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CAVITATION-EROSION STUDY IN ELBOW TUBES OF A LOW-PRESSURE EVAPORATOR OUTLET HEADER

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Abstrak

Makalah ini menyajikan hasil studi erosi-kavitasi yang terjadi pada *elbow tubes* yang tersambung dengan *low-pressure evaporator outlet header* pada sebuah unit *HRSG (heat-recovery steam generator).* Di dalam *elbow tubes* mengalir fluida kerja berupa air panas dengan tekanan 10 bar dan temperatur 160 °C. *Elbow tubes* terbuat dari baja karbon rendah, memiliki diameter luar 31,8 mm dan tebal dinding 2,6 mm. Sebelum masuk ke dalam *elbow tubes*, fluida kerja mengalami pemanasan di dalam panel *evaporator tubes* menggunakan gas panas hasil pembakaran yang berasal dari sebuah unit *gas turbine power plant.* Dalam studi ini ada 4 (empat) buah *elbow tubes* paska-operasi yang digunakan, yaitu *elbow tube* dengan sudut penyambungan 90°, 75°, 60° dan 45°. Jenis pengujian yang dilakukan meliputi uji makroskopik, analisa komposisi kimia, uji metalografi, uji keras dan analisis EDS (*energy dispersive spectroscopy*). Hasil studi yang diperoleh menunjukkan bahwa *elbow tubes* mengalami proses penipisan pada dinding bagian dalam sisi kurvatur luar dengan tekstur atau penampakan permukaan yang kasar dan bergelombang. Jenis kegagalan yang terjadi ini dikenal sebagai erosi-kavitasi. Tingkat kegagalan erosi-kavitasi yang terjadi sangat dipengaruhi oleh sudut penyambungan *elbow tube* dengan *low pressure evaporator outlet header*. Semakin besar sudut penyambungan atau semakin kecil radius belokan *elbow tube*, maka semakin tinggi laju erosi-kavitasi yang terjadi. Tingginya laju erosi-kavitasi yang dialami oleh keempat *elbow tubes* kemungkinan juga disebabkan oleh tingginya tingkat turbulensi aliran fluida kerja yang terjadi di dalam *elbow tubes*. Peningkatan turbulensi yang terjadi kemungkinan disebabkan oleh pengaruh penurunan tekanan fluida kerja di dalam panel *evaporator tubes* sehingga mengakibatkan sebagian dari fluida kerja berubah menjadi uap dan menimbulkan aliran dua fasa berupa campuran air dan uap ketika memasuki *elbow tubes*.

Kata Kunci: Erosi-kavitasi, elbow tube, low pressure evaporator outlet header, turbulensi, kurvatur luar

Abstract

This paper presents the results of the cavitation-erosion study that occurred on elbow tubes that connected to the low-pressure evaporator outlet header on an HRSG (heat-recovery steam generator) unit. Inside the elbow, tubes flow the working fluid in the form of hot water with a pressure of 10 bar and a temperature of 160°C. Elbow tubes are made of low carbon steel, have an outer diameter of 31.8 mm, and a wall thickness of 2.6 mm. Before entering into the elbow tubes, the working fluid warms up inside the evaporator tubes panel using hot flue gases coming from a gas turbine power plant unit. In this study, there were 4 (four) pieces of post-service elbow tubes used, namely elbow tube with the connecting angle of 90°, 75°, 60°, and 45°. The types of tests carried out included macroscopic tests, chemical analysis, metallographic examinations, hardness tests, and EDS (energy dispersive spectroscopy) analysis. The study results obtained show that the elbow tubes undergo a process of thinning on the inner wall of the outer curvature with a rough and jagged surface appearance. This type of failure is known as cavitation- erosion. The level of cavitation-erosion that occurs is very much influenced by the elbow's connecting angle with the low pressure evaporator header outlet. The greater the connecting angle or, the smaller the radius of the elbow tube, the higher the level of cavitation-erosion that occurs. The high rate of cavitation-erosion experienced by the four elbow tubes is also related to the level of turbulence of the working fluid flow that occurs in the elbow tube. The increase in turbulence that occurs is caused by a decrease in the pressure of the working fluid in the evaporator panel so that some part of the working fluid turns into steam and produces a two-phase flow consisting of a mixture of water and steam.

Keywords: *Cavitation-erosion, elbow tube, low pressure evaporator outlet header, turbulence, outer curvature*

1. INTRODUCTION

Erosion has been long recognized as a potential source of problems in much industrial equipment, is a complex process affected by multiple factors present in the operational conditions. Possible mechanisms that could cause significant erosion damage are particulate erosion, liquid droplet erosion, erosion-corrosion, and cavitation [1]-[3]. Extensive research on erosion has been carried out, based on which theoretical and empirical erosion models were developed [4]-[6].

In the boiler or HRSG (heat recovery steam generator) of a thermal power plant, the most vulnerable areas prone to erosion are the auxiliary feedwater system, economizer tubes, condensers, moisture separation drains, re-heater drains, bends in evaporators, and risers [7]-[9]. In general, components such as elbows, bends, tees, reducers, and pipe entries are more susceptible to erosion. The eroded surface has, by and large, a shiny appearance without any corrosion products and has a structural like dunes. The exact appearance of the damaged surface is a function of the type of flow. The flow pattern in bend or elbow is subject to significant changes in flow direction and flow velocity, thus leading to a substantial difference in erosion behavior at different locations of bend or elbow [4]-[5],[9]. Due to the sudden change in the flow pattern, the wall thinning by flow-accelerated erosion is exacerbated at bend or elbow.

In many circumstances, the flow-accelerated erosion can also be combined with other flow damage mechanisms such as cavitation, which is referred to as cavitation-erosion. Cavitation is a type of failure wherein the rapidly formed small bubbles in a fluid near the tube/elbow surface collapse or implodes to impact the metal surface, resulting in the removal of material from the inner surface of the tube/elbow. The energy with which the bubbles implode may be just sufficient to rupture the protective magnetite layer or may damage the underlying metal as well. Bubbles form the pressure of the fluid drops below the vapor pressure (i.e., the pressure at which a liquid becomes a gas). A sudden drop in the pressure and the turbulent flow of fluid accentuate cavitation phenomena. In other words, low pressure generates a high degree of turbulence within the fluid, favoring cavitation [7],[9]-[10]. Pits formed due to cavitation exhibit a rough and jagged appearance. The damaged surface can also exhibit a spongy and honeycomb appearance [9]-[11]. Cavitation is a localized form of damage in the sense that the pits formed are generally confined to a specific area of the tube/elbow. The extent of damage due to cavitation cannot be controlled simply by proper material selection because it is a result of the system, which includes the tube material, the fluid flowing, and its properties (density, viscosity, surface tension, and flow rate), as well as the temperature and pressure of the fluid. However, it is possible to minimize the extent of damage due to cavitation by using a material with higher fatigue strength or by using overlays. Still, it cannot be stopped [12].

2. EXPERIMENTAL METHOD

This study aims to research elbow tubes that often experience leaks, where the elbow tubes are connected to the low pressure evaporator outlet header on an HRSG plant. Figure 1 shows the sketch of the arrangement and construction of 4 (four) elbow tubes connected to the low pressure evaporator outlet header. From the operating manual, it is known that the four elbow tubes in the low pressure evaporator outlet header are connected to the low pressure evaporator inlet header located on the other side of the HRSG through 4 (four) panel tube lines as a heat exchanger system which is heated using flue gas from a gas turbine power plant. Each line of the heat exchanger panel uses finned tubes, while the elbow section uses plain tubes. Material tubes and elbow tubes, as well as the two headers, use low carbon steel, and the working fluid flowing therein is hot water with a maximum pressure of 10 bar(g) and a maximum temperature of 160 °C. Both panel tubes and elbow tubes have an outer diameter of 31.8 mm and a wall thickness of 2.6 mm. From Figure 1, it can be seen that the elbow tube 1A at the lowest position forms an angle of 90° with the low pressure evaporator outlet header. In contrast, in the above position, other elbow tubes are connected at an angle of 75° (elbow tube 2A), 60° (elbow tube 3A), and 45° (elbow tube 4A). From Figure 1, it can also be seen that the higher the angle of the elbow tube connected to the header, the smaller the elbow or bend radius that is formed, and this can affect the level of wall thinning occurred in the elbow tube.

In this research work, four damaged elbow tubes shown in Figure 2 were cut away from the low pressure evaporator outlet header in which one of the elbow tubes that connected at 90° to the outlet header showed a leaking hole (pinhole) on its outside curvature. Each elbow tube shown in Figure 2 was sectioned into two halves (see Figure 3) and subsequently cut into several specimens for laboratory examination. The macroscopic test on the damaged surface of the elbow tubes was performed using a stereomicroscope. Chemical analysis of the prepared sample was carried out using an optical spark emission spectrometer. The purpose of this chemical analysis was to determine whether the material used for the damaged elbow tubes met the specification. Besides, metallographic examinations were also performed on the prepared samples using an optical microscope at various magnifications. The metallographic samples were mounted using epoxy and prepared by grinding, polishing, and etching. The etchant applied was Nital solution [13]. A hardness survey was also carried out on the same samples for the metallographic examination using the Vickers hardness method at a load of 5 kg (HV5). Furthermore, tensile tests at room temperature were also performed using a universal testing machine. Moreover, an examination of some damage surface of the elbow tube was also performed using an EDS (energy dispersive spectroscopy) analysis to detect any corrosion by-product.

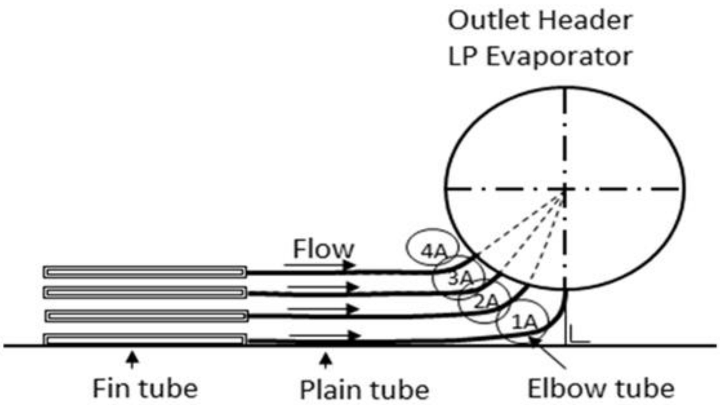


Figure 1. The elbow tube's connection angle with the low pressure evaporator evaporator outlet header, i.e 90° (elbow tube 1A), 75°(elbow tube 2A), 60° (elbow tube 3A), and 45° (elbow tube 4A)

Figure 2. Four elbow tubes (1A to 4A) cut away from the low pressure evaporator evaporator outlet header, where one of the elbow tubes (1A) shows a pinhole on the outer side of the elbow curvature

Figure 3. The four elbow tubes (1A to 4A) divided into two parts for the preparation of laboratory test samples

3. RESULTS AND DISCUSSIONS

3.1. Visual and Macroscopic Examination

The macroscopic observation results on the inner walls of the four halves of the elbow tubes 1A, 2A, 3A, and 4A are shown in Figures 4-7. It is clearly seen that most of the inner walls of the four elbow tubes exhibit a rough and jagged appearance. This indicates that all of the elbow tubes had experienced cavitation-erosion [9]-[10],12]. Figures 4-7 show that most of the wall thinning on the elbow tube due to cavitation-erosion only occurs on the inner wall around the elbow's outer curvature. While on the inner wall at the elbow's internal shape, there is no wall thinning occurred. The thinning that occurs on the outer surface of the elbow tube looks insignificant. The thinning is probably caused by corrosion and or oxidation due to flue gas flow through the HRSG unit. Moreover, in Figures 4-7, it can be seen that the higher the connecting angle or, the smaller the radius of the elbow tube, the higher the level of cavitation-erosion that occurs. The high rate of cavitation-erosion experienced by the four elbow tubes is also related to the level of turbulence of the working fluid flow [4]-[5], [8]-[9], [12], i.e., the elbow tube with an angle of 90° (1A) experiences more considerable turbulence when compared to the elbow tube with an angle of 75° (2A), 60° (3A) and 45° (4A).

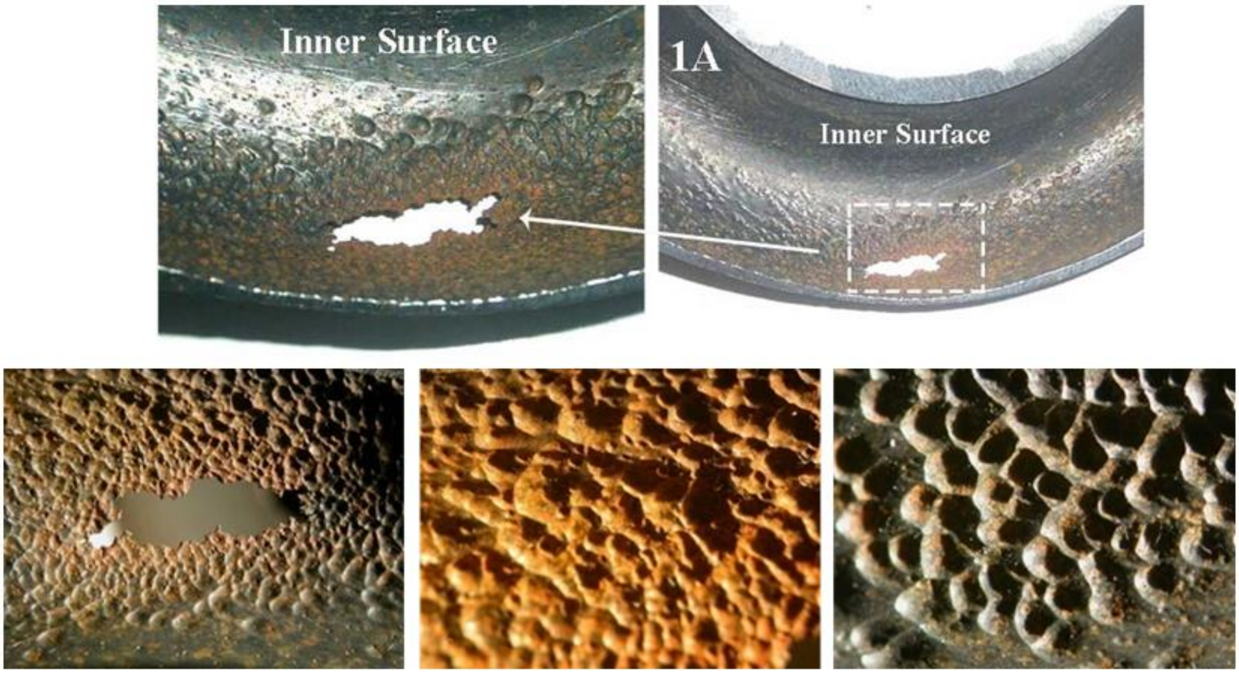


Figure 4. The inner wall of the elbow tube 1A showing a pinhole and a rough and jagged appearance in the cavitation-erosion area

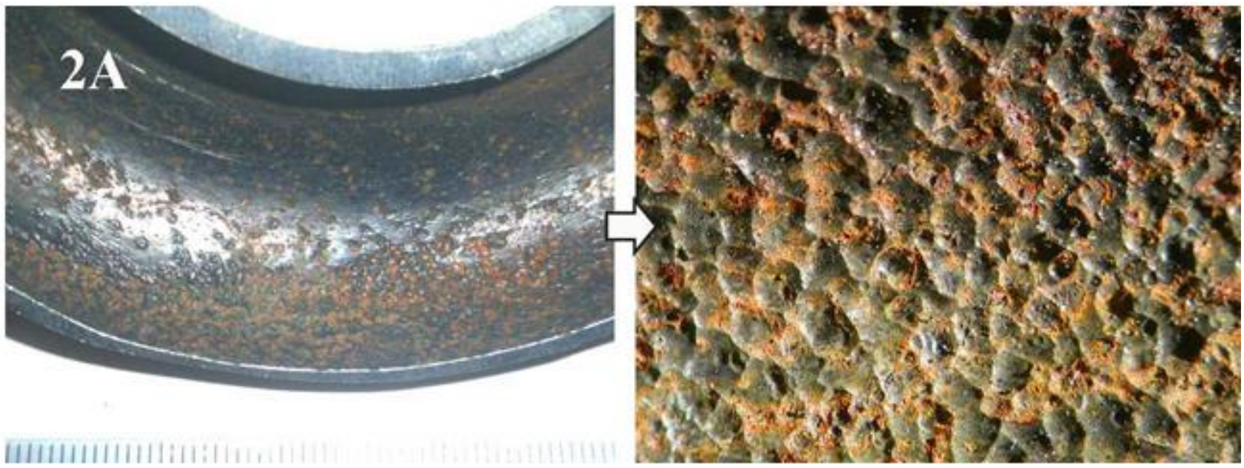


Figure 5. The damaged area due to cavitation-erosion in the elbow tube 2A showing similar rough and jagged appearance as shown in Figure 4, but at a lesser degree and no formation of any pinhole observed

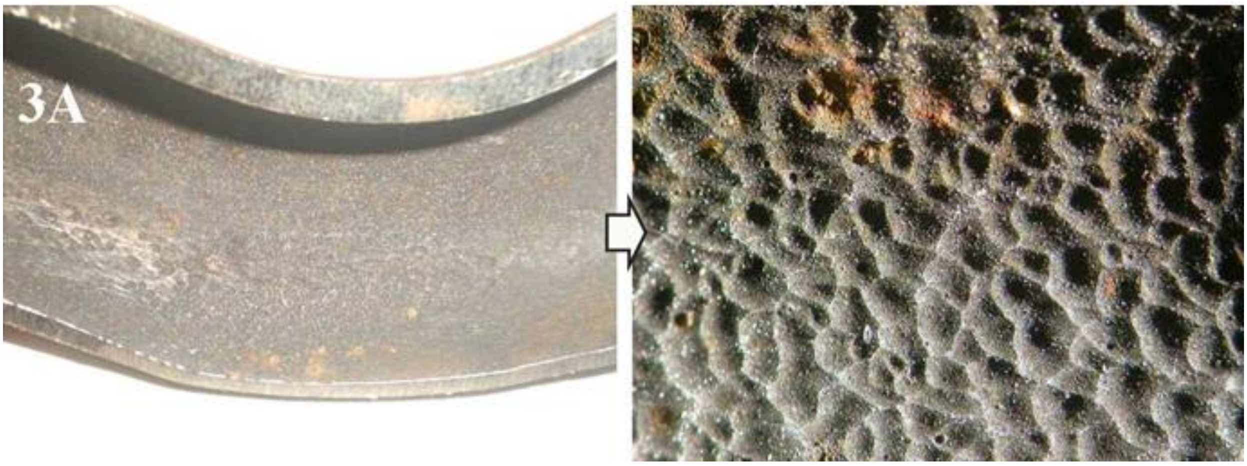


Figure 6. The damaged area due to cavitation-erosion in the elbow tube 3A showing similar rough and jagged appearance as shown in Figures 4 and 5, but at a lesser degree and no formation of any pinhole observed

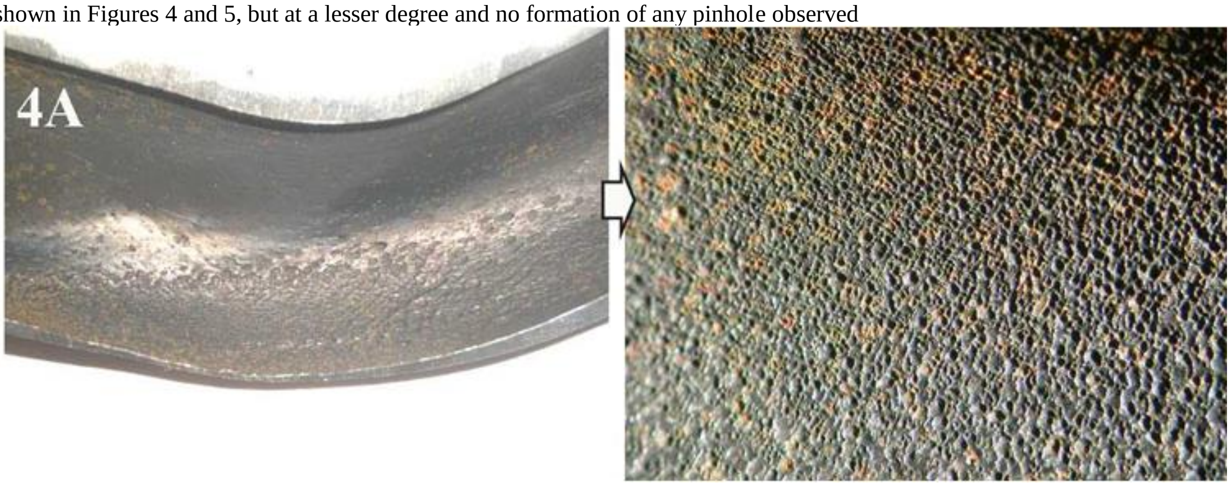


Figure 7. The elbow tube 4A showing the lowest degree of cavitation-erosion damage due to the largest its bend radius

3.2. Chemical Analysis

Results of the chemical composition analysis of the elbow tube material are given in Table 1, which shows the elements content obtained from the elbow tube with an angle of 90° (1A) and 75° (2A). As mentioned in the operating manual, the four elbow tubes (1A to 4A) of the low pressure evaporator outlet header are made of the same material spesification. Therefore, the two elbow tubes (1A and 2A) are expected to represent the four elbow tubes. It can be seen from Table 1 that the elbow tube material is made of low carbon steel and approximately met to DIN Grade St 35.8/I specification.

3.3. Metallographic Examination and Analysis

The metallographic observations on samples from the elbow tube 1A, 2A, 3A, and 4A in the transverse and longitudinal directions are given in Figures 8-11. The test results obtained show that the microstructures of the four elbow tube materials consist of the ferrite phase as matrix and pearlite phase as the second phase, a typical low carbon steel microstructure, which is by the results of the chemical composition analysis shown in Table 1.

Table 1. Results of chemical analysis obtained from the elbow tube materials 1A and 2A in comparison with the standard material

Element	Composition, wt-%		
	Elbow Tube 1A	**Elbow Tube 2A**	**Standard Material DIN Grade St 35.8/I**
Fe	Balance	Balance	Balance
C	0.11	0.11	≤ 0.17
Si	0.24	0.24	≤ 0.35
Mn	0.48	0.48	≤ 0.40 – 0.80
P	0.022	0.035	≤ 0.045
S	0.012	0.0050	≤ 0.045
Cu	0.063	0.061	-
Al	0.024	0.023	-
V	0.0089	0.010	-
W	0.095	0.082	-
Nb	0.0062	0.0070	-

The microstructure conditions in the four elbow tube materials are still in good condition where the ferrite and pearlite structure patterns are always clear; no significant change or degradation formed. This may be caused by the fact that the elbow tube is operated at a relatively low temperature (below 200° C). Figures 8-11 also shows that scales or deposits in relatively low amounts generally only form on the outer surface of the elbow tube, while on the elbow tube inner walls whose experiencing moderate to severe cavitation-erosion, there is almost no significant scales or deposits formed. This indicates that the inner wall of the elbow tube does not undergo substantial corrosion. Corrosion seems to occur only on the outer surface of the elbow tube. However, its level is thought to be still at an early stage and is insignificant compared to the level of damage that occurs in the inner walls of the elbow tube due to cavitation-erosion. Besides that, in Figures 8-11, it can also be seen that almost all of the elbow tube inner walls that are experiencing cavitation-erosion show a surface with a fluctuating or wavy pattern.

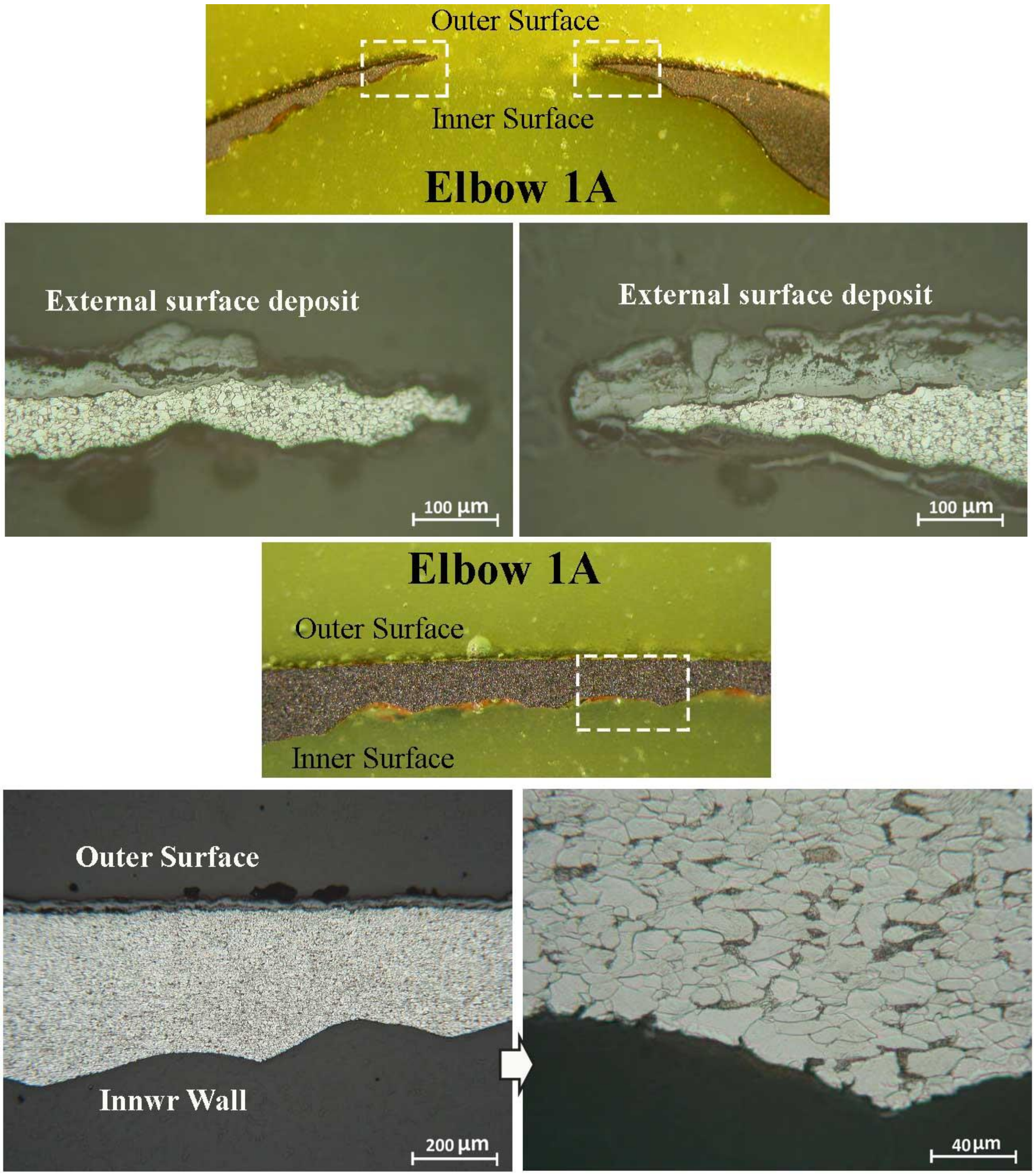


Figure 8. Microstructures obtained from the elbow tube material 1A at different locations (etched with 5% Nital solution)

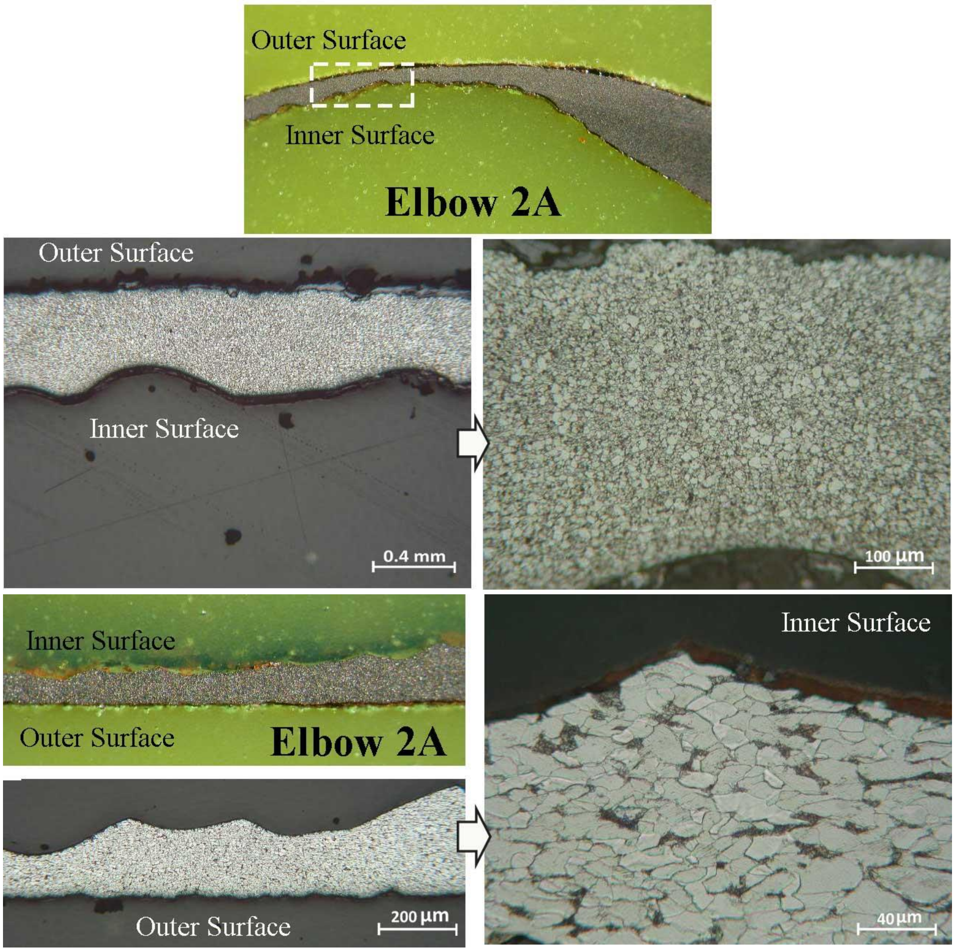


Figure 9. Microstructures obtained from the elbow tube material 2A at different locations (etched with 5% Nital solution)

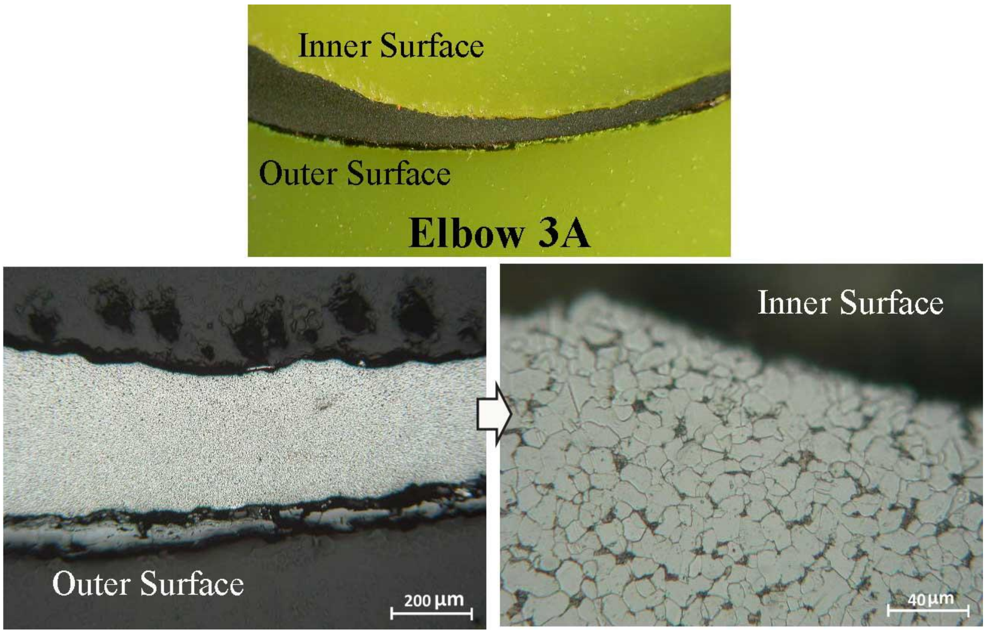


Figure 10. Microstructures obtained from the elbow tube material 3A at different locations (etched with 5% Nital solution)

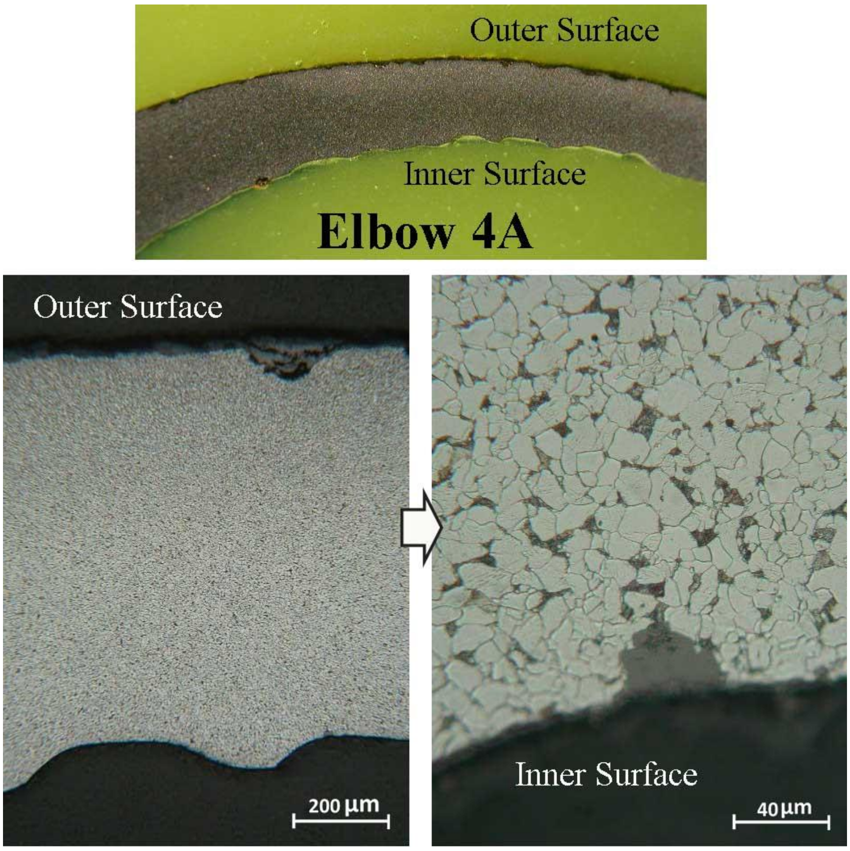


Figure 11. Microstructures obtained from the elbow tube material 4A at different locations (etched with 5% Nital solution)

3.4. Mechanical Test and Analysis

Gambar 5 In this study, there were 2 (two) mechanical tests conducted on the elbow tube material, namely the hardness test and tensile test. The results of the hardness test are shown in Table 2, while the results of the tensile test are given in Table 3. Tensile tests are performed on specimens taken on the straight elbow tube. From Table 2 it can be seen that the hardness values for the four elbow tube materials (1A to 4A) show almost the same average value in the range of 183 HV to 196 HV (although for the elbow tube material made of low carbon steel, the value tends to be rather high. In as annealed low carbon steel, the average hardness value generaly around 150 HV max) [14]. This is probably caused by the strain hardening on the elbow tube material due to the cold bending process at the time of manufacture [14]. Furthermore, the tensile test results presented in Table 3 show the important tensile properties, namely yield strength, tensile strength, and Elongation. From Table 3, it can be seen that the tensile properties of the elbow tube material obtained are generally higher when compared to the minimum tensile properties requirements for low carbon steel according to DIN Grade St 35.8 / I specification. Thus, the material used for the low pressure evaporator evaporator outlet header's elbow tube follows the material specification according to the operating manual. However, for the application of the elbow tube in a fluid flow condition which consists of two phases (a mixture of water and steam) and has the potential to cause cavitation-erosion, the use of low carbon steel with DIN Grade St. 35.8/I specification is estimated to be inadequate.

Table 2. Results of hardness test obtained from the elbow tube materials 1A, 2A, 3A and 4A using Vickers hardness method (HV)

Test Location	Elbow Tube Material			
	1A	2A	3A	4A
1	210	214	214	195
2	210	210	195	188
3	192	195	199	181
4	187	185	181	175
5	175	175	181	175
Average	195	196	194	183

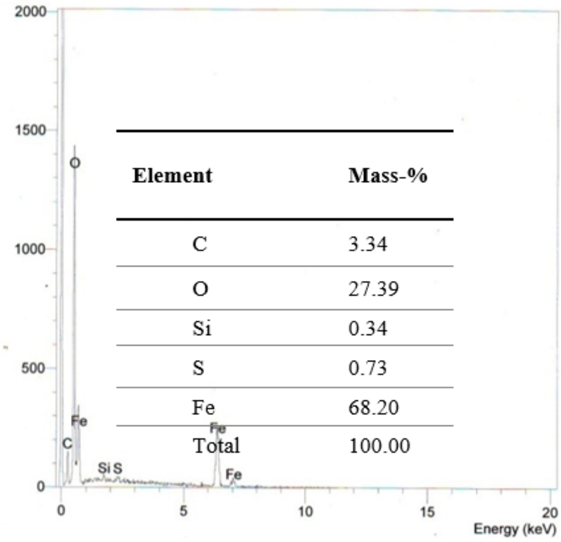
Table 3. Results of tensile test obtained from the elbow tube materials 1A and 2A (tensile test was performed at room temperature)

Elbow Tube Material	Yield Strength (MPa)	Tensile Strength (MPa)	Elongation (%)
1A	327.1	453.6	36.0
2A	350.7	470.6	36.0

Note: Requirement to the specification of DIN Grade St 35.8/I; Tensile Strength (min) = 370 MPa and Elongation (min) = 30.0%

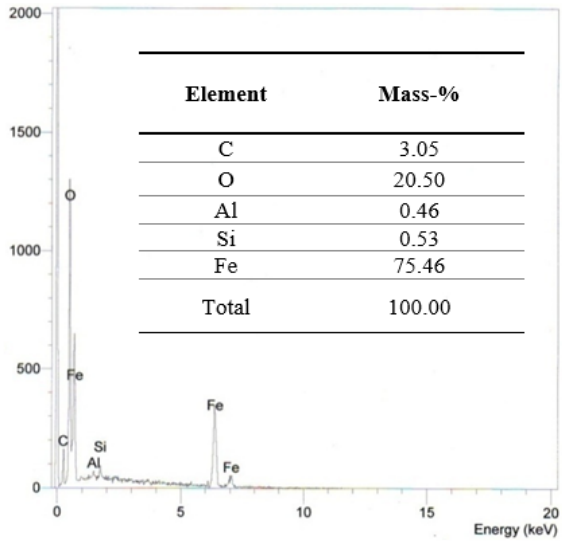
3.5. EDS Analysis

The EDS (energy dispersive spectroscopy) analysis obtained from the elbow tube 1A around its leaked area is presented in Figures 12-13, in which Figure 12 was showing some deposits that formed on the external surface, while Figure 13 was showing some deposits that formed on the inner wall around the cavitation-erosion area. The deposits that formed in both surfaces shown in Figures 12 and 13 contained iron (Fe) as a major element from which the elbow tube is made. Besides that, both deposits are shown in Figures 12, and 13 also contained oxygen (O) and carbon (C) as other significant elements coming from some oxides and or other surface contamination. There are also some trace elements found in the deposits formed on both surfaces of the elbow tube. Most of the trace elements found in the external surface deposits included S and Si, while the trace elements found around in the cavitation-erosion area included Si and Al. The trace elements found in the outer surface deposit may be coming from the flue gas circulated in the HRSG's evaporator tube panel. They may have been responsible for some surface corrosion on the outer elbow tube. Whereas, the trace elements found in the internal wall deposit may be coming from the HRSG water used. The presence of these trace elements may not have been significantly contributing to some corrosion in the inner walls of the elbow tube that experiencing the cavitation-erosion.



Element	Mass-%
C	3.34
O	27.39
Si	0.34
S	0.73
Fe	68.20
Total	100.00

Figure 12. Result of EDS analysis obtained from some surface deposits that formed around the external surface of the elbow tube 1A



Element	Mass-%
C	3.05
O	20.50
Al	0.46
Si	0.53
Fe	75.46
Total	100.00

Figure 13. Result of EDS analysis obtained from some inner surface deposit that formed around the cavitation-erosion area of the elbow tube 1A

4. CONCLUSION

According to the damage topography and mode of failure, the elbow tubes of the low pressure evaporator evaporator outlet header had experienced cavitation-erosion in most of the external curvature's inner walls of the elbow tubes. The texture of cavitation-erosions occurred to have a rough and jagged appearance in which the wall thinning occurred on the elbow tube walls show a wavy pattern. The rate of thinning happened on the inner walls of the elbow tube due to cavitation-erosion is largely determined by the connecting angle or bend radius of the elbow tube to the low pressure evaporator evaporator outlet header. The higher the connecting edge or, the smaller the bend radius of the elbow tube, the higher the cavitation-erosion rate.

From the microstructures and the result of EDS analysis obtained, it shows that the elbow tubes' inner walls that experience cavitation-erosion did not reveal any significant deposit formation and found no signs of corrosion. However, corrosion at very low levels is thought to have occurred on the elbow tubes' outer surface. This corrosion may be influenced by some corrosive agent such as sulfur or its compound present in the outer surface deposit of the elbow tube. Most likely, this sulfur or its compound comes from the flue gas of the gas turbine power plant that is in a combined cycle with the HRSG unit. However, the level of corrosion that occurs on the elbow tube outer surface is not expected to cause a significant reduction in the elbow surface thickness in comparison with the wall thinning occurred due to cavitation-erosion.

The important factor which is expected to accelerate the rate of cavitation-erosion is a possible increase in turbulence flow within the elbow tube due to the formation of some steam in the water flow, causing a two-phase flow in the elbow tube. This is likely to occur due to the influence of increased pressure drop that occurs when fluid enters the elbow tube. Besides, other factors that are also expected to increase the cavitation-erosion in the elbow tube are the air entering or escaping steam due to leakage in the low pressure evaporator evaporator circulation system, or the occurrence of flow-induced vibration in the low pressure evaporator evaporator equipment.

The material used for the elbow tube of the HRSG'S low pressure evaporator outlet header is approximately met to the material specification of DIN Grade St. 35.8/I. This is by the operating manual. However, since the elbow tube material is only low-carbon steel, it is thought that the existing elbow tube material is inadequate for fluid flow conditions prone to cavitation-erosion.

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