ABSTRACT

Boiler pipe failures are the most common cause of forced shutdown of power generation units. The oxide layer formed in the inner wall of those pipes is the main cause of overheating failures. From the measured value of the inner oxide layer, it is possible to estimate the remaining life of the component through correlation with parameters already established by the scientific community. Methodologies to estimate remaining life of components in power plants have been developed by Cepel, in accordance of global tendencies and the needs of Brazilian facilities. With the recent equipment acquisition for the detection of defects and measurement of thickness by ultrasonic, it became possible to measure both the pipeline wall and the internal oxide layer thicknesses. This paper presents a comparison between internal oxide layer thickness measurements of pipes performed by ultrasonic (non-destructive technique) and by metallographic preparation associated to optical microscopy (destructive technique), in different ranges of thickness layers. Finally, the work analyzes the remaining life calculation based on the measurement of the oxide layer thickness. The results obtained from the calculation were corroborated with a microstructural characterization of the samples. For this analysis, were used pipes taken from the same power unit with different values of inner oxide layer thickness and with the same operation time.

Keywords: ultrasonic test, integrity evaluation, boiler, steel-oxide interface

1. Introduction

The life extension of boilers components in industrial plants is a subject of great interest and it’s directly related to the component that operates under high temperature. The overheating caused by an inner oxide layer formation has a considerable influence in the life of pipelines and boiler components that operate under creep regime. The presence of these deposits and films on the pipe wall increases the metal temperature, which accelerates the damage mechanism, drastically reducing the material life (1).
Due to fluctuations in the load and in the growth of internal oxide layer during operation, it is unlikely that the metal temperature is maintained constant during operation. It is a common established practice in the industry to estimate an average or equivalent metal temperature of operation using observation methods of parameters such as hardness, microstructure and thickness of the inner oxide layer, the latter being specifically used in the evaluation of the pipes. Since changes in those parameters are functions of time and temperature, the values obtained in this study can be used to estimate the thermal history for a certain time of operation. The estimated temperature can then be used in conjunction with tensile strength parameters to calculate the remaining life. In the specific case of the inner oxide layer of superheaters and reheaters pipes of boilers, there is an established method in the literature (2) for remaining life calculation.

This paper presents a methodology for validation of inner oxide layer measurements made by ultrasonic technique. Moreover, the study examines the remaining life results, obtained from the measured thickness of the oxide layer, in a critical manner. These results are corroborated with a microstructural evaluation of the samples. For this analysis pipes taken from the same power unit with different values of the oxide layer and the same operation time were used.

2. Materials and Methods

Until the early 80’s, the only way to measure the internal oxide layer in the superheaters and reheaters pipes of boilers was through destructive testing by removing samples. The oxide layer was then measured in the laboratory by means of metallographic preparation. By taking care to avoid breaking of the layer during preparation of the sample, it was possible to obtain an accurate measurement. This methodology has several drawbacks, since the removal and replacement of samples is time consuming and represents a cost to maintenance.

In the late 80’s, the ultrasonic technique proves to be a good alternative to the destructive method of sample removal (3, 4). The thickness of the oxide layer is calculated by measuring the time interval of the ultrasonic wave echo from the steel/oxide interface layer and echo reflected on the inner surface of the tube. The steel/oxide interface echo is much smaller than the echo of the oxide/air interface or liquid on the inner surface of the tube. The major difficulty in measuring these echoes is to separate and measure the time interval between them. Measurements can be performed on equipment that has the more traditional observational mode, A-Scan, which is the visualization of echoes from reflections at the interfaces of the inspected part. Since then, several manufacturers have been developing ultrasonic equipment capable of measuring the internal oxide layer.

Facing the possibility of expanding the range of nondestructive testing that can help the results of the integrity evaluations of the most critical boiler components, Cepel bought an appropriate equipment to perform measurements of wall thickness of pipes, as well as measurements of internal oxide layer thickness, specifically Magnetite. According to literature (5), the minimum thickness obtained with such system is 130μm.

The present study was performed to estimate the remaining life of two pipes removed from the final superheater of a boiler in a Brazilian power plant. The pipe material is ASTM A387 grade 22, which is a 2.25Cr-1Mo steel type, widely used in high temperature applications. Both pipes had been operated for about 191,000.00 hours. One pipe presented an inner layer of less than 130μm and the other a layer of more than 700μm. Figure 1 shows a schematic drawing of the components analyzed. The pipes were removed from the region called 7X. The nominal operation pressure and temperature are 10.8MPa (110kgf/cm²) and 510°C, respectively. The nominal thickness and outer diameter of the tubes are 31.8mm and 5.6mm, respectively.
Figure 2 shows the received samples for thickness measurements in the laboratory by optical microscopy (OM) and by ultrasonic method (UT). For the thickness measurements the pipes were divided in four quadrantes A, B, C and D, as shown in Figure 3. The measured results by ultrasonic testing were compared with results obtained by optical microscopy. The tests were performed in order to evaluate the range of reliable measurements of the equipment. The main idea of the tests was to verify, through a statistical analysis of results, if the ultrasonic equipment is capable of performing measurements similar to the ones obtained by the optical microscope. The most appropriate statistical analysis for the tests, which consisted in proving the equality of the statistical average values of the oxide layers, was based on the use of statistical hypothesis tests available in Microsoft Excel®. The calculation method for estimating residual life based on measurements of Magnetite (Fe₃O₄) inner layer can be divided into three modules (2). The modules and the input data for each are shown below:
Fig 2. Pipe samples from the boiler superheater: (a) Pipe 1, with layer thickness below 130μm; (b) Pipe 2, with layer thickness over 700μm

Fig. 3. Overview of the quadrants adopted for the thickness measurements.

**Module 1 - Geometric data of the tube under investigation.** The inputs in this module are:
- The inner and outer radii of the tube at time $t = 0$ (i.e., the nominal or design values informed before the operation of the equipment);
- The number of hours of equipment operation until shut down,
- The minimum measured value of the outer radius of the tube after shut down of the unit,
- The internal steam pressure.

The output data are the wear rate on the outer wall of the tube and the variation of the outer radius of the tube as a function of time.

**Module 2 - Estimation of the oxide layer thickness evolution on the inner wall of the tube and the effective metal temperature.** The inputs in this module are:
- The average thickness of the oxide layer measured in the field after shutting down the unit;
- Model adopted for the growth of the oxide layer: linear or quadratic.

The quadratic model was adopted, because this one showed more conservative results.

The output data is the average effective metal temperature at the time instant corresponding to the time of operation until the moment of analysis.
Module 3 - Remaining life and total damage accumulation. In this module, the remaining life may be calculated from two methods. In the first one, the mechanical stresses are calculated, afterwards, the intersection points between the curves of stress and creep strength of the material is obtained. Then it is possible to estimate the total time of operation. Subtraction of the operating time from the total time gives the remaining life of the component. The second method utilizes Robinson’s linear damage accumulation rule [14] to calculate the creep damage obtained at the moment of the inspection. For both methods the creep strength curves of the ASTM A 387 Grade 22 steel were used (13). The literature recommends the use of the most conservative result.

In order to validate the results of the remaining useful life assessment obtained from the calculation related to the inner oxide layer, a microstructural evaluation of the pipes was performed. The idea was to verify the effect of the internal oxide layer in the microstructural degradation and in the reduction of mechanical strength of tubes used in superheaters of boilers. Microscopy techniques were used to compare the microstructures of the samples. Optical microscopy was performed for a preliminary evaluation and possible correlation with the Toft and Marsden criterion (6). By means of extraction replicas of each of the samples, the precipitates were observed and identified by transmission electronic microscopy. The precipitates were identified by means of EDS results presented in the literature (7).

3. Results and Discussion

Figure 4 shows the thickness values of the inner oxide layer measured by optical microscopy and by ultrasonic technique in the samples received. For Pipe 1, it was obtained an average of 130μm by ultrasonic testing, indicating the lower limit of the equipment, while the average obtained by optical microscopy was 34μm. For Pipe 2, the values obtained from both techniques were considered statistically equal, with 95% certainty, by hypothesis tests performed with the average of each of the quadrants (8).

![Graph of Oxide Layer Thickness](image)

**Fig. 4.** Values of the oxide layer thickness obtained by the ultrasonic equipment and by optical microscopy along the quadrants of Pipes 1 and 2.

The C quadrant of Pipe 2 showed a 993μm inner oxide thickness. This region of the pipe is the area exposed to the burner of the boiler, i.e., exposed to the highest thermal load. The higher temperature in this tube region can have contributed to a more pronounced growth of the inner Magnetite layer.
It is important to emphasize that the oxide layer is formed from the pipe wall, so besides acting as a thermal insulator that increases the temperature of the metal, the layer also acts by reducing the thickness of the pipe and consequently the resistant section of it.

Figure 5 shows the ultrasonic signals obtained in Pipes 1 and 2. In Figure 5(a), in which the device measures a layer with a value of 130μm, this value is obtained when the measuring gates of the equipment are placed in the first and second signal inflections, respectively. Such placement of the gates does not mean that the device is detecting the two echoes necessary for measuring the inner oxide layer, such as in Figure 5(b).

![Ultrasound signals](image)

**Fig 5. Ultrasonic signals obtained from the pipes: (a) Pipe 1, oxide layer thickness below 130μm; (b) Pipe 2, oxide layer thickness above 700 μm.**

To perform the remaining life estimation, the value of the Magnetite inner layer used to Pipe 1 was 130μm, because this is the lower limit of the equipment. Even the pipe having a layer thickness lower than the one adopted, the value was used to simulate a field analysis, in which the removal of a sample for measurement by optical microscopy is not feasible. The value of 933μm, average on quadrant C exposed to the flame of the boiler, was used for Pipe 2. Table 1 presents a summary of the main results obtained by the method of calculation.

Table 1. Remaining creep life calculation methodology based on measurement of the inner oxide layer.

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Oxide Layer Thickness (μm)</th>
<th>Representative Stress (MPa)</th>
<th>Effective Temperature (°C)</th>
<th>*Remaining Life Method 1 (h)</th>
<th>**Remaining Life Method 2 (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>130</td>
<td>28.2</td>
<td>509.8</td>
<td>2.04 x 10^6</td>
<td>1.05 x 10^6</td>
</tr>
<tr>
<td>2</td>
<td>993</td>
<td>31.6</td>
<td>601.8</td>
<td>2.57 x 10^5</td>
<td>1.06 x 10^5</td>
</tr>
</tbody>
</table>

*Method 1 - stresses are calculated, afterwards, the intersection points between the curves of stress and creep strength of the material is obtained. Then it is possible to estimate the total time of operation. Subtraction of the operating time from the total time gives the remaining life of the component.

**Method 2 - utilizes Robinson’s linear damage accumulation rule to calculate the creep damage at the inspection moment.

As previously mentioned, the layer is formed at the expense of the thickness of the pipe, so, an increase in the mechanical stress of the pipe containing the thicker layer was expected.

The metal temperature calculated for Pipe 2 due to the presence of a high oxide layer, which acts as a thermal insulator during operation of the boiler, was 601.8°C. For Pipe 1, the temperature...
remained in accordance with the nominal operation, indicating that a layer of 130μm does not influence the heat exchange in the pipe.

The above results clearly show that the inner oxide layer can affect the remaining life of the material. It is possible to notice that the presence of a thick layer was able to reduce by approximately one order of magnitude the remaining life of Pipe 2 when it is compared with the Pipe 1 for both calculation methods. Following the recommendation of the literature (2) to adopt the most conservative result, the remaining life of Pipes 1 and 2 are 1.05x10^6 and 1.06x10^5 hours, respectively.

An analysis was performed to determine which Magnetite layer thickness would be necessary to cause severe damage to the pipes in the analyzed component. Considering the geometric and operating conditions of the boiler at the time of study, it was found that a layer of 1500μm and 1350μm would be necessary to extinguish the life of the Pipes 1 and 2, respectively, under the creep regime.

The literature emphasizes that not always the measurements of the oxide layer can provide a correct metal temperature record during all its operation as the oxide layer often suffers crashes due to various reasons such as vibration, shock between the coil pipes or chemical cleaning (9). According to Jauhiainein et al (10) it is more likely to find broken layers in older plants. Despite causing problems, layers breakage can increase the residual life of the tubes, since the insulating effect is reduced when it decreases its thickness.

Figure 6 presents the micrographs obtained from optical microscopy. In all the samples a microstructure composed by ferrite and pearlite was found. From the presented results, it is possible to see that Pipe 1 is in a C/D stage microstructure, according to the Toft and Marsden criterion (6). As it was expected, due to the presence of a very thick internal oxide layer, Pipe 2 presented a higher level of degradation, in stage D/E.

![Fig. 6. Micrographs obtained by optical microscopy: (a) Pipe 1, few signs of degradation;(b) Pipe 2, higher level of microstructural degradation.](image)

Figure 7(a) presents a micrograph made by transmission electron microscopy in an extraction replica of Pipe 1. The literature shows that boiler tubes exposed to long term operation conditions tend to present the coarsening of precipitates in the grain boundaries, as it was observed, also there is a loss in the pearlitic structure, this detail is shown in the left side of the micrograph (11, 12). However, the presence of M_{23}C precipitates in the ferritic grain of the material, right side of the micrograph, may indicate that it does not present an advanced degree of microstructural degradation. Figure 7(b) presents the EDS spectrum of the M_{23}C_{6} precipitate, mostly found in the grain boundaries of the microstructure. The EDS spectrum is in accordance with previous results from the literature (7).
Fig. 7. Transmission electron microscopy analysis of the extraction replica of Pipe 1: (a) Region showing coarsening of precipitates in the grain boundary; (b) EDS spectrum of the $\text{M}_2\text{C}_6$ precipitate.

Figure 8(a) presents a micrograph made by transmission electron microscopy in an extraction replica of Pipe 2. Literature shows that boiler tubes exposed to long term effects of temperature and mechanical stress tend to show excessive coarsening of the precipitates in the grain boundaries (11, 12). In the specific case of Pipe 2, coarse $\text{M}_6\text{C}$ precipitates were found. These precipitates are expected to be found for advanced stages of microstructural degradation (11, 12). Figure 8(b) presents the EDS spectrum of the $\text{M}_6\text{C}$ precipitate, found in a higher amount in the grain boundaries of the sample microstructure. The EDS spectrum is in accordance with previous results from the literature (7).

As opposed to what was observed in Pipe 1, in all the samples of Pipe 2 there were no regions rich in $\text{M}_3\text{C}$ precipitates to indicate the pearlitic region nor $\text{M}_2\text{C}$ precipitates, which can offer some of strength in the ferritic grains.

Considering that Pipe 1 and Pipe 2 operated the same amount of time under the same design conditions, it is possible to say that the presence of a Magnetite layer with a significant thickness, which acts as a thermal insulator during operation, may have been responsible for the
localized overheating of Pipe 2. Hence, the microstructural degradation was accelerated in this sample. The microstructural findings, combined with the remaining life assessment, confirm the deleterious effect that the Magnetite inner layer has on the design life and microstructure of boiler pipes subjected to it. As a result of the information obtained, it is recommended, as a good engineering practice, to monitor the metal temperature by measuring the thickness of the inner oxide layer on a continuous basis, for a more accurate analysis of creep damage on superheater pipes and reheaters of boilers used in industrial plants.

4. Conclusions

Based on these results, it is possible to conclude that:

- The measurements performed by the ultrasonic equipment could be statistically considered equal to those obtained by optical microscopy for oxide layer thicknesses above 130μm, which is the minimum measurement threshold of the equipment in the current configuration;
- There is a correlation between the presence of the oxide layer and the format of ultrasonic signal. For layer thickness near the lower boundary, becomes more difficult to separate the echoes from interfaces steel/oxide and oxide/air. For thickness above 140μm, it is possible to identify on the echoes of each of the interfaces more easily;
- From the results obtained for estimation of residual life when creep is the dominant damage mechanism, it was found that a layer of 130μm does not contribute in a deleterious manner to the pipe life. In the other hand, a layer above 700μm, reduces the pipe life in an order of magnitude, indicating that a thick layer of Magnetite can significantly influence the residual life of superheaters and reheaters pipes of boilers;
- Microstructural characterization tests clearly showed that tubes that present thick internal Magnetite layers will suffer an accelerated microstructural degradation, due to the fact that the layer will act as a thermal insulator, causing a localized overheating of the tube. For 2.25Cr-1Mo steels, the accelerated degradation was confirmed by the identification of coarse M₆C precipitates located at the grain boundaries of Pipe 2 microstructure;
- The use of the procedures and methodology described in this paper may be applied in the field without difficulty, effectively aiding decision making during a shutdown for boiler inspection in industrial plants.

5. References