



Corrosion Failure Study in an Oil Cooler Heat Exchanger in Marine Diesel Engine

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ABSTRACT

In this article, the failure of a heat exchanger during its operation in the marine environment has been analyzed. This heat exchanger was used for cooling the oil in a marine diesel engine. Based on the existing failure history, damages in engine components were observed after 89 hours of engine working due to the leakage of the sea water to the oil. For the objective of the failure analysis, each component was investigated under the stereo optical microscopy and the scanning electron microscopy (SEM). The diameter of pits was also recorded as 8 micrometer. Besides, the chemical composition of corrosion products on the surface and in pits was additionally analyzed with the energy dispersive X-ray spectroscopy (EDAX). Results indicated that two corrosion mechanisms were failure root causes of leakages, including the crevice corrosion and the pitting corrosion. In such situation, in the engine, the oil and the sea water in tubes of the heat exchanger mixed and decreased the oil viscosity and damaged the oil film on crankshaft bearings, and finally caused damages of the engine.

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1. INTRODUCTION

Nowadays, heat exchangers are widely used in different industries including chemical, petroleum, medicine, engine and nuclear technologies. One application is in marine diesel engines for oil cooling. Failures such as cracks and holes in heat exchangers are common problems. Generally, such cracks and holes have been initiated and propagated by fatigue [1-3] and corrosion [4-10] phenomena. In the case of corrosion failures, different mechanisms could be failure root causes in materials, including stress corrosion cracking [4-7], pitting corrosion [8, 9], crevice corrosion [10], and galvanic corrosion [11].

Such failures due to the corrosion in heat exchangers have been reported and analyzed in the literature. Guo et al. [4] studied failures of the stainless steel tube bundle in condensate/heavy gas oil heat exchangers in a petrochemical plant. They showed that the intergranular stress corrosion cracking was the main reason for the failure, and welding micro-fissures promoted the failure. El-Amoush et al. [5] investigated the stress corrosion

cracking of the pre-immersed tin brass heat exchanger tube by using slow strain rate testing in an environment containing ammonia. Their failure analysis of the brass tube revealed that a dezincification had occurred after slow strain rate testing and the severity of a dezincified area through the tube depends on the pre-immersion conditions. Xu et al. [6] analyzed the cracking failure of a new heat exchanger during the first start-up operation. They showed that heat exchanger tube cracking was caused by stress corrosion cracking. The residual tensile stress due to the seal expansion was the source of stress.

Corte et al. [7] studied failures of tubes from a tube shell heat exchange in one of the compression stages used to cool and purify the gas produced in an off-shore platform. Results of the failure analysis indicated that the AISI 321 tube of the heat exchanger failed by stress corrosion cracking due to the high chloride content of the cooling water. Cracks initiated in the outer surface and were located in the region of the crevice between the tube and the tube sheet. Gong et al. [9] discussed a localized failure that took place after beginning of the service on heat exchanger tubes inside a purified terephthalic acid (PTA) dryer in a petrochemical works. They showed that the pitting corrosion occurred on

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316L austenitic stainless steel tubes of one PTA dryer, and even resulted in a peculiar ‘Yin-Yang’ corrosion morphology. Peltola and Lindgren [10] reported the failure analysis of a finned heat exchanger which leaked in the pressure test during commissioning. Their investigation indicated that the failure was a consequence of ant-nest corrosion, or formicary corrosion. This form of local corrosion attacks on copper could be described as micro-pitting.

Allahkaram et al. [8] studied heat exchanger tubes made of Inconel 625 which failed after only two years of operation. Their results indicated that the failure was caused by the pitting corrosion in two contact regions, tubes and baffles as well as in tube sheet and shell contact regions, in spite of sufficient corrosion resistance of Inconel 625 to the sea water. In addition, the cause of failed exchanger tubes was also due to the crevice corrosion. They suggested that periodic cleaning of the heat exchanger from deposits is essential in order to prevent precipitations. Parrott [11] described the hazards of the undetected corrosion in a heat exchanger on an offshore gas storage platform. The investigation revealed the localized corrosion of the carbon steel tube sheet in areas exposed to the acidic containing hydrogen sulphide. The corrosion was galvanic, where hydrogen generated cathodically and formed titanium hydride in the interfacial region of titanium cladding.

In this research, a failure analysis was performed for the leakage in an oil cooler system in a marine diesel engine. For this objective, each component was studied under the stereo optical microscopy, the scanning electron microscopy (SEM) and the energy dispersive X-ray spectroscopy (EDAX).

2. BACKGROUND

In marine diesel engines, to cool the oil, heat exchangers are widely used. These heat exchangers are placed in the oil chamber and utilize the sea water for cooling the engine oil. Components of this cooling system can be seen in Figure 1(a). According to this figure, the heat exchanger includes tubes and a shell. The engine oil moves through the shell and the sea water moves through tubes. Tubes, made of 316L stainless steel are brazed to the tube sheet made of brass. There are also some baffles to cause turbulence for better heat transfer.

Maximum sea water and oil pressure are 2.8 bars, respectively. Maximum temperature of in the sea water and the oil are 50°C and 100°C, respectively. In order to protect tubes against corrosion, some tubes have copper coating as the cathodic protection in the oil environment, as shown in Figure 1(b). In addition, some cathodic protection bolts are placed through the sea

water to protect tubes against the corrosion phenomenon in the salty water environment. These bolts should be changed during their service lifetime.

3. OBSERVATIONS

After 38 hours of engine working, the oil volume reduced. By continuing upto 89 hours, failures were observed in crank shaft bearings. The cause of this failure was the reduction in the oil volume due to leakage in the oil cooler heat exchanger. During a leakage test, as an observation, leakage effects were seen on the hub exposed to the sea water with rust effects (Figure 2a).

Another leakage was observed between tubes and the tube sheet (Figure 2b). The joint between tubes and the tube sheet in one side in was the sea water environment and in other side, in the oil environment, where rust effects can be seen. At another instance, after the disassembly of tubes, tiny holes were observed on the external surfaces of tubes, (Figure 2c).

As a first question, the third observation (includes tiny holes on tubes), should be investigated that in which environment (the oil or the sea water), this hole was initiated.

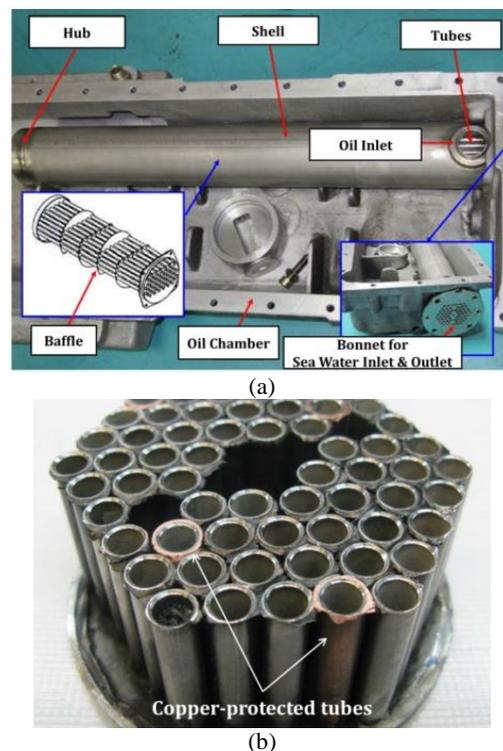


Figure 1. (a) Components of the heat exchanger for the engine oil cooling system and (b) the cross section of tubes

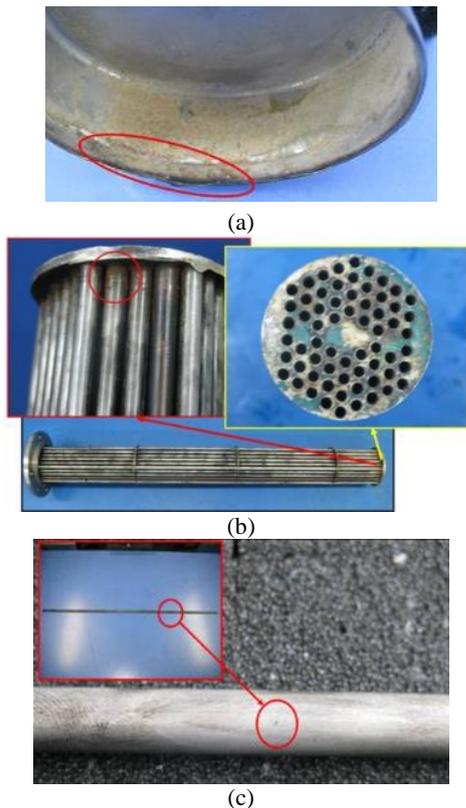


Figure 2. Leakage regions (a) in the hub, (b) between tubes and the tube sheet, (c) on the external surfaces of tubes as tiny holes

4. EXPERIMENTS AND MATERIALS

To analyze the failure in the oil cooler heat exchanger and to see the leakage, each component was studied under the stereo optical microscopy. Then, the diameter of pits was recorded and investigated through the scanning electron microscopy (SEM).

The chemical composition of corrosion products on the surface and in pits was analyzed with the energy dispersive X-ray spectroscopy (EDAX). It should be noted that the sea water had the pH of 8.07 ± 0.01 and 3.4 ± 0.2 %wt salt [12].

The material composition of different components in the heat exchanger is shown in Table 1. Based on these results, tubes, the hub and the shell were made of 316L stainless steel. The tube sheet was made of brass and the tubes coating layer was made of copper.

5. RESULTS AND DISCUSSIONS

5.1. The Leakage in the Hub Figure 2(a) shows the presence of salt deposits in the hub. Factors that created these salts often include the solubility reduction of salts (such as magnesium or carbonates salts) at high

temperatures (the oil temperature was about $100^{\circ}\text{C}.$), corrosion and biological (environmental) phenomena. These factors were not separated by the filter at the heat exchange inlet.

5.2. The Leakage Between Tubes and the Tube Sheet

As shown in Figure 2(b), the damage was normally confined to the brass sheet, at localized areas between tubes and the tube sheet. The damage was from the side that the joint area of tubes and the tube sheet was in the sea water. Rust effects on the oil side of tubes were due to engine working for 89 hours, after the oil volume reduction at 38 hours of working. The reason for the mentioned damage was the sea water reverse osmosis desalination plant. It seems that the damage was of the crevice corrosion type, since common locations for the crevice corrosion in heat exchangers could be at a gap between tubes and tube sheet or at gasketed joints (Figure 3).

One cause of failure root of the crevice corrosion could be due to the improper brazing process and the lack or low diffusion of brazing materials between tubes and the tube sheet.

TABLE 1. The material composition of different components in the heat exchanger

Components	Tubes	Hub	Tubes Coating	Tube Sheet
C	0.02	0.03	-	-
Mn	1.58	0.87	-	-
Si	0.46	0.56	-	-
P	0.02	0.02	-	-
S	0.003	0.003	0.003	-
Cr	17.05	17.00	-	-
Mo	2.05	2.06	-	-
Ni	11.40	10.50	-	-
Cu	0.45	0.24	-	-
W	0.10	0.03	-	-
Co	0.24	0.11	0.01	-
Fe	Bal.	Bal.	-	0.04
Zn	-	-	0.01	34.00
Pb	-	-	0.02	0.13
Sn	-	-	0.01	-
Cu	-	-	Bal.	Bal.
Al	-	-	-	1.23

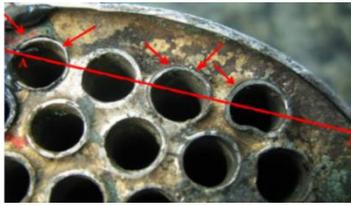


Figure 3. Damages between tubes and the tube sheet

Another cause of failure root could be due to the galvanic corrosion. The most severe attack occurred at the joint between these two dissimilar metals. Further away from the bi-metallic joint, the degree of the accelerated attack reduced. If a sacrificial anode is used (such as brass in the marine environment), these anodes would corrode.

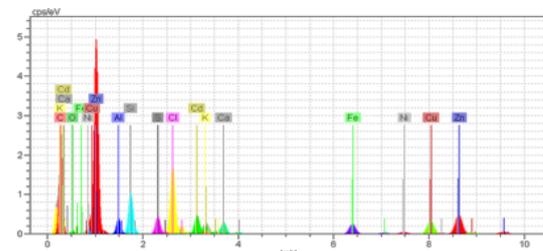
Therefore, the stainless steel would be protected. The potential difference (i.e., the voltage) between these two dissimilar metals was the driving force for the destructive attack on the active metal (anode: brass). The current flowed through the electrolyte to the more noble metal (cathode: stainless steel) and the less noble metal would be corroded.

The conductivity of the electrolyte would also affect the degree of the attack. In addition, the ratio of cathode to anode area is directly proportional to the acceleration factor. The crevice corrosion generally occurs due to either high concentration of impurities in the crevice (e.g., chlorides, acid, or base), or the differential electrolyte chemistry between inside and outside of the crevice [13]. In other words, a single metal part undergoing corrosion is submerged in two different environments [14]. Chlorides concentrated inside the crevice (the anode) worsen the situation. Ferrous ions form ferric chlorides and attack the stainless steel rapidly. Generally, two colors (green and red) can be observed on the tube sheet as corrosion products as shown in Figure 4. EDAX results are also indicated in Figure 5. These different colors reflect various chemical compositions of the rust, as follows. Green rusts are unstable corrosion product, typically produced in a low-oxygen environment such as the rebar in the chlorine-rich environment of the sea water.

Such rusts may result in $[\text{Fe}^{\text{II}}_3\cdot\text{Fe}^{\text{III}}(\text{OH})_8]^+ [\text{Cl}\cdot\text{H}_2\text{O}]^-$, a series of iron hydroxides [15]. EDAX results indicated the presence of chlorine in 6.09 %wt., iron in 3.88 %wt., and oxygen in 2.25 %wt. in green color - corrosion products. Comparing EDAX results for green and red rusts, it could be concluded that the chlorine concentration in the green rust was about two times higher than the same content in the red rust. The de-passivation of stainless steels to form green rusts occurs when the ratio of concentrations of chloride ions to hydroxide ions is greater than 1, as mentioned in the literature [15]. This ratio was about 2.7 as shown in EDAX results.



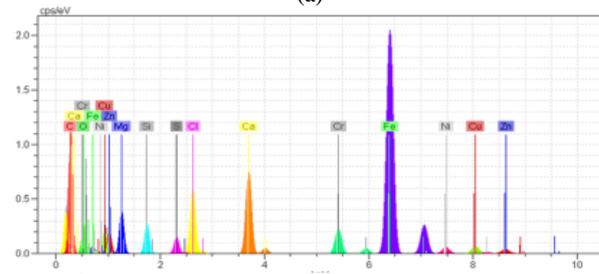
Figure 4. Red color and green color - corrosion products on the tube sheet



Spectra: GREEN

Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K series	21.53	32.91	67.36
Oxygen	K series	1.47	2.25	3.48
Aluminum	K series	0.80	1.23	1.12
Silicon	K series	2.00	3.06	2.68
Sulfur	K series	0.92	1.41	1.08
Chlorine	K series	3.99	6.09	4.23
Potassium	K series	0.23	0.35	0.22
Calcium	K series	0.88	1.34	0.82
Iron	K series	2.54	3.88	1.71
Nickel	K series	0.81	1.24	0.52
Copper	K series	3.35	5.08	3.08
Zinc	K series	19.70	28.59	10.75
Cadmium	L series	2.98	4.55	1.00

(a)



Spectra: RED

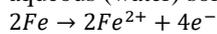
Element	Series	unn. C [wt.-%]	norm. C [wt.-%]	Atom. C [at.-%]
Carbon	K series	11.18	15.53	41.70
Oxygen	K series	2.55	3.96	7.88
Magnesium	K series	1.98	1.92	2.55
Silicon	K series	0.76	1.06	1.21
Sulfur	K series	0.44	0.62	0.62
Chlorine	K series	1.92	2.66	2.48
Calcium	K series	3.32	4.61	3.71
Chromium	K series	2.41	3.35	2.08
Iron	K series	40.97	56.92	32.88
Nickel	K series	1.96	2.72	1.49
Copper	K series	2.72	3.78	1.92
Zinc	K series	2.07	2.87	1.42

(b)

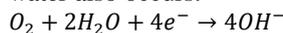
Figure 5. EDAX results for the tube sheet, including (a) green color and (b) red color - corrosion products

In the presence of moisture, the copper oxide layer slowly reacts with sulfur dioxide and carbon dioxide from the air to eventually form corrosion products. These corrosion products are green, including hydrated copper sulfate, $\text{Cu}_4\text{SO}_4(\text{OH})_6$, or hydrated copper carbonate, $\text{Cu}_2\text{CO}_3(\text{OH})_2$ [15].

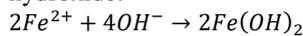
The formation rate of corrosion products and the proportion of components depend upon the humidity and the amount of air pollutants. EDAX results showed the presence of carbon in 32.91%wt. and sulfur in 1.41 %wt. Therefore, this brass was not suitable for sea water, when the working temperature exceeded 45°C [16]. Naval brass (Cu-38Zn-1Sn) or aluminum brass (Cu-22Zn-2Al) is now practically the only brass used for the sea water heat exchanger. For the red rust, two distinct electrochemical reactions occur. There is an anodic dissolution, or oxidation of iron going into the aqueous (water) solution.



The cathodic reduction of oxygen that is dissolved in water also occurs.



Iron ions and hydroxide ions react to form iron hydroxide.



Iron oxides react with oxygen to yield the red rust, $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$. EDAX results for the red rust showed the presence of chlorine in 2.66 %wt., iron in 56.92 %wt., and oxygen in 3.96 %wt.

5. 3. The Leakage in Tubes The leakage in tubes of the heat exchanger was clearly observed, as shown in Figure 2(c). In order to study this phenomenon deeply, tubes were sectioned. Images of the inner tube surface under the stereo optical microscopy were seen. As shown in Figures 6 and 7, tiny holes in tubes were created in the internal part (exposed to the sea water) and then continued to the external part (exposed to the oil). The reason is that chlorides as one of the contents of the sea water are corrosive. In other words, these holes or pits were caused due to the localized corrosion. In particular, it was a pitting corrosion.

Corrosion products were adhered to internal surfaces of tubes, leading to the rusty appearance (Figures 7). Pits on the internal surface of tubes were obscured by corrosion products (the iron oxide). The pitting corrosion could produce pits with their open mouths (uncovered pits) or could be covered with a semi-permeable membrane of corrosion products [17].

In the suggested model, three different regions of a growing pit are assumed. One region is the passive region near the pit mouth or the lacy cover where the concentration of metal ions is low. The second region is a limited diffusion region at the pit bottom where the pit is covered with a salt layer. The last region is an actively dissolving region at pit sides where there is

neither passive film nor salt layer to limit the dissolution [17].

The EDAX resulting corrosion products can be seen in Figure 8. Corrosion products include oxygen and iron, which are rusty effects as Fe_xO_y . In this pattern, chlorine and calcium also were presented in about 1.11 and 4.59 %wt., respectively. In other words, chlorine and calcium which came from the sea water were trapped in corrosion products.

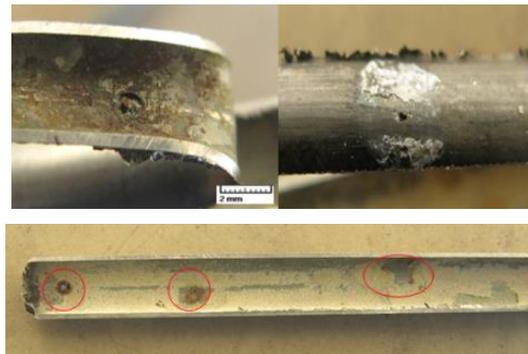


Figure 6. Optical microscopy images of the leakage region in the tube of the heat exchanger

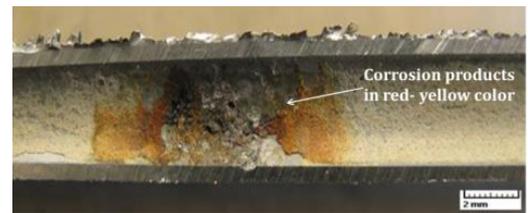


Figure 7. Optical microscopy images of the leakage region with corrosion products

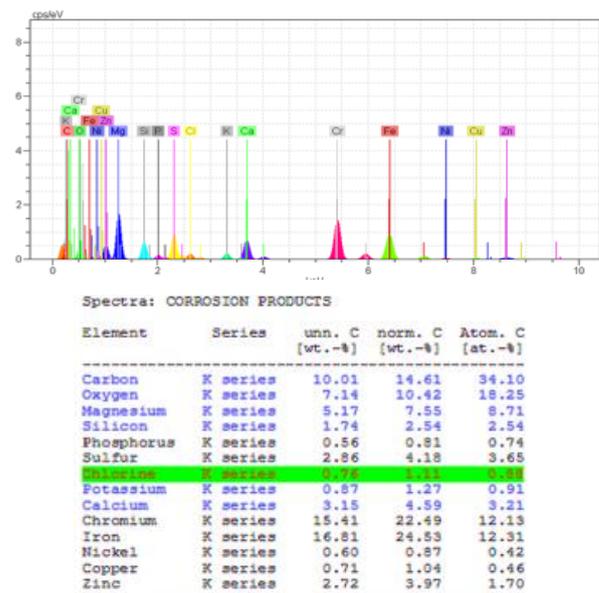


Figure 8. EDAX results for corrosion products

The size of pits was less than 200 micrometer, as shown in SEM images (Figure 9). This pits size was obtained after 89 hours of engine working. It seemed that pits were aggregated together and created a new tiny hole, which the overall size reached above 400 micrometers. The shape of pits was elliptical.

The results of elemental analysis by EDAX (Figure 10) indicated that there were about 10.02 %wt. of oxygen and 0.76 % wt. of chlorine in tiny holes and pits. Adsorbed chloride ions broke down the passivity of the stainless steel, thus increased the corrosion rate. The adsorption process of chloride on metal surfaces has been demonstrated by other researches [17, 18]. In addition, pits in the stainless steel are often associated with manganese sulphide (MnS) inclusions which are found in most commercial steels. The role of MnS inclusions in promoting the breakdown and the localized corrosion of stainless steels has been reported in the literature [17].

Figure 11 shows the pitting corrosion at different regions of the tube. Pits were initiated from the grain boundary of the austenite phase in stainless steels, as these sites had higher energy compared to the grains. As shown in Figure 7, the minimum size of pits size was about 1 micrometer. The maximum size of pits would be 8 micrometers.

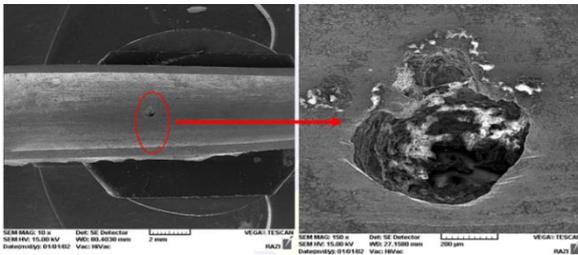


Figure 9. SEM images of pits in the internal part of the tube

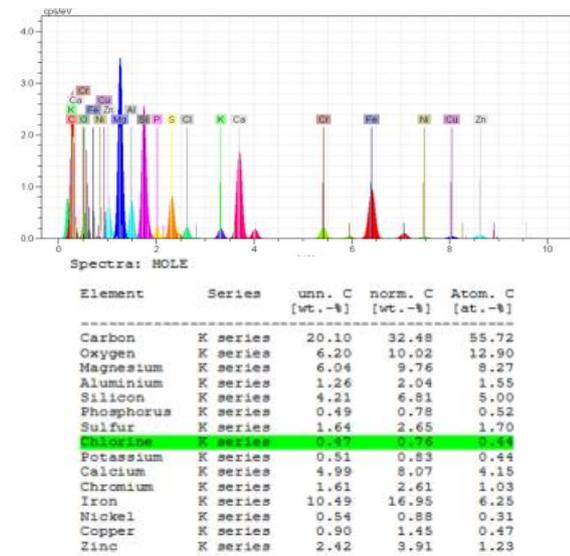


Figure 10. EDAX results for tiny holes and pits

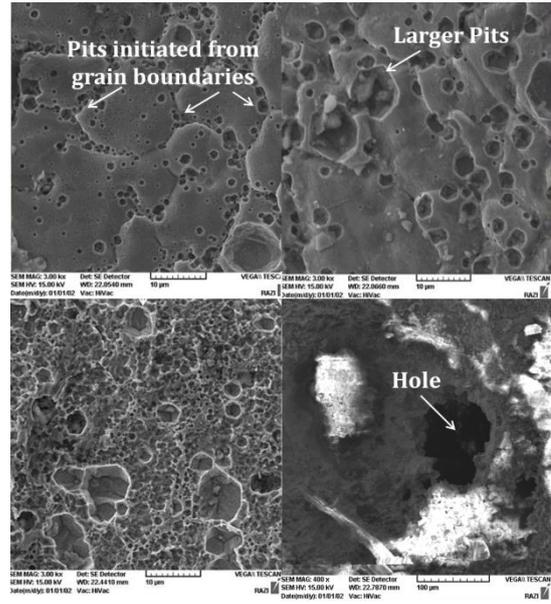


Figure 11. SEM images of pits in the internal part of the tube

Such pits were made after 38 hours of engine working. In some situations, some pits were aggregated together.

The resistance of stainless steels against pitting and the crevice corrosion is primarily determined by the amount of chromium, molybdenum and nitrogen. An index for comparing the resistance to these types of attacks is often evaluated in terms of these elements. The index is called the pitting resistance equivalent number (*PREn* or *PREn*). It is defined in weight percent, using the following equation for austenitic stainless steels [14].

$$PREn = \%Cr + 3.3\%Mo$$

The higher the *PREn* number, the better the performance of an alloy in chloride environments. The *PREn* number for tubes was 24 and this was lower than the range of the protection. The *PREn* number should be more than 32 for the sea water [14]. Therefore, the 316L stainless steel is not suitable for marine environments. It is suggested that the alloy 20 stainless steel (a nickel-iron-chromium austenitic alloy: super alloy) with the *PREn* number higher than 33 or 254SMO-1.4547 (a 6% molybdenum and nitrogen-alloyed austenitic stainless steel) with the *PREn* number higher than 43 could be suitable for such case [19].

6. CONCLUDING REMARKS

In the present article, the failure analysis has been performed for the leakage in the oil cooler of a marine diesel engine. Results showed that the leakage was from different regions. One leakage was from the hub which exposed to the sea water with rust effects. Another leakage was observed between tubes and the tube sheet.

The last leakage was on the external surfaces of tubes as tiny holes. Failure root causes of leakages were the crevice corrosion due to improper brazing process and the pitting corrosion due to unsuitable material for the marine environment.

7. ACKNOWLEDGEMENT

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Pitting Corrosion

Failure Analysis

در این مقاله، خرابی یک مبادله‌کن حرارتی در طول کارکرد آن در یک محیط دریایی تحلیل شده است. این مبادله‌کن حرارتی برای خنک کاری روغن در موتور دیزل دریایی به کار می‌رود. براساس تاریخچه خرابی موجود، آسیب در قطعات موتور پس از ۸۹ ساعت کارکرد، بر اثر نشستی آب دریا به روغن موتور، مشاهده گردید. به منظور تحلیل خرابی، هر یک از قطعات با میکروسکوپ نوری و میکروسکوپ الکترونی روبشی بررسی شدند. بر این اساس، قطر هر حفره (Pits) برابر با ۸ میکرون اندازه گیری شد. به علاوه، ترکیب شیمیایی محصولات خوردگی بر روی سطح و درون حفره‌ها با استفاده از طیف سنجی پرتوی ایکس (EDAX) تحلیل شد. نتایج نشان داد که دو مکانیزم خوردگی به عنوان ریشه‌های خرابی ناشی از نشستی بودند که شامل خوردگی شیار و خوردگی حفره‌ای می‌باشند. در چنین شرایطی در موتور، روغن و آب دریا در لوله‌های مبادله‌کن حرارتی مخلوط شده و باعث کاهش گرانروی روغن، و در نتیجه پارگی فیلم روغن در بلبرینگ‌های میل لنگ موتور شده و در نهایت باعث خرابی موتور گردیده است.

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