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# FAILURE ANALYSIS OF A SUPERHEATER PIPE BASED ON MICROSTRUCTURE / MECHANICAL PROPERTIES STUDY

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Original scientific paper

The fundamental role of superheater pipes in turbines is to produce superheated steam and direct it to the turbine. These parts are subjected to damage due to the creep, corrosion and oxidation resulting from combustion exhaust. In this research, the affecting factors of failure in a plantain superheater pipe was investigated. Wet chemistry and SEM/EDS analysis were used to investigate the combustion exhaust deposits and a scanning electron microscope (SEM) was used to study the fracture surfaces in order to determine the mechanisms of the fracture. The results showed that exposure of the superheater pipes at temperatures higher than the standard limits caused strength reduction and occurrence of plastic deformation. Furthermore, the combustion exhaust deposits, caused reduction in heat transfer, in addition to severe corrosion as well as cavity formation due to the presence of hydrogen were the main reasons of the pipes failure.

***Keywords:*** *Combustion deposits; Failure analysis; Superheater pipes; Thermal power plant*

## 1 Introduction

Stationary power generators are one of the most important industries in the country. Many of these generators are steam types which are supplied by fossil fuels. Industrial boiler systems are one of the main parts of a power plant, producing steam for the process units and supplying it to generate electricity. Any factor which leads to shut down of boilers is considerable from an economic aspect. Therefore, preventing these factors is essential. One of the problems that continually results in overhaul of power plants is failure of the boiler pipes. In drum boilers, output steam at higher temperatures, which is called dry steam or superheated steam, has more energy. The process of producing superheated steam takes place in superheaters which are composed of parallel pipes placed in the path of hot gases produced from combustion exhaust. The heat of combustion exhaust is transfered from the outside into the pipes. Then, the saturated steam is converted to superheated steam which is transfered to the higher pressure parts of the turbine [1]. Superheated steam is important according to the following:

- Condensation of steam is impossible due to the heat loss, which is helpful where the steam has to travel long paths.

– The superheated steam prevents corrosion and damage of the turbine blades.

The damage of boiler pipes that causes shut down of a power plant for a while is one of the fundamental problems of steam power plants. Repair processes lead to heavy expenses for the steam power plants in the country. Superheater pipes are repaired and replaced periodically, but the possibility of tubal rupture in times shorter than the deadline time highlights the importance of this issue. Several factors are reported about the failure of superheater pipes. Exposure of metals to high temperatures can reduce the strength and at higher temperatures, the possibility of creep increases. Measuring instruments cannot gather detailed information about the characteristics of the fluid and boiler. However, radiation heat transfer of the pipes could be studied using fluid dynamic modeling techniques. In this method, critical points of the pipe can be identified that shows that pipe bending is the most likely damage mode due to the effects of overheating [2]. Software analysis on pollutants exhausted from combustion shows that the pollutants can increase the pipe temperature. These pollutants are deposited on the surface of superheater pipes causing an increase in temperature and corrosion rate. High temperature corrosion has different mechanisms and therefore different prevention and protection strategies such as thermal barrier coatings.

Tarshizi et al. [3] reported a case study on a superheater pipe and its failure. In this case, an evaluation of pipe lifetime was performed using computational methods with an emphasis on creep lifetime reduction. Kahrom et al. [4] also focused on the joints between the superheater pipe and header output. Microstructural studies on damaged areas using simulation software showed that thermal stresses, due to excessive heat, had a considerable effect on the properties of the joints between pipes and header. Afterward Nemati et al. [5] investigated the wall thickness reduction of pipes under high temperature and pressure in a power plant boiler. The results attempted to predict the time of replacement before failure or breakdown and determining the mechanism of thickness reduction. For this purpose, thickness measurements using the ultrasonic method were carried out on superheater and re-heater pipes during periodic maintenance intervals. The results led to identification of critical points susceptible to failure. Using this method, making proper decisions about replacement of the pipes was possible properly.

In this research, failure analysis of a failed superheater pipe was carried out using SEM/EDS analysis and wet chemistry analysis, and the fracture surfaces were also studied using a scanning electron microscope (SEM).

## 2 Experimental method

In order to investigate the causes of failure, some samples of failed superheater pipes from the Bistoon heat power plant were studied. The samples for testing were prepared from different parts of the pipes. One of the samples was from an undamaged pipe. In the first stage, the chemical compositions of an original pipe and a damaged pipe were determined using spectrometry analysis. Then the deposits formed on the damaged pipes were removed and their chemical composition was determined using wet chemistry analysis. Hardness testing was carried out according to Vickers, Brinell and Rockwell B methods and the related standards. These measurements were done on different parts of the damaged pipes and hardness profiles were obtained as a function of the distance from the failure region. The ultrasonic method was used to determine the thickness reduction at some parts of the superheater pipes. Scanning electron microscopy (SEM) was used to study the microstructures. Furthermore, an SEM/EDS analysis was used for phase analysis. The SEM and SEM/EDS analysis were also used to study the fracture surfaces.

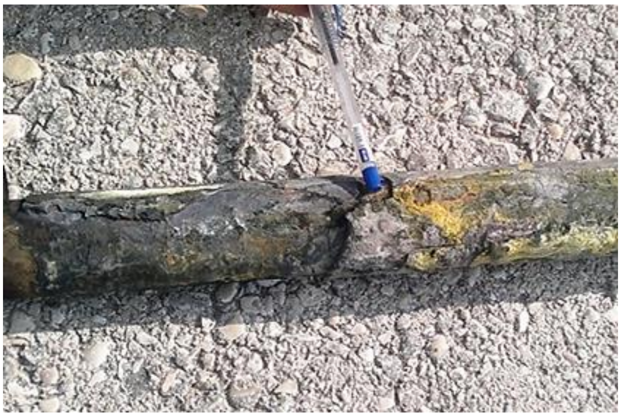


**Figure 1.** Combustion deposits on the outer surface of the damaged superheater pipe.

**Table 1.** Chemical composition of the pipe at different conditions (wt.%)

| | S | Cu | Co | Al | Ni | Mo | Cr | Mn | Si | C | Fe |
|---|---|---|---|---|---|---|---|---|---|---|---|
| As-received sample | 0.003 | 0.01 | - | 0.04 | 0.04 | 0.65 | 0.92 | 0.68 | 0.31 | 0.17 | Base |
| Damaged sample | 0.011 | 0.06 | 0.003 | 0.095 | 0.074 | 0.55 | 0.87 | 0.44 | 0.14 | 0.25 | Base |
| Standard sample (SA-335 P 12) | 0.025 | - | - | - | - | 0.44-0.65 | 0.8-1.25 | 0.30-0.61 | 0.50 | 0.05-0.15 | Base |

## 3 Results and discussion

### 3.1 Visual study

The damaged pipes were studied visually. The observation showed that the whole outer surface of the pipe was covered with a thick and continuous layer which was the deposits of combustion exhaust (Fig. 1). Formation of the deposits on the outer surface of the pipe increased the working temperature of the pipe which resulted in severe hot corrosion and oxidation. Therefore, the pipe was exposed to damage under higher internal pressure and higher working temperature than the design. The deposited layer thickness was determined to be 6 mm which was high enough to cause damage.

### 3.2 Chemical analysis of the damaged pipe

Chemical composition of the original pipe and damaged pipe, determined using spectrometry analysis, is shown in Table 1. The chemical composition of the original pipe was generally consistent with ASTM SA-335 P12 steel which specifies ferritic low alloy steel for seamless superheater pipes. These pipes are known as plantain superheater pipes used in the steam power plants. Table 1 also shows that the content of some of the elements in the chemical composition of the damaged pipe are increased or decreased, compared to those of the original pipe. For example, the content of some elements such as sulfur, cobalt, nickel and carbon are increased. The service conditions of the pipes and particularly high temperature can cause changes in the weight percentage of elements just on the pipe surface, which can affect surface properties of the pipes. Therefore, the differences can be generally due to the different production lots for the damaged and original parts. For example, sulfur, which can be transferred to the surface of superheater pipes via the boiler fossil fuels, can cause a reduction in the pipe strength. Carbon, which can form intermetallic compounds, increases the probability of the brittle fracture in the pipes. Furthermore, reduction of Mo and Cr in the damaged pipe, decreases the corrosion resistance at the high temperatures.

### 3.3 Hardness

In order to determine the hardness variation in the damaged area of the pipe, a hardness profile was plotted (Fig. 2). The results showed that the hardness of damaged area was the highest value but this value was not high enough to cause brittle behavior. Cold working at the fractured area at the service conditions can be the reason for slightly higher hardness of this area.

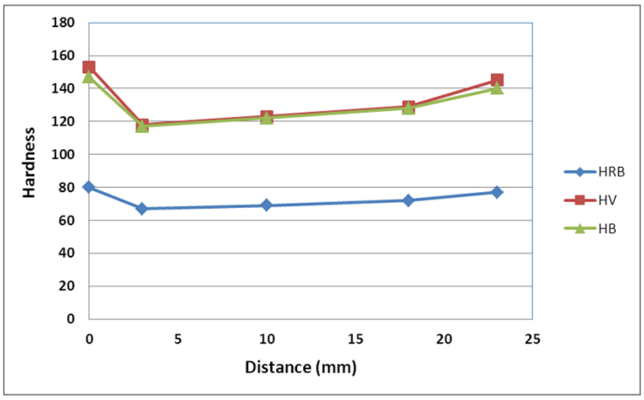



**Figure 2.** Hardness profile as a function of distance from the fracture area of the damaged pipe.

### 3.4 Corrosion on the inner surface of the pipe

Inner surfaces of the superheater pipes are in contact with hot and high pressure steam. Therefore, oxidation occurs on the inner surface of the pipe and thickness reduction will result due to the pressure and flow of the steam. This can be a factor in superheater pipe failures. Fig. 3 shows the inner surface of the damaged superheater pipe which contains layered oxidation. These oxidations are visible at the surface and their thickness can show the oxidation volume. Studies have shown that these layers could be iron oxide that formed with the presence of oxygen under favorable thermodynamic conditions. The related reaction is the following:

$$2Fe+H_2O+O_2 \rightarrow Fe_2O_3+2H\uparrow \quad (1)$$

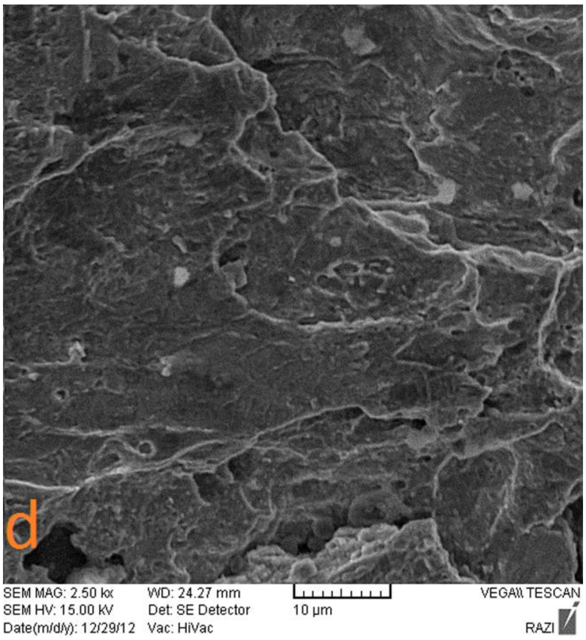



**Figure 3.** SEM micrograph of inner surface of the damaged pipe containing layered iron oxide.

For further study, the internal diameter of a new and damaged pipe of a similar lot was measured. Fig. 4 shows the comparison of the thickness reduction for the pipes. Results showed that the internal diameter of the damaged pipe increased by 2 mm and its thickness was reduced.

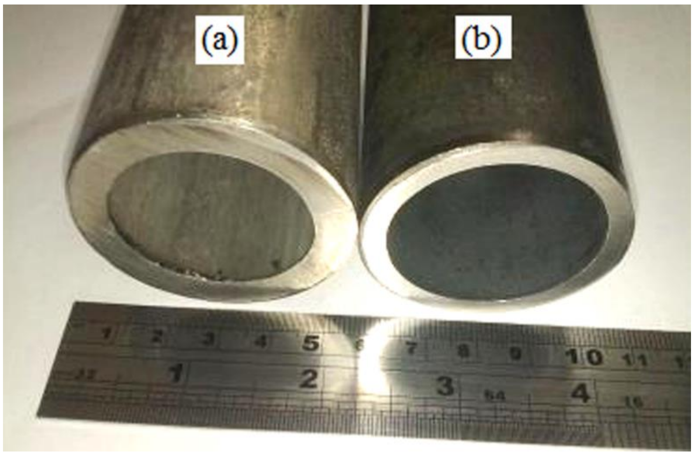



**Figure 4.** Comparison of thickness reduction between the (a) original and (b) damaged pipes.

### 3.5 Thickness measurement of the damaged pipe

In order to determine the thickness reduction of the damaged pipe, ultrasonic thickness measurement was used. The results showed that the damaged pipe thickness was reduced compared to the standard thickness of the original pipe of a similar lot (6 mm). The thickness was non-symmetrical as 5.70 mm on one side and 4.78 mm on the other side of the damaged pipe. The maximum thickness reduction was at an area where corrosive agents made of boiler fossil fuels caused deposition and therefore excessive corrosion.

### 3.6 Corrosion on the outer surface of the pipe

Wet chemistry analysis was used to determine the chemical composition of the deposits on the outer surface of the pipe. The results showed that the deposits were mostly organic compounds (96.85% organic+3.15% inorganic). Table 2 shows analysis of the chemical composition of inorganic material. The fuel of power plants is generally Mazut in winter which causes the deposition rate to increase. Another fuel used in power plants is natural gas mostly used in the warm seasons. Gas combusts more easily than Mazut and therefore has a higher oxidation rate. Therefore, the risk of damage when using gas as the fuel is higher than the Mazut.

The presence of sulfur and iron in the analysis (Table 2) shows that inorganic deposits on the outer surface of the damaged pipe includes sulfide compounds formed due to the presence of sulfur sources in the environment. Higher content of sulfur in the analysis compared to other elements confirms this. On the other hand, the presence of elemental sulfur in the environment is a factor to increase the penetration of hydrogen in the steel. An oxide layer, formed on the outer surface due to corrosion, reduces the cooling effect of the steam and causes the temperature of the pipe to increase, and therefore reduces the life time. The presence of various metal impurities such as sodium, nickel and vanadium and non-metallic impurities such as sulfur and nitrogen in the form of organic compounds in the liquid fuels causes various problems. These metals in the combustion gases could be absorbed on the pipe surface which can cause failure due to the oxidation and reaction with the pipe alloy. As a result of this reaction, complex compounds are formed with low melting points.

**Table 2.** Chemical composition of inorganic material on outer surface of the damaged pipe (wt.%)

| Ni | Fe | S | Cr | Fe |
|---|---|---|---|---|
| 4.4 | 0.077 | 36 | 6.76 | 0.0036 |

According to Table 2, the compounds also contain nickel and chromium. There are several sources of nickel to be deposited on the outer surface of the pipe such as boiler fuel in the combustion chamber and the burner nozzle. These nozzles are generally made of nickel-based superalloys, which could release nickel to be deposited on the adjacent pipes. Line scan analysis of nickel across the fracture area on the outer surface of the pipe is shown in Fig. 5. This profile indicates a high content of nickel in the surface deposits.

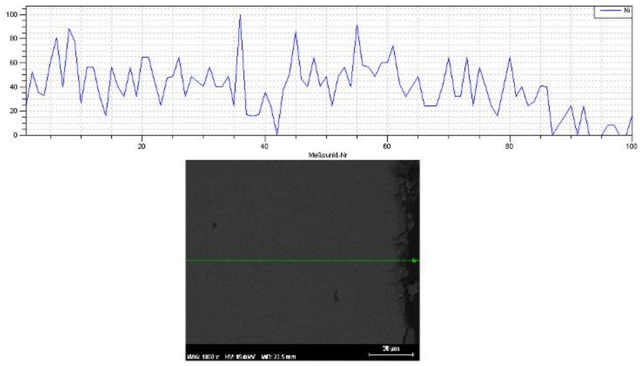
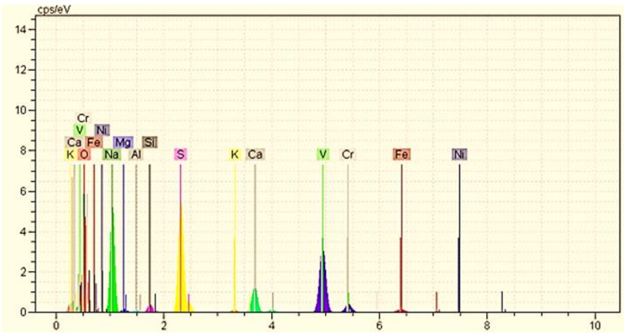


**Figure 5.** Line scan analysis of nickel across the fracture area on the outer surface of the pipe.

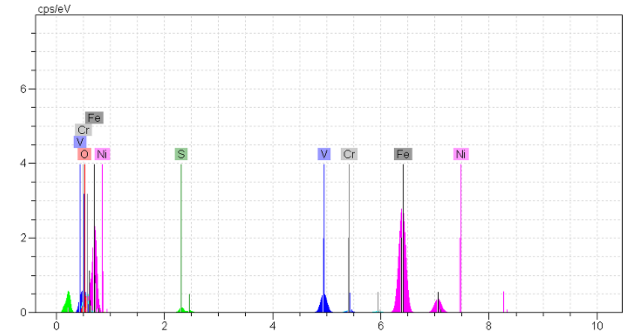
The most harmful elements in fossil fuels are vanadium, sodium and sulfur. These elements can form low melting point (249-677oC) complexes. The resulting liquid dissolves iron oxide, and this molten layer facilitates oxygen transport and oxidation of the pipe outer surface. The SEM/EDS analysis of dark green deposits on the outer surface is shown in Fig. 6. Due to the high percentage of vanadium in the deposits and also the presence of sulfur and sodium, the formation of Na2SO4 and its combination with V2O5, which leads to formation of sodium vanadate complexes, is probable. These complexes have low melting points and cause adhesion of ash particles on the pipe outer surface and therefore reduction of heat transfer.

Analysis of yellow-green deposits (Fig. 7) showed that the content of elemental vanadium was the highest. Some vanadate complexes is known as the most corrosive compounds. Furthermore, the content of sulfur is considerable (according to Fig. 7), and sulfur compounds have an important role on the corrosion of the pipe. Therefore, combustion deposits could be considered as one of the most important factors of failure in the superheater pipes. The results of all analyses showed the content of calcium of 2-4% which caused high strength scale deposits to form on the outer surface of the pipes.




| O | Na | S | Mg | Al | Si |
|---|---|---|---|---|---|
| 52.15 | 15.42 | 16.81 | 2.38 | 0.38 | 1.03 |
| V | Cr | Fe | Ni | Ca | K |
| 5.09 | - | 0.79 | 1.00 | 3.10 | 1.84 |

**Figure 6.** SEM/EDS analysis of dark green deposits on outer surface of the damaged pipe (wt.%).




| O | Na | S | Mg | Al | Si |
|---|---|---|---|---|---|
| 4.30 | - | 0.85 | - | - | - |
| V | Cr | Fe | Ni | Ca | K |
| 6.19 | 1.17 | 87.48 | 0.01 | - | - |

**Figure 7.** SEM/EDS analysis of yellow-green deposits on outer surface of the damaged pipe (wt.%).

### 3.7 Fracture surface studies

In this study, fracture of superheater pipes was observed to occur at the knee bends in some cases (Fig. 8). Due to the high heat concentration at knee bends, severe deformation and rupture occurs. Therefore, these parts are among the most frequently fractured areas in the boiler. Being in direct contact with flame and hot corrosion and oxidation, as well as deposits from fossil fuel combustion exhaust, causes thickness reduction of the pipe and finally a sudden failure.

In other damaged samples, the failure occurred next to the knee bends. According to Fig. 9, these damaged pipes have sharp edges. In this case, plastic yielding at high temperatures can result in opening up the pipe and forming sharp edges. Also, the fracture mechanism can be crack nucleation at the parts which lost their thickness and then a rapid crack growth and final fracture. The rapid growth of cracks can be due to sudden increase of pressure in the pipes.

In this study, some of the damaged pipes had relatively brittle fracture in which the pipe has been cut in half and no plastic deformation was visible. In this case, sudden increase of pressure in the pipes was the main reason for the failure.

**Figure 8.** Fracture of a superheater pipe at the knee bends.

**Figure 9.** Fracture of a superheater pipe next to the knee bends (Highlighted area is the location used for SEM studies).

An SEM micrograph of the fractured area at a knee bend (Fig. 8) is shown in Fig. 10. According to this figure, growth of deposits because of exposure at high temperatures caused formation of cavities at the fracture surface. In steels, hydrogen damage takes place generally in the presence of atomic hydrogen. In humid atmospheres and at high temperatures, corrosion and electrolysis reactions can lead to atomic hydrogen formation via the reduction of hydrogen ions. Some of these atomic hydrogen form molecular hydrogen again and the others penetrate into the steel structure. The penetrated hydrogen atoms gather in grain boundaries and form cavities. Furthermore, some dimples are visible in Fig. 10. The dimples can show relatively ductile fracture. As discussed before, the plastic deformation caused formation of sharp edges at the damaged pipe.

Fossil fuel combustion deposits on the outer surface of pipe surfaces can lead to hot corrosion and severe oxidation. In Fig. 11.a, the deposits, which can be mainly sulfur-riched, are accumulated and have cavities. In Fig. 11.b, vanadium-riched deposits, with higher hardness in comparison with those of Fig. 11.a, can be detected which have a melting point at about 600°C.

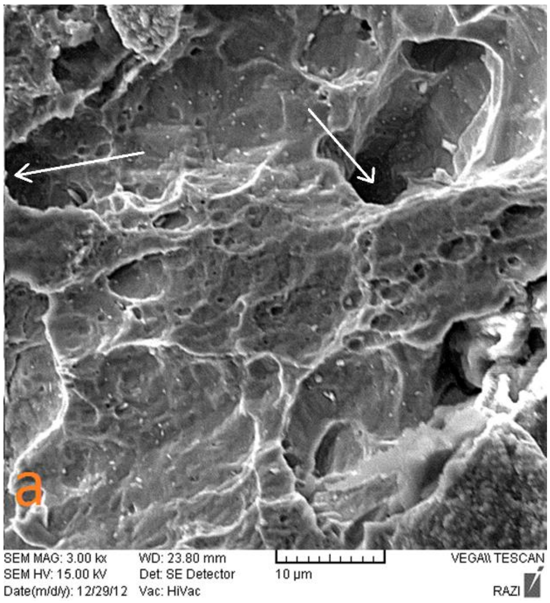



**Figure 10.** SEM micrograph of the fractured area at a knee bend including cavities (indicated as white arrows).

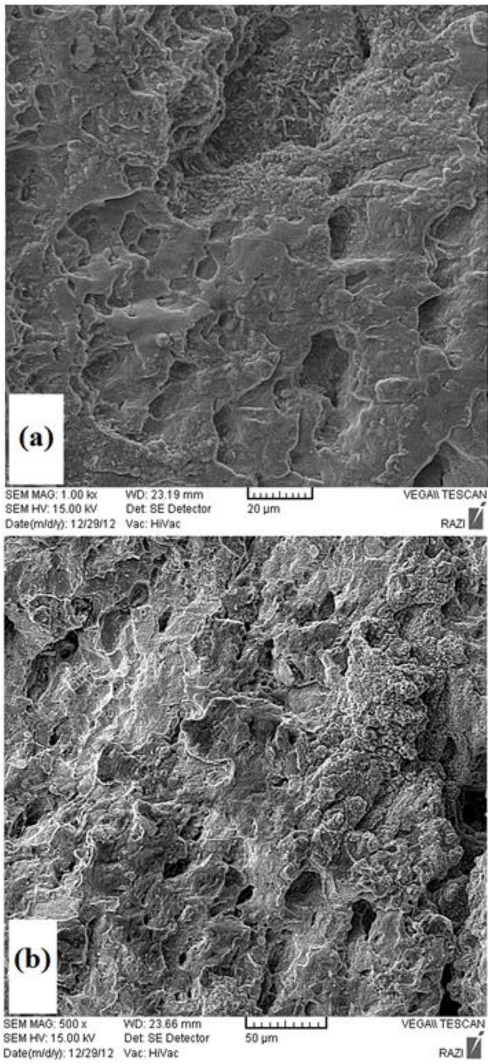



**Figure 11.** SEM micrograph of (a) fossil fuel deposits and (b) hard oxide layer on the outer surface of the damaged pipe.

1Cr-0.5Mo steels are used in boiler pipes which working temperature is 510 to 540°C. 2.25Cr-Mo steels, which have a higher oxidation resistance and creep strength compared to 1Cr-0.5Mo steels, are good choices to use at temperatures up to 650°C in environments without hydrogen and at temperatures up to 480°C in environments contained hydrogen. Since the standard temperature limit for using ASTM SA-335 P12 steel pipes (the steel used in this study) is 500°C, being exposed to higher temperatures could be critical. One of the damage mechanisms in superheater pipes is microstructural changes occurred at high working temperatures. These changes includes changes in structure, size and the spacing distances of carbides, compositional changes of ferrite and variation of solid solution strengthening. Creep is an important failure mechanisms in boilers and specially in their superheater pipes. Carbides are the main source of creep cavities. At high temperatures, conversion of carbides is the following:

$$M_3C \rightarrow M_3C + M_2C \rightarrow M_3C + M_2C + M_7C_3 \rightarrow M_3C + M_2C + M_7C_3 + M_{23}C_6 \qquad (2)$$

These carbides cause the grain boundaries to become serrated. These grain boundaries are unstable and cause strength reduction at service conditions. At high temperatures and under high stresses, cavities could be formed at these carbides. Generally, grain boundary carbides could be main factor of creep fracture [6,7].

## 4 Conclusions

Failure analysis of a superheater pipe was carried out using microstructural analysis and hardness measurements. The results showed that corrosion and the related deposits on the pipe surface, as well as cavity formation due to the hydrogen absorption were the main mechanisms of the pipe failure. The evidences were the following:

- Working temperature was higher than the permitted limit of the steel which caused strength reduction and occurrence of plastic deformation.
- Reduction of pipe thickness resulted in decrease of pipe strength especially at the knee bends and excessive heat applied to the knee bends increased the rate of microstructural changes.
- Deposits had a major role in the pipe corrosion and its thickness reduction. Vanadium and sulfur elements had the greatest content in the deposits.
- SEM micrographs showed cavities at the fracture surfaces. The presence of hydrogen could be the source of cavity formation.

To prevent and control the damages in the studied pipes, the following is recommended:

- Controlling the boiler temperature to prevent unwanted temperature rise during service.
- Selecting appropriate steel for service conditions of the boiler.
- Lowering oxide deposits inside the pipe using proper acid washing.
- Using fuels with appropriate composition to control the content of undesirable elements such as sulfur.
- Using sandblast to clean the outer surfaces of the pipes.

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