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Tube Damage Mechanism and Analysis in Feed Water Heaters

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Abstract

Steam power plants are responsible for the production of most electric in the world. A small increase in the thermal efficiency of the plant means a large saving of fuel consumption. Therefore every effort is made to improve the efficiency of the cycle on which steam power plants operate. One of the major elements that increase the efficiency of the power plants is feed water heater.

The study has been carried out to investigating the causes of tube failure of the high pressure feed water heaters in an electric power stations. Specimens of the failed tubes were examined and photographs of the microstructure of the tube material were taken. Mechanical properties and chemical composition of the tube material were also examined. Comparison between the failed tube and new tube was made. The results of the laboratory test showed that the main reason for the tube failure is the OD (outside diameter) erosion. This effect is very clear especially in desuperheating zone

Key words: feed water heater, erosion, corrosion, desuperheating zone

الخلاصة:

ان المحطات الحرارية (البخارية) هي المسؤوله عن توليد معظم الطاقة الكهربائية في العالم. ان أي زيادة في الكفاءة الحرارية للمحطة يعني توفير كبير في استهلاك الوقود. لذلك بذلت الجهود لتحسين الكفاءة الحرارية للمحطات الحرارية. ومن الأجزاء الرئيسية في المحطات لزيادة الكفاءة الحرارية هي مسخنات الماء المغذي. هذه الدراسة نفذت لتقصي الأسباب التي تؤدي الى فشل الأنابيب في مسخنات الماء المغذي عالية الضغط في محطات توليد الطاقة الكهربائية الحرارية. تم فحص عينات من الأنابيب الفاشلة وتصويرها مجهريا، كما تم فحص الخواص الميكانيكية والتركيب الكيمياوي للعينات ومقارنتها مع العينات من الأنابيب الجديدة. النتائج المختبرية أظهرت ان السبب الرئيسي لفشل الأنابيب هو تعرية سطح الأنابيب في منطقة دخول البخار الى المسخنات.

Introduction

Feed water heater is basically a heat exchanger, where steam could produce more work by expanding further in the turbine then it is used to heat the feed water of the power plant instead either by mixing the two fluid streams or without mixing them. The importance of feed water heaters comes from the following points:-

Feed water improve cycle efficiency of the power plants by raising the temperature of the water entering the boiler which means fuel saving. In addition, it is necessary for modern pressure boiler, to avoid sudden thermal stresses resulting from cold water entering the boiler that cause rupture to boiler parts.

They provide convenient means of de-aerating the feed water (removing air that leaks in the condenser) to prevent corrosion in power plant elements especially the boiler.

(Huijbregts et. al. 1997) [1], studied the causes of heat exchanger failures due to erosion-corrosion. They found that the carbon steels are not yet specified on erosion-corrosion resistance. Small amount of alloying elements appeared to be very beneficial for erosion-corrosion resistance (Cu, Cr, Mo, and C). They recommended a modified carbon-steel should be applied in water steam system to prevent erosion-corrosion, and can result in large money savings. ***(Leferink and Huijbregt 2000)[2]***, studied the effect of dry ammonium nitrate, that can cause Intergranular corrosion Attack (IGA) and Stress Corrosion Cracking (SCC). They recommended that alloying elements in several types of steel influence its resistance to IGA, elements such as Mo, Mn, and Cr have a positive effect on the resistance to IGA and SCC, whereas carbon and copper determental. Also, they studied the microstructure of the steel taken from in-service failures, strings of carbide precipitates were found to be present at grain boundaries. Therefore, that the presences of carbides at grain boundaries increases the susceptibility of steel to IGA. ***(Denial 2003)[3]***, studied the corrosion in power generation heat exchangers, and categorized the corrosion in two groups, general corrosion and localized corrosion accelerated by an electrochemical mechanism. He studied the Microbiological Influenced Corrosion (MIC) and found that manganese concentration as low as 20 ppm can initiate the MIC. ***Golovin et. al. 2003 [4]***, studied the tubes of heat exchanger constructed of bimetallic and they found that the high gradients in chemical potential and temperature are responsible mainly for focal corrosion damage. They have developed a technology and set of METAKOR-VIKOR material that effective anti-corrosion and reconstructive repair with this type of corrosion. ***(Igolkin et. al. 2006)[5]***, studied the damage to heat exchanger tubes, it is local represented by erosion in the initial parts of the tubes, pitching or corrosion cracking in the shoulder region and damage to areas of emergence from tube grid and so on. They have recommended an effective technology for repairing heat exchangers tubes which is placed on the mechanical pressing of protective tubes into the defective parts. ***(Gopi et. al. 2007) [6]***, the effectiveness of a corrosion inhibitor in association with a bivalent cation like Zn^{2+} were investigated by measuring the corrosion losses using electrochemical techniques. The corrosion of 304 S.S. was inhibited by complexation of the inhibitor. ***(Andre et. al. 2009) [7]***

studied the heat exchanger tubes of Steam Generation (SG). The degradation of SG tubes occurs by different mechanisms such as chemical corrosion, stress, deposits, mechanical fretting or combination of these. The corrosion defects are the most common in SG causing replacement of the tubes. They recommended a method that controlling the corrosion using Eddy-Current Testing (ECT) inspection allows for the localization and dimensioning of defects in the tubes.

Tube Damage Mechanism and Analysis

HP feed water heaters are fails due to one of the following mechanisms:

1- Uniform or General Corrosion

Uniform or general corrosion is the most common form of corrosion. It is characterized by a chemical or electrochemical reaction that proceeds uniformly over the entire exposed surface or a substantial portion of that surface. The metal becomes progressively thinner and eventually fails because of the stress loadings imposed on it.

2- Crevice Corrosion and Pitting

Crevice corrosion and pitting are partly discussed together because they are mechanically similar and partly because, in feed water heater tubes, they are often phenomenologically similar. Strictly speaking, the term "pitting" should only be used to describe the corrosion that follows the local breakdown of a protective (e.g., passive) film on a fully exposed metal surface. Crevice corrosion, on the other hand, is a localized corrosion of a metal surface at, or immediately adjacent to, an area shielded from full exposure to the environment material. Crevice corrosion may occur, for instance, under porous scales, corrosion products, mud or debris, or beneath shells (barnacles, clams, etc.) attached to the tube surfaces. When the creviced areas are small, the resulting localized corrosion may resemble pitting attack. It is sufficient to say that it is associated with the depletion of oxygen in the stagnant liquid pool, which results in corrosion of the metal walls adjacent to the crevice. In pitting and crevice corrosion, chloride plays a critical role. The tubes will have localized corrosion when water containing more than 10000 ppm chloride is used [8].

3- Galvanic Corrosion

Galvanic corrosion is the accelerated corrosion of a metal that occurs because of an electrical contact with more noble metal in a corrosive solution. Corrosion of the less corrosion-resistance metal is accelerated and that of the more resistance metal is decreased, as compared with their behavior when they are not coupled electrically. The less resistance metal is described as anodic and the more resistance metal as cathodic. Usually corrosion of the cathode is virtually eliminated [8].

4- Erosion Corrosion

In HP feed water heaters, erosion corrosion is also called water side "impingement attack". Erosion corrosion is a form of localized corrosion that occurs on the water side of the tubes in areas where the turbulence intensity at the metal surface is high enough to cause mechanical disruption of the protective oxide film. Pit-like feature develops which has a shape that is often influenced by the local flow condition. Consequently, this form of attack has some times been given descriptive name such as "horseshoe", "star", and "slot" attacks [9].

5- Dealloying Corrosion

Dealloying, sometimes called "selective leaching" is a form of corrosion whereby the more active components of an alloy corroded preferentially, leaving a surface layer that is rich in more noble alloying elements. The rate of dealloying generally increases with the increases of the temperature or chloride content of the feed water. Dealloying of the tube occurs when the local pH and potential conditions at the metal surface allow corrosion of the more active component, and maintain the nobler component in the immune condition [8]. Thus, the role of deposits, hot spot, and stagnant in the dealloying mechanism is to create the required pH and potential conditions locally.

6- Stress Corrosion Cracking

Stress corrosion cracking (SCC) is a form of slow crack growth that occurs when a susceptible alloy is stressed in tension in a specific corrosive environment. All alloys are susceptible to SCC in at least one environment. But SCC does not occur in all environments, nor does an environment that induces SCC in one alloy necessarily induce SCC in another alloy**.**

In HP feed water heaters, most of the SCC failures are initiated on the steam side of the tube, but a limited number of SCC failures are reported in water side. In either case, failures occur only where the tensile stress (residual or applied) is high enough to promote cracking. Consequently, SCC is most frequently found at highly stressed location such as the tube inlet where high residual stress results from the tube expansion at locations where the tubes have been mechanically damaged [8].

7- Impingement Attack

Impingement attack, is also called steam side erosion, has become one of the most frequently failure modes in feed water heaters. Attack occurs primarily on the peripheral tubes that receive the direct impact of the turbine exhausted and other high energy fluids, which are drained into feed water heaters. The problems arise when droplets, entrained in the steam, enter the feed water heater and impact tubes at high velocity. The repeated impacts of these droplets cause sever corrosion. In early stage of attack, tubes may look on a polished appearance, but in the later stages, the surface becomes increasingly rough, eventually leads to perforation of the tube wall [8].

Tube Damage Analysis

Scanning of the metal structure allows checking the condition of the microstructure of the metal after exposing to long operation period. This may be beneficial to understand the change in the properties of the metals. For successful macroscopic scanning, selection of the specimen of the failed tube must be considered to represent the aim from the macroscopic test. Before the test, the specimen must be first polished to obtain a scratch-free surface. In polished state it is not possible to see the microstructure, the specimen is flat and like a mirror so the illuminating light is reflected evenly from the surface, which exhibits no visible topography. For this reason a mildly corrosive liquid is applied to the surface, like a solution of 2% nitric acid in ethanol. Then using a microscopic device the microstructure of the metal is applicable to be seen and a photographic record is useful in comparison between the specimens of the used and new tube.

Water Analysis

The treatment of feed water of the thermal power plant is the most important and technical subject and requires careful water analysis. Details of any treating process for a plant should be determined, since they may materially affect the plant design. As an example, a series of stainless steel heat exchangers, cooled with reticulating treated water, had given over 10 years problem-free service. However, in an emergency, untreated river water is used to cool the units for 48 hours.

The presence When tube failure occur, a complete root cause analysis should be performed in order to determine the active damage mechanism and the steps that need to be taken to prevent additional failures. Specific aspects of a root cause failure investigation include a review of failure locations and operating history, a laboratory evaluation for the tube specimen from failing locations, water analysis to check if there is any deviation from the standard conditions.

Visual Examination

To the trained eye, much can be learned from a visual examination of the structure and location of the corrosion attack tubes. In some types of corrosion, visual examination can often suggest the cause and mechanism of attack. A photographic record is useful for subsequent reference or comparison.

Typical examples of such corrosion diagnosis are the horseshoe shaped pits associated with erosion-corrosion, or impingement attack. Corrosion pitting of steel may present a variety forms, which can be characterized to some extent. Thus, pitting caused by dissolved oxygen is commonly in the form of isolated rather shallow oval pits overlaid with brown crusts. Pitting due to acidic condensate occurs most often as irregular shaped, smaller and steeper-sided pits than are caused by dissolved oxygen [10].

Chemical Analysis

The tube material in HP feed water heater of the case study is low alloy steel (15Mo3), where low alloy steel contain up to 3% of various alloying elements, notably chromium, nickel, copper, manganese, vanadium, and molybdenum. These alloying additions improve the mechanical properties and reduce the rate of general corrosion problem [10]. Some elements promote the production of adherent oxide layers on the surface of steel and so improve its corrosion resistance. Chromium is particularly useful in this respect. Copper is also used to promote corrosion resistance.

Chemical analysis for tube samples taken from the failed construction is very important to identify if there are any changes in the material alloys percentage compared with original percentage, where this could lead to asses the reason of damaged condition. As example, the carbon content have a great effect on the mechanical properties of the carbon and low alloy steel tube material, where any reduction will lead to a general reduction in the mechanical properties of the tube material. Other reduction in the tube alloys like chrome content has an effect on the corrosion resistance of the tube material.

Mechanical Analysis

Mechanical properties are the principle guide to the selection of materials for the high-temperature and high-pressure power plant construction. From this point any change in design mechanical properties of the material of the heat exchanger tube will affect the construction capabilities against circumference condition. As example, the surface hardness is an indication of the material ability to resist wear. Thus, any reduction of this property will lead to reduction in the wear resistance of the tube material against liquids containing suspended solids which likely to causing erosion.

Macroscopic Scanning

Macroscopic of dissolved iron is a good indicator of corrosivty of the feed water of the plant. This happens when an increase in the dissolved oxygen, carbon dioxide, and ammonia is present in the feed water of the power plant. Dissolved oxygen, which becomes very active as the water temperature increases, will unit with the atomic hydrogen, forming H_2O and producing the necessary cathodic reaction for progressive corrosion [10]. Oxygen corrosion occurs typically as small pits and depressions, often covered with a crust or scab of black Fe_3O_4. In such cases deep pits are formed and rapid failure follows.

Hydrogen ion concentration in water indicates the acidity or alkalinity of the water. There is a continual association and dissociation in the water of HOH and H plus OH. The hydrogen ion concentration is expressed as the pH value, which is the logarithm of the reciprocal of the fraction of the hydrogen ions present. A pH value of more than 7 indicates alkalinity, while less than 7 indicate acidity. pH value determines the intensity of corrosion.

Results and Discussion

Two types of laboratory tests are discussed. The first is the results of the tests employed to the damaged heater tubes, while the other tests results are related to the feed water and the steam passing through the shell sampling.

Results Of The Failed Tubes

From the results of the laboratory investigation concerning the damaged heater tubes, the following notes have been obtained:-

1- From the visual notation of the failed feed water heater tubes, it has been found that the most failed tubes are located in the desuperheating zone, where the tubes at these sections suffer from severe OD erosion problems. Moreover, it has been noticed some thinning tubes in the U-bend section. Finally, pit tubes are found in location **(Figures 1, 2, and 3).**
2- The tests of mechanical properties of the tube samples are carried out including yield and tensile stress, elongation, and hardness. The test results are shown in **Table 1**. The mechanical test results show a general reduction in mechanical properties of the used tubes as compared with the new tubes, especially for the sample from the desuperheating section.
3- The tests of chemical composition of various tube samples are carried out in metallurgical laboratory using emission spectrometer (IRL 31000, Swiss) and results are listed in **Table 2**. The analysis results of tubes alloy material show significant reduction in the alloy additive percentage as compared with that of the new tube. A reduction in the chrome and copper percentage is observed, where the chrome content depression from 0.17 for the new tube sample to 0.087 and 0.109% in the desuperheating section and in the randomly samples respectively. This happens also to the percentage of the copper, where the reduction in the percentage is found to be from 0.28 for the new tube sample to 0.24 and 0.25% for the same used sampling. This reduction means the loss of more corrosion resistance alloy in the tube material. A depression in carbon content from 0.18 to 0.141 and 0.166% is observed in the desuperheating and in the randomly samples respectively. This definitely affects on the mechanical properties, since the reduction of the carbon content means a general reduction in mechanical properties.
4- The macroscopic scanning for the tube samples shows that carbon segregation is randomly distributed through the microstructure as compared with the new tube samples

scanning. This in turn leads to moderate loss in mechanical strength of the material. This result from prolonged overheating at a temperature above the permissible operating temperature for the tube alloy material. This process is highly accelerated when the heaters are used as a by-pass for the steam pass through the shell side, while no water routed through the tube side. **Figure 4**, shows the location from where the sampling tubes are taken from the tube bundle. **Figures (5, 6, 7, 8, and 9)** are the microscopic scanning photographic of different samples.

Results Of The Water Analysis

Statistical analysis for the feed water and the steam of the power plant of the case study has been carried out to check deviations from the recommended limits. The analyses have been carried out for a number of samples for more than three months. A period as short as 24 hours is considered in sample analysis. The test results are listed **Table 3**. The water analysis results show deviation in the pH values, dissolved oxygen, and dissolved iron from the recommended limits. As indicated, the presence of the dissolved iron is a very good indicator of the corrosivty of the water of the power plant, where the periodic tests show that the iron content increased from 0.01 ppm as a recommended value to the range 0.9-2.7 ppm in the feed water passed through the tube side. The dissolved iron content in the steam passing through the shell side ranges from 0- 0.016 ppm although there must be no dissolved iron in the steam as recommended.

High increase in the dissolved oxygen content is observed in both the feed water and the steam. The oxygen content is ranges between 1.3- 7.5 ppm for the feed water and 1.6- 6 ppm for the steam, while the recommended value is 0.005 ppm for the both sides. A depression in pH value under the recommended value is noticed also, where the pH value ranges between 7.18-8.54 ppm and 7.6-8.69 ppm for the feed water and steam respectively, while its recommended value in the range of 8.7-9.2 ppm. The deviations in both pH value and dissolved oxygen are the most effective reasons of the corrosivty of the power plant water.

Conclusions

1- All types of damage mechanism were studied, it was found that OD (outside diameter) erosion is the major type of damage mechanism that leads to tube failure in feed water heater of power plant. The location of the most susceptible to OD wear is in desuperheating zone at the entrance of steam. This occurs even with the presence of the impingement baffle. From the visual examination it has been noticed that the highest affected region is just shifted further down at the end edge of the baffle.
2- The depression in the carbon content and carbon segregation, which is randomly distributed throughout the microstructure of the used tube, is the two main causes of the

depression in the mechanical strength of the tube material, which accelerates the OD erosion mechanism.

3- Deviation from the feed water and steam specifications recommended limit of the power station especially in the oxygen content and pH value lead to highly increase in the general corrosion in all heater parts. As an evidence, the highly increase in the iron content in the water of the station was noticed.

Recommendations

1- Tubes in the feed water heater should be periodically inspected to determine their conditions. For a regular inspection, the plan should include tubes in the desuperheating zone, tubes in drain cooler section, tubes around previously plugged tubes and some tubes at random. In addition to regular inspections, inspection after a tube failure is highly recommended.
2- Leaking tubes should be immediately plugged. Such action leads to effective plugging and avoids future outages.
3- Construct a bypass system for the steam in the shell side to avoid overheating of tubes resulted from steam passing the shell with the absence of water flowing through tubes.
4- Regular checking and calibration of the instruments used in feed water analysis are necessary to avoid any deviation of water specification from recommended values.

Table (1) Mechanical properties testing results of 15Mo3 alloy material

Sample type	*Cross area mm^2*	*Tensile N/mm^2*	*Elongation %*	*Brinell hardness*	*Yield stress N/mm^2*
New tube	80.299	493	23	158	360
Used tube*	76.372	428	25	137	289
Used tube**	79.673	454	25	149	332

* Used tube sample is taken from the desuperheating section.
** Used tube sample is taken randomly.

Table (2) Spectrometric analysis of 15Mo3 alloy material by (spec. IRL-31000)

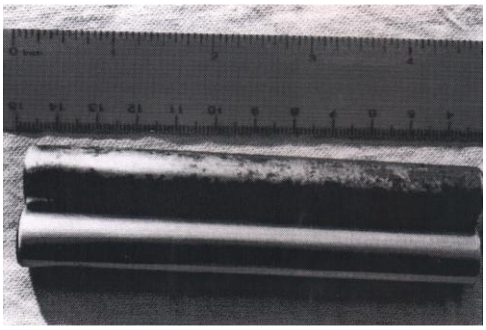
Sample type	**Composition**													
	C	**S**	**Si**	**Mn**	**Cr**	**Ni**	**Mo**	**Cu**	**Co**	**Al**	**Nb**	**Ti**	**V**	**W**
New tube	.180	.016	.29	.78	.17	.094	.29	.28	.029	.023	.008	.041	.005	.025
Used tube*	.141	.032	.33	.81	.078	.009	.25	.24	0.26	.027	.008	.014	.003	.025
Used tube**	.166	.032	.32	.81	.109	.031	.26	.25	.026	.025	.008	.021	.003	.025

Table (3) Water analysis testing results

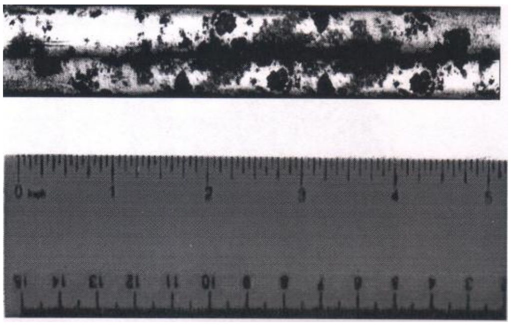
Determination	pH	Conduc.	Total Hard.	Cl	O_2	NH_3	Fe	SO_4
Feed water	7.18-8.54	75.79-133	0-22.2	9.5-26.73	1.3-7.5	Nil	0.9-2.7	16-23.6
Steam	7.60-8.69	34-68.907	0-13.32	4.7-31-59	1.6-6.0	Nil	0-0.16	1.3-4.2

Table (4) Recommended power plant water specifications

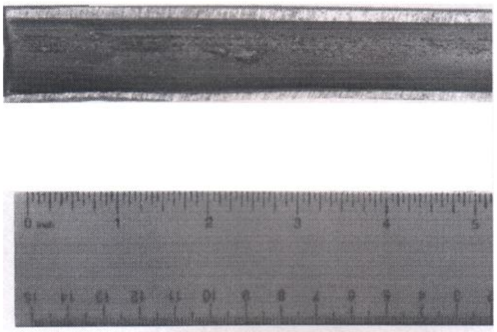
Determination	pH	Conduc.	Cl	O_2	NH_3	Fe
Make-up	6.5-7.5	0.2				0.01
Cond. Pump discharge	8.7-9.2	1.5-7	0.1	0.01	0.2-1	0.01
Boiler dearator out	8.7-9.2	1.5-7		0.005		
Feed water	8.7-9.2	1.5-7		0.005	0.2-1	0.01
Saturated steam	8.7-9.2	1.5-7			0.2-1	
Main steam	8.7-9.2	1.5-7			0.2-1	



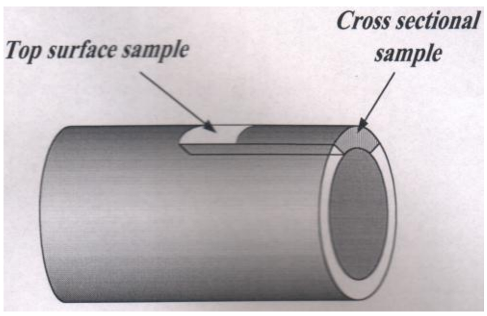
(Fig. 1) Pitting of 15Mo3 tube in heat compared new tube



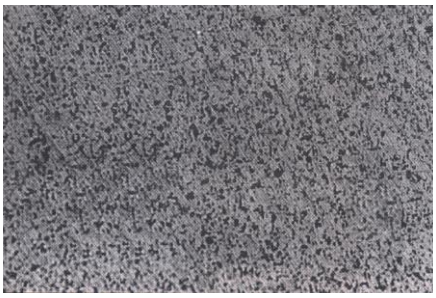
(Fig. 2) Impingement attack of 15Mo3 exchanger with tube in desuperheating zone



(Fig.3) Inside tube erosion-corrosion For tube in desuperheating zone

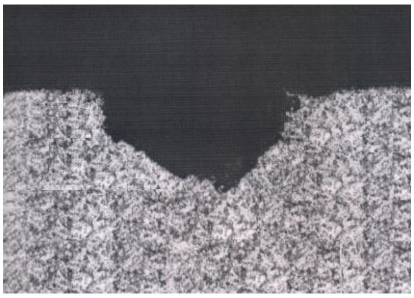


(Fig. 4) Location of the samples carriedout for microscopic scanning.

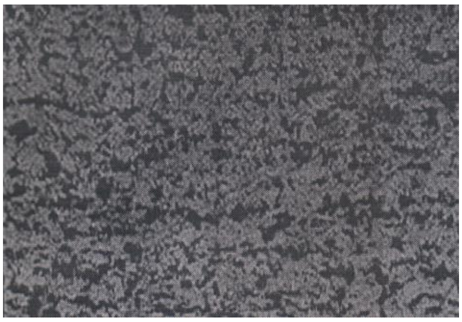


(Fig. 5) Microstructure of low alloy steel used tube shows randomly distributed throughout the microstructure, dispersed carbide in ferrite

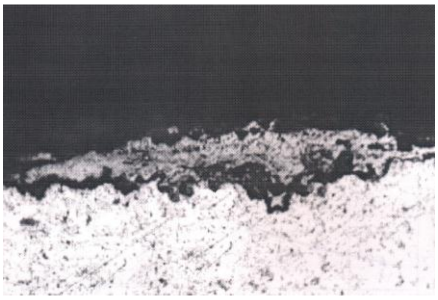
(Fig.6) Microstructure of low alloy steel new tube shows homogeneously distributed of ferrite (light) and pearlite (dark)



(Fig.7) Microstructure of cross section used tube, shows the top edge hole and carbides



(Fig. 8) Microstructure of cross section of new tube.



(Fig. 9) Microstructure of cross section of used tube Shows corrosion which leads to cut part from the top Surface, producing a hole with time.

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