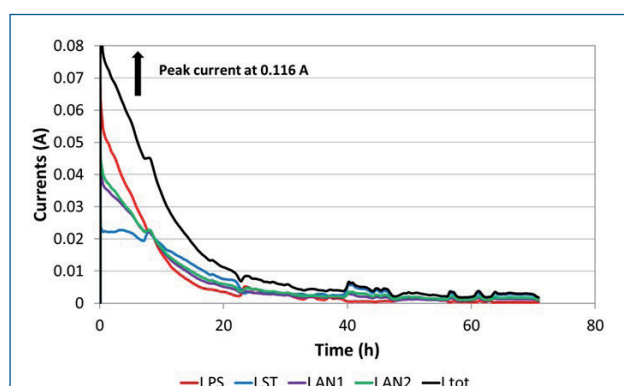
Fig. 7 - Partial current trends (absolute values) in cathodic protection conditions with stagnant water.

Fig. 7 - Variazione delle correnti parziali (in valore assoluto) in condizioni di protezione catodica con acqua stagnante.

Test conditions	$I_{average}$	M_{Fe}
	(A)	(g/day)
Circulating water at 20 L/min	0.023	0.575
Circulating water at 30 L/min	0.024	0.599
Circulating water at 40 L/min	0.046	1.149
Stagnant water after 20 hours	0.011	0.274
Stagnant water after 50 hours	0.001	0.025

Tab. 1 - Summary of the average consumption of an anode in grams per day.

Tab. 1 - Riepilogo del consumo medio di un anodo espresso in grammi al giorno.

Test conditions	Life time	
	(days)	(months)
Circulating water at 20 L/min	920	30
Circulating water at 30 L/min	882	29.5
Circulating water at 40 L/min	460	15
Stagnant water after 20 hours	1925	64
Stagnant water after 50 hours	21180	706

Tab. 2 - Summary of anode life time in different conditions, given both in days and in months

Tab. 2 - Riepilogo della durata di un anodo, espressa sia in giorni sia in mesi.

year can be made: for the main part of their life, they are berthed to a mole and, for the remaining time, they are sailing, in particular during summer. Therefore, a possible hypothesis of the yacht use is three months (90 days) of sailing with circulating water at a flow rate of 40 L/min while for the remaining 9 months (365-90 = 275 days) in the condition of "stagnant water after 50 hours" (see Table 1).

With reference to the values reported in Table 1, the annual consumption of an anode will be:

$$M_{Fe,year} = 1.149 * 90 + 0.025 * 275 = 110 \ g/year \ (2)$$

Therefore, the anode time life in these conditions will be:

$$t_c = \frac{M_{anode}}{M_{Fe,year}} = \frac{\left(\pi * \emptyset^2/4\right) * l * \rho}{M_{Fe,year}} = \frac{\left(\pi * 35^2/4\right) * 70 * 7.86 * 10^{-3}}{110} = \frac{529}{110} = \ (3)$$

$$= 4 \ years \ and \ 9 \ months$$

Finally, in the present hypothesis, it can be suggested that it is necessary to substitute the anodes after about 4 years of the yacht use.

CONCLUSIONS

In this work, experimental tests were performed for studying the cathodic protection efficiency obtained by the use of sacrificial plain steel anodes with respect to a propeller shaft-stern tube system, installed in large–medium sized ships and subject to localized corrosion. For this aim, a monitoring workstation was organized for measuring the currents and the potentials.

From the results, in the presence of cathodic protection, the whole system showed potential values under the repassivation potential of all materials, in almost all conditions tested in this study and therefore the localized

corrosion can be excluded. With more details, in stagnant water, the potentials reached low values but sufficiently high to avoid the hydrogen evolution which can produce the dangerous steel embrittlement. In moving water, with a flow rate of 40 L/min, the system was found in a condition of localized corrosion risk. Furthermore, in this case a presence of biofilms on the metal surface was observed. Particular attention must be paid to this phenomenon which increases the steel corrosion potential and, as a consequence, it increases its susceptibility to localized corrosion. Therefore, in these conditions, cathodic protection is essential.

In a first approximation, a theoretical calculation of the

durability of an anode was done: 4 years and 9 months. This result was obtained hypothesizing for a yacht a period of inactivity of 9 months and a period of sailing activity for the remaining 3 months, during a year. Practically, the anodes substitution could be done after 4 years.

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Prove in campo dell'efficacia della protezione catodica in un sistema di propulsione di una nave

Parole chiave: Corrosione localizzata - Protezione catodica - Anodi sacrificali - Acciai inossidabili - Acqua di mare

La presente ricerca ha riguardato l'analisi dell'efficacia della protezione catodica di un asse portaelica del motore di imbarcazioni medio-grandi. L'asse è di acciaio inossidabile 17 4PH indurito per precipitazione, inserito in un astuccio cilindrico di acciaio inossidabile AISI 304. Nell'intercapedine tra i due componenti si trova acqua di mare, che risulta stagnante per la maggior parte del tempo, poiché le imbarcazioni considerate (yacht) restano ferme in acqua per circa nove mesi all'anno. Tenendo conto che in simili condizioni, più di un asse ha dato luogo a preoccupanti fenomeni di corrosione localizzata, in questo lavoro è stata verificata l'efficacia della protezione catodica utilizzando anodi sacrificali di acciaio dolce come metodo preventivo per evitare tale tipo di corrosione. La sperimentazione è stata eseguita su un sistema asse-astuccio di dimensioni reali (di lunghezza di poco superiore ai 3 metri) a cui sono state apportate delle modifiche per permettere il monitoraggio dei potenziali e delle correnti in gioco, al fine di effettuare la valutazione oggetto del presente studio. I test sono stati effettuati sia con acqua di mare stagnante, che con acqua fatta circolare con varie portate fino a 40 L/min per simulare le condizioni che si hanno in fase di navigazione.

Dai risultati ottenuti, è emerso che tutto il sistema, quando la protezione era attiva, si trovava al di sotto dei potenziali di pitting relativi ai materiali che lo costituiscono, quindi risultava essere escluso un innesco della corrosione di questo tipo. L'uso di anodi di acciaio comune portava il sistema a valori di potenziale che dipendevano dalle condizioni operative in cui esso si trovava a lavorare e, in quasi tutte le prove realizzate, esso si trovava a potenziali inferiori rispetto a quello di ripassivazione e quindi in condizioni di passività perfetta, che sono appunto le migliori per prevenire i fenomeni corrosivi localizzati. In condizioni di acqua stagnante si raggiungevano valori di potenziale più bassi rispetto al caso di acqua circolante ma, fortunatamente, non si arrivava a valori tali da permettere lo sviluppo di idrogeno, che può indurre all'infragilimento dell'asse, trattandosi di un acciaio ad alta resistenza e pertanto, come altri materiali di questo tipo, soggetto a tale fenomeno. Di contro, in condizioni estremamente ossigenate (40 L/min), il potenziale del sistema tendeva ad innalzarsi e ad avvicinarsi addirittura al potenziale di pitting. La maggiore ossigenazione dell'acqua non è stata probabilmente la principale causa dell'innalzamento del potenziale, osservato in queste condizioni, per il sistema in studio, poiché a questo risultato sperimentale ha contribuito la formazione di una certa quantità di biofilm sulle superfici dei metalli testati. Esso produce le condizioni specifiche che conducono all'innalzamento dei potenziali di corrosione degli acciai inossidabili come quelli testati, aumentando in modo critico la probabilità di corrosione localizzata. Proprio per ridurre tale probabilità, si rende indispensabile l'impiego della protezione catodica per il sistema oggetto di questo studio.

È stato eseguito infine il calcolo teorico approssimativo della durata di un anodo. Il valore determinato, di 4 anni e 9 mesi, potrebbe risultare relativamente attendibile poiché è stato ottenuto ipotizzando una storia di navigazione annua in cui l'imbarcazione rimane attraccata in banchina per nove mesi, mentre per i restanti tre mesi risulta sempre in navigazione. In pratica, gli anodi potrebbero essere sostituiti dopo 4 anni.

In fase di progettazione, oltre a studiare forme e dimensioni che consentano di massimizzare la durata dell'anodo, vanno anche studiati dei sistemi che ne permettano il cambio in modo agevole ed economico.