**Investigation into the formation and removal of adhesion substance on possible heat exchanger materials in Singapore seawater**

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In seawater the adhesion substances that forms on many alloys is a mixture of biofouling and carbonate scale. This is bad news for heat exchanger operation since localized corrosion can occur beneath the biofouling and the carbonate scale prevents effective heat transfer. To have a better understanding of the formation of adhesion substance on heat exchanger materials in Singapore seawater, three sets of test coupons, each with 7 pieces of different materials of Al-brass, Cupro-nickel, Ti, γ-Super stainless steel (UNS S31254), Duplex-Super stainless steel (S31260, S32750) and 316L, were dipped in the open sea for 157 days. During the test period, a series of pictures were taken (Fig. 1). The effect of adhesion substances on heat exchanger materials were evaluated by chemical composition analysis and ignition loss of adhesion substances. Acid pickling agents of 10% nitric acid; 5% HCl + 0.5% inhibitor; 5% sulfamic acid + 0.5% inhibitor; and 5% citric acid were applied and evaluated as the removal of the remaining adhesion substance. The rate of scale removal was initially defined as:

$$\boldsymbol{Rate = \frac{Weight\ of\ scale}{Surface\ area\ x\ Time\ \ for\ complete\ removal}}$$

In practice such a definition proved to be too simplistic, as the adhesion substance appeared to consist of two layers, a thick outer one that could be rapidly removed and a hard inner scale. The implications for this will be discussed in the paper.

The results showed that Al-brass and Cupro-nickel materials attracted the least adhesion substance compared to the stainless steels and Ti materials, which is consistent with the known toxicity of $Cu^{2+}$ions. However, befouling, including the growth of barnacles still occurred on the copper alloys. Crevice corrosion and shallow pits were observed under the adhesion substance on all the grades of stainless steel except for duplex-super stainless steel type S32750. All of the stainless steel materials remained shiny surface after testing. Localized corrosion in the form of dezincification and deep pits were observed on Al-brass material. Denickelification, crevice corrosion, and deep pits were also seen on the Cupro-nickel test coupon, which also showed signs of tarnish over its entire surface.

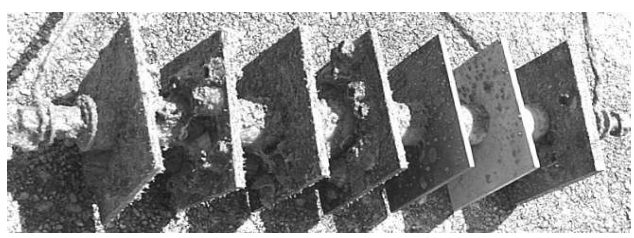
Analysis of the adhesion substance suggested that in all cases it mainly consisted of $CaCO_3$ and a range of different shellfish. With regards to the removal of adhesion substance it was found that for the stainless steels the order of the scale removal rates was $HNO_3$ > inhibited HCl > inhibited sulfamic acid. For copper alloys the scale removal rate was in the order HCl > sulfamic acid > citric acid (Table 1). The corrosivity of acid pickling agents on parent materials was also investigated. The results revealed that corrosion rates of parent material in all of the tested acid pickling agents were much higher than that of the material in raw seawater indicating that excessive pickling should be avoided.

**Table 1 Difficulty of removal of adhesion substance**

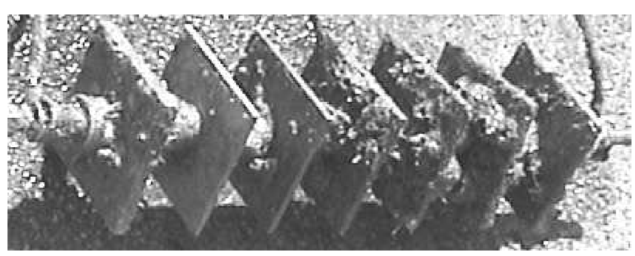
| | Rate of scale removal (g/m2min) in 5% HCl + 0.5% inhibitor | Rate of scale removal (g/m2min) in 5% citric acid + 0.5% inhibitor | Rate of scale removal (g/m2min) in 5% sulfamic acid + 0.5% inhibitor | Rate of scale removal (g/m2min) in 10% nitric acid |
|---|---|---|---|---|
| ALB | >1.90* | 0.52 | 0.97 | -- |
| CUP | >1.49* | >0.49* | >0.63* | -- |
| SMO | 3.97 | -- | >0.29* | - |
| D329 | 3.47 | -- | 0.83 | 15.45 |
| 2507 | 2.99 | -- | 1.68 | 13.68 |
| 316L | 1.95 | -- | >0.24* | - |

* Scale completely removal in after first acid dip: leads to an underestimate of removal rate.

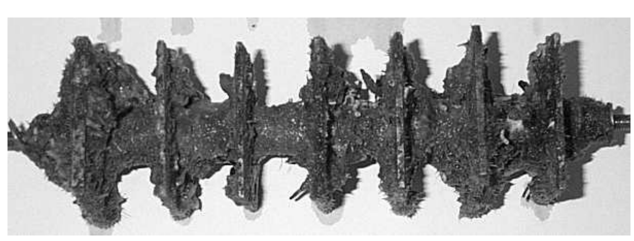
a: Immersed in open sea for 31 days



b: Immersed in open sea for 95 days



c: Immersed in open sea for 125 days



d: Immersed in open sea for 157 days

**Fig. 1 Test coupons immersed in open sea**