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IDENTIFYING FAILURE FACTORS DUE TO CORROSION EROSION ON PRESSURED STEAM PIPE ELBOW IN GEOTHERMAL POWER PLANT

Iskandar Muda
Doctor of Materials Engineering, Lecturer*
Bambang Widyanto
Corresponding author
Doctor of Materials Engineering, Professor*
E-mail: bambwid98@gmail.com
*Department of Metallurgical and Materials Engineering
Jenderal Achmad Yani University
Terusan Jend Sudirman, Cimahi, Indonesia, 40525

This paper presents the findings of a corrosion erosion failure analysis of elbow pipe materials used to flow high-pressure water from underground. The failed elbow pipe material was above the wellhead forming a straight line in the longitudinal direction with a pipe length of 6200 feet below the ground surface. The working fluid in the elbow pipe was 25 % steam and 75 % water, flowing in the elbow pipe with a media flow rate of 180 tons per hour, a pressure of 22 bar, and a temperature of 220 °C. Elbow tubes were made of low carbon steel with Standard ASTM A234 having an outer diameter of 304.8 mm and a wall thickness of 9.271 mm. Macroscopic testing, chemical composition analysis, metallographic testing, hardness testing, X-ray diffraction testing, SEM, and EDS are a few of the test types conducted. The study's findings showed that the elbow tubes experienced a thinning process on the inner wall of the outer curvature side with a rough and wavy surface texture or appearance. This type of failure is known as erosion-corrosion. The level of erosion-corrosion failure that occurs is greatly influenced by the pH of the fluid being flowed reaching 2.67–2.91, this is due to the very high Cl- of 1290 ppm, so the higher the rate of erosion-corrosion that occurs. These materials are the most popular and widely used in the oil and gas sector. However, this pipe has weaknesses because it is susceptible to erosion-corrosion Therefore, it is very important to choose the right material, namely, a material that is resistant to erosion-corrosion

***Keywords:** corrosion erosion, elbow pipe, turbulence, tubercles, fibrous fractures, thinning thickness*

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1. Introduction

This failure analysis was done at the geothermal company's request. This elbow material damage must be dealt with thoroughly so that no similar damage will occur in the future. Material selection errors, fabrication errors, and incompatibility of material types with working conditions are some examples of why many industrial components or equipment malfunction in usage.

Based on the theory of failure analysis, all indications are studied and examined to decide whether the component is suitable to be repaired or not used anymore. The failure can be caused by corrosion erosion, which is an extreme failure that has broken this elbow in just a year. These damage cases must be very detrimental, there is an operating delay, and repairs that require new spare parts and energy to think about and find the cause of failure to avoid similar events then the causes damage occurs.

Investigation of the causes of damage will be beneficial especially to avoid excessive cost losses. By knowing the cause of damage, various preventive maintenance measures can be carried out. Errors may occur since the design stage. These errors can be caused by dimensional planning errors, material errors, misplacement in certain environmental conditions, voltage calculation errors, and others.

2. Literature review and problem statement

In the geothermal power plant, there is only one heat pipe for each steam generator that flows steam and water with high steam and water pressure (22 bar) with a high temperature of 220 °C, a media flow rate of 180 tons/hour from underground to the steam generator. The pipe stretches relatively straight at 1890 meters from the ground surface then turns at an angle of 90° towards the steam generator. Due to the bend in the pipe, the flow of steam and water will be divided, causing fluid eddies, erosion-corrosion, and vibrations that cause increased pressure and pressure concentration at one point on the pipe elbow wall. Corrosion-erosion is a type of corrosion that uses a mechanical process through relative movement between the flow of gas and corrosive liquids with metal. In this case, damage due to corrosion and erosion support each other. Metal that has been eroded due to wear and tear causes sharp and rough parts. These parts are easily attacked by corrosion and if there is friction, it will cause even more severe abrasion and so on. Sulfides are the outcome of examining the microchemical makeup of the corrosion erosion product at the inner surface surrounding the pinhole [1]. At a specific flow rate, significant corrosion erosion exposes an uneven thinning. The majority of the liquid phase fraction is found on the elbow's interior, where more sour water collects and causes localized corrosion thinning [2], wall thinning, and corrosion products on the interior surface [3]. Erosion corrosion can also be caused by impingement corrosion, which is caused by very fast fluids and can erode the protective film on the metal, resulting in corrosion of the metal. The most susceptible sections of production systems are those where there are abrupt changes in flow direction, large volumetric flow rates, or high flow velocities as a result of flow constraints [4]. Corrosion pits are seen on the

90- and 60-degree elbow departure areas when microscopic surface imaging of eroded elbow surfaces is performed, whereas erosion scars were created on the 30-degree elbow entry regions [5]. The hydrodynamics and sand particle distribution at the elbow are well-matched with the corrosion erosion rate distribution [6]. Failure of high-pressure steam elbow pipes occurred in geothermal power plant exploitation. In this case, the cracks formed a straight line in the longitudinal direction and the material used was low-carbon steel in the form of ASTM A234 pipes with a diameter of 12 . The fluid in the pipe consists of 25 % steam and 75 % water, most of which such as additives and salts are in the liquid phase. These materials can form deposits in the pipe, which combined with hydrodynamic flow, encourage corrosion erosion and damage the elbow components. This elbow pipe failed in just 6 months, from a design life of 20 years, caused by corrosion erosion, where there is a thinning of the thickness and the formation of small holes due to erosion corrosion and the presence of high pressure, causing the elbow pipe to break. Corrosion erosion is often a potential source of problems. This is a complex process that is influenced by various factors that exist in field conditions such as fluid aggressiveness and flow patterns. One significant cause is the pH of the fluid changes to acidic, this acidic fluid causes corrosion, and with high-pressure flow, the fluid causes corrosion erosion.

Research on corrosion erosion has been widely conducted, both based on theoretical and empirical corrosion erosion models. The results of the examinations carried out, namely visually, macroscopically, and metallographically, show that elbow pipes are more susceptible to corrosion erosion and the formation of the most severe corrosion erosion such as erosion on the inner surface of the elbow, generally on the inner surface of the broken pipe, rust products are found to form large hilly deposits called tubercles, which are light brown on the outer layer and dark brown on the inside. The actual appearance of the damaged surface is a function of the type of flow. The flow pattern at the elbow can experience significant changes in flow direction and flow velocity, causing significant differences in erosion-corrosion behavior at different elbow locations. The main influences on flow-accelerated corrosion are turbulence, geometry, mass transfer, and material [7], oxidation and corrosion erosion resistance, fatigue strength, and thermal conductivity [8]. These include the typical locations of flow-accelerated corrosion, the differences between single-phase and two-phase variants, the possibility of oxide growth in the desired areas, alternative cycle chemistries, and especially the potential effects on oxide forms. The amount of silicic acid and other admixtures present has a significant impact [9].

Due to the sudden change in flow pattern, wall thinning due to erosion will be faster and more severe at the elbow. This is a process that occurs when abrasive solids suspended in flowing corrosive fluids interact with the internal walls of the elbow pipe resulting in significant material loss that can cause the pipe to leak or fail rapidly. The location of the pipe that experiences a sudden change in flow direction, such as an elbow, experiences severe hydrodynamic intensity caused by high-angle impacts by particles in the moving fluid and changes in flow at various positions in the elbow. This is a process that happens when abrasive solids suspended in corrosive geothermal fluids that include dissolved gases, fluid flow velocity, salinity, pH, and temperature interact with the elbow pipe's internal wall, leading to a significant loss of material that can quickly fail or leak [10]. The rate of erosion increases with increasing joint angle or decreasing elbow tube bend radius [11]. One important contributing factor to material loss in erosion and corrosion is the synergistic effect of wear and corrosion [12]. Erosion corrosion causes the high-pressure steam elbow pipe in geothermal to fail, requiring a complete overhaul. Usually, a complete overhaul is carried out every two years, and preventive maintenance is carried out once a year. The repair work is mainly aimed at preventing erosion corrosion and replacing elbows that are susceptible to erosion corrosion. The overall economic loss associated with metal erosion-corrosion, namely how to prevent it from happening again like this and to eliminate the consequences and prevent the above problems from recurring. Because this will make the cost of electricity production high, due to equipment failure and outages, forced outages, and claims from factory customers that cause delays and losses due to coil breaks during the process in a continuous factory, such as cold rolling mill, continuous galvalume line, tension leveler, shearing line, recoiling line, and overall reduced power plant efficiency. As a result, the annual economic loss per unit of electricity generation is large. In terms of pipe materials, there may be errors in material selection, fabrication errors, and incompatibility of material types with working conditions, where the pH of the fluid becomes more acidic.

Many industrial systems, including this pipe elbow, are subject to corrosion erosion, particularly those involving harsh geothermal fluid applications and acidic environments that demand very high mechanical and corrosion resistance. Numerous researches have been conducted in recent decades to improve our understanding of the connections between corrosion-erosion in these systems. The wear and corrosion processes include complicated mechanical and electrochemical mechanisms, the combined action of which typically results in significant amplification of material degradation. High-strength low-alloy (HSLA) steels, stainless steel, and other passive alloys frequently exhibit synergism, an improvement. This improvement, known as erosion, modifies the kinetics of the two distinct processes and has an impact on both the former and the latter. The mechanisms behind this synergism have to do with the extra challenge of restoring the passive layer after fluid impact has damaged it, as well as the creation of highly deformed tubercles and easily corroded zones. It is frequently present in passive alloys, including steels that are high-strength low-alloy (HSLA). There are several ways to explain how corrosion and wear work in concert. Among them are the measurements of current intensity during wear, penetration rate, and wear volume or mass loss. When corrosion and erosion interact, the total amount of material degradation frequently exceeds the degradation of each component acting alone [13]. During corrosion-erosion, the material undergoes microstructural changes and subsurface deformation mechanisms [14]. Because of their poor wear qualities and extremely low intrinsic corrosion resistance, low-carbon steel pipe products exhibit very unsatisfactory corrosion-erosion behavior [15]. The area where the particles strike the surface at an angle that is almost exactly 90 degrees has the highest rate of erosion and corrosion [16]. Because of the elbow design's abrupt bend, which allows sand particles to strike the material wall at a certain speed, the corrosion-erosion performance measured against the rate of sand volume loss indicates that the elbow portion experiences the most erosion [17]. The research findings suggest that the complex hydrodynamic conditions in the inner elbow are caused by local variations in the late stages of development [18]. The outcome of the wear process due to erosive corrosion is quite significant [19]. According to the traditional method, synergism is the difference between the total mass loss from corrosion and wear and the total mass loss from corrosion and wear, assessed independently. Utilizing electrochemical methods, the synergy between erosion and corrosion has also been evaluated. Madsen investigated the synergism by mass loss analysis measures and introduced the use of potentiodynamic experiments for corrosion-erosion.

The papers [1–3, 6, 9, 14, 18] present the results of the research shown that corrosion erosion has a significant effect on the failure of the pipe elbow, but there were unresolved issues related to the very acidic fluid conditions in the Sarulla area, North Sumatra. Indonesia. The lifetime of a pipe elbow should be 20 years, but in fact, it only takes a year for the pipe to fail. The reasons for this may be the difficulties associated with the fundamental impossibility of obtaining sample data on the chemical composition of fluids at very long well depths, not yet fully sampled and mapped, partly the cost in terms of construction is limited, which makes relevant research impractical. A way to overcome these difficulties can be to conduct a failure analysis due to corrosion erosion on a pressurized steam pipe elbow in a geothermal power plant. This approach was used in many kinds of literature. Analysis of the chemical composition of rust on low carbon steel pipe elbows using X-ray diffraction, found compounds Fe_2O_3, FeS_2, and $FeCl_2$ because the fluid is acidic [1]. The corrosion rates increase rapidly with increased velocity. [2]. The failure of the elbow pipe was caused by an erosion-corrosion with the presence of wall thinning in the leak area [3]. Maximum erosion rates are obtained for 90° bends, and the maximum erosion rate decreases as the pipe diameter increases. From a bend curvature perspective, the calculation shows that the erosion rate increases as the bend curvature increases [6]. Results of the computational and practical studies conducted at the Verkhne-Mutnovsk geothermal power station to examine the variations in silicic acid and other admixture concentrations in the working loop and turbine flow route. It is shown that surface-active inhibitors can be used to stop deposits from forming erosion-corrosion processes in the equipment of geothermal power plants [9]. The corrosive environment is also believed to have played a significant role in the initiation and propagation of cracks. Crack initiation and propagation due to the mechanical and electrochemical processes enhances the material mass loss as the crack networks coalesce and subsequently cause material spalling [14]. Complex fluid rate hydrodynamic conditions impose mixed attack modes due to local variations in impact angles at pipe elbows [18]. However, all this suggests that it is advisable to conduct a study on

The results of the study above indicate that corrosion erosion has a significant effect on the failure of the pipe elbow, but there are unresolved problems related to the very acidic fluid conditions in the Sarulla area, North Sumatra. The lifetime of a pipe elbow should be 20 years, but in fact, it only takes a year for the pipe to fail. One way to overcome this difficulty is to conduct a failure analysis due to corrosion erosion on a pressured steam pipe elbow in a geothermal power plant. This approach is used to solve problems that occur in the geothermal power plant, but this failure analysis only solves the rupture problem, all of this shows that there are differences in material selection planning, with fluid conditions in the field, because each well has its unique. It is recommended to research the elbow material that will be used with this fluid.

3. The aim and objectives of the study

The aim of the study is to determine the variables that affect the failure rate of elbow pipes with a 20-year design that lasts only a year. The findings of this study are anticipated to help geothermal companies identify the reasons behind Elbow 12 ASTM A234-2015 failures. Also offer recommendations for future enhancements and predictive and preventive maintenance, which will help ensure that the elbow's service life is in line with its design or if properly maintained, extend the material's life expectancy and lower production costs while it's in use.

To achieve this aim, the following objectives are accomplished:

– to carry out a visual and macroscopic Inspection, on pipes that are broken in the thinnest longitudinal direction of the fracture, to find fibrous fractures due to overload and gray deposits of pipe corrosion on the surface of the pipe in the form of tubercles that are clustered and reddish brown at the core;

– to execute tensile test on samples, to determine the conformity of pipe material specifications with ASTM A234 material specification standards;

– to perform hardness testing, as it decreased by almost 1.6 times, especially around the fracture edge, the hardness decreased to 147 HV from 230 HV;

– to observe the microstructure using metallographic method on the damaged elbow pipe using optical microscope and scanning electron microscope;

– to undertake SEM-EDS observation and Mapping tests on the inner crust of the elbow pipe, to determine the Cl_- and S elements.

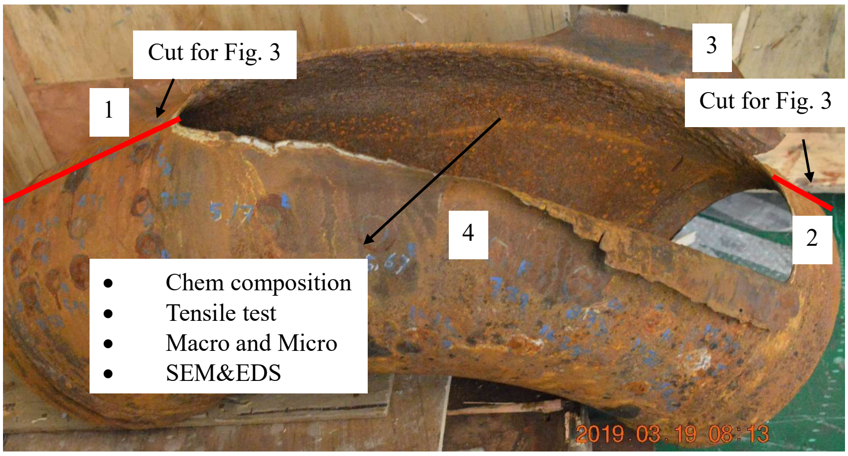
4. Materials and Methods

The object of the study is There has been damage to the elbow 12" ASTM A234-2015 material which functions as a geothermal steam distributor containing corrosive fluids. The main hypothesis of this study is flow-accelerated corrosion called erosion corrosion when there are hard particles in the fluid. Erosion corrosion is accelerated by the flow at a 90° elbow that experiences a large change in flow direction and flow velocity, because of the sudden change in flow pattern, wall thinning occurs by flow-accelerated corrosion and is exacerbated in the elbow area. The assumptions made in this study are the estimation of higher fluid corrosivity (pH 2.67–2.91) and the presence of solid particles [3]. The simplification adopted in this study is to study the historical background of failure, visual and macro detection, types of mechanical failure, metallurgical aspects of component failure with tensile testing, hardness and metallography. Studying the relationship between processing structure properties, metallurgical imperfections, processing defects, surface defects and erosion corrosion, the propagation of erosion corrosion defects with scanning electron microscopy.

The study examined a 90° long radius steel elbow pipe made of low-carbon steel ASTM A234. Table 1 displays the steel's chemical composition test findings.

Fig. 1 displays typical macroscopic images of erosion-corrosion on the inner side of the ruptured area. The pipe elbow underwent a metallographic inspection at the position shown in Fig. 2, which corresponds to the visual examination.

Fig. 1. Erosion corrosion condition on the inner surface of the pipe



- Chem composition
- Tensile test
- Macro and Micro
- SEM&EDS

Fig. 2. Location of inspection and testing on the broken elbow pipe

Table 1

Chemical composition test Results of low carbon steel used

Element	Sample 1 (wt. %)	Sample 2 (wt. %)	ASTM A234-2015
Carbon(C)	0.205	0.206	0.23 max
Silicon (Si)	0.229	0.242	0.10 Min
Mangan (Mn)	0.527	0.367	0.29–1.06
Phosphorus(P)	0.0225	0.0175	0.05 max
Sulfur(S)	0.0116	0.0047	0.058 max

The inspection begins by observing the technical data of the elbow pipe in the technical data table. A pipe sample has been sent as shown in Fig. 2, namely the broken pipe. This pipe will be tested for physical, mechanical, and metallographic properties. The image also shows the type of testing or inspection that will be carried out and its location. The inspection location is concentrated on the damage to the elbow pipe. Visually, a broken pipe can be seen at both ends of the broken pipe, it looks different, the left side (position 1) is thicker than the right side of the broken pipe (position 2). On the right side of the split pipe, there has been thinning at the top, and the upper lip is broken (position 3), with a thickness of between 0.8–1.2 mm, the right side is broken (position 2) has also been thinned by 0.8 mm–2.5 mm, the lower lip of the broken (position 4) with a thickness of 1.2–1.5 mm while the left edge of the broken area (position 1) is 2.6–3.1 mm thick.

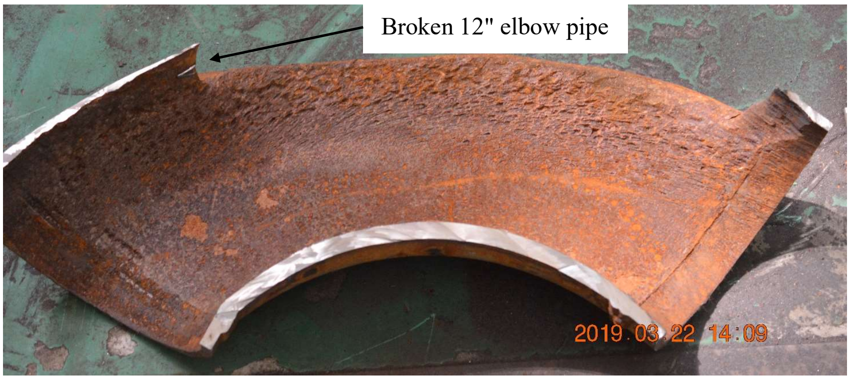


Fig. 3. Broken 12" elbow pipe with ASTM A234 low carbon steel specification and inspection location

The thickness of various positions in this elbow shows the flow pattern of the gas and water fluids it carries, from left to right.

Samples from one of the obtained pipe elbows were cut for the investigation, and some preparatory activities were completed, including cutting, mounting, and sanding with SiC paper grit sizes of 320, 400, 600, 800, and 1200. Then, polishing was done using MD-Dac 3 μm and MD-Nap 1 μm polishing cloths. Finally, Nital solution, which is made of 2 % nitric acid and 98 % ethanol, was used to etch the surface for 30 seconds [12, 13]. A Nikon inverted optical microscope MR200 was employed to investigate the microstructure. To identify the primary damage causes, the worn surfaces of the tested elbows were assessed using a JEOL JCM 7000 scanning electron microscope (SEM-EDS). This report will describe the results of damage analysis in connection with the rupture of Elbow 12" ASTM A234 2015 material at the Geothermal Company.

5. Results of investigation corrosion erosion on pressured steam pipe elbow in geothermal power plant

5. 1. Visual and macroscopic examination

On the broken pipe, a cut was made according to the red line in Fig. 2 showing the shape and direction of the fracture, which is longitudinal. The results of macrostructure observations show that the location of the fracture begins in an area that is already very thin. Fig. 3 shows that fibrous fractures occur due to the mechanism of thinning of the surface area and excess load on the thinnest surface. The fibrous part is evidence that the area is still ductile when it breaks. Severe corrosion causes thinning of the material and excess load fracture. Gray sediment from pipe corrosion is found inside the pipe surface in the form of clustered tubercles and is reddish brown at the core.

The fluid flow at high velocity will cause instability of hydrostatic pressure in certain parts of the pipe. The bubbles produced in the elbow surface by the hydrostatic pressure will form corrosion erosion. The mechanic effect is due to flow dispersion causing the bubble to coalesce and break to release enough force. If this force is stronger than the metal elasticity limit, the surface of the elbow will experience erosion corrosion; As a result, the protective membrane breaks, and corrosion begins again. In turn, the rough surface becomes a better place to form new bubbles, so that the erosion-corrosion process takes place again faster and wider.

The corrosion path depicted in Fig. 4 appears to be rather deep. Compared with its surroundings, this location has a more open corrosion flow. Due to the long-term exposure to heat on the material and the decomposition of pearlite, decarburization occurs and the pearlite is less and has formed in the groove, so it has a lower hardness.

Fig. 4. Surface corrosion path in the defect area

The elbow pipe measurement results that were acquired before installation were 14.27 mm, which complies with the specified pipe thickness and did not experience thinning. Table 2 displays the results of a very significant alteration that was discovered in the area where erosion-corrosion occurred, specifically thinning. Therefore, corrosion strikes rather quickly, particularly in the damaged area. If the design refers to the ASTM A234-2015 steel elbow pipe standard, which is intended for boilers that produce steam and water fluids with a relatively neutral pH, the actual situation on the job site differs greatly. The fluid that emerges from this geothermal well has a pH of 2.67 to 2.91, which is significantly lower than the ambient pH because steam and water are acidic. For this reason, this pipe has a comparatively short service life of roughly one year.

Table 2

Thickness measurement results for low-carbon steel used

Position (Fig. 2)	ASTM A234 12" thickness (mm)
1	0.8–1.2
2	2.6–3.1
3	1.2–1.5
4	0.8–2.5
Average	1.35–2.075

From the results of the average thickness measurement in Table 2, it can be seen that the corrosion rate of elbow steel used is: with a standard thickness of 14.27 mm and the corrosion rate for low carbon steel is 0.02 mm/year, then the thickness of the elbow become 14.03 mm, but the most critical is 0.8 mm. This means that the corrosion rate is 14.03 mm/year, or 702 times faster than normal conditions, thus the thickness of this elbow steel does not enter into tolerance anymore, because it is too large. Then it will make the elbow age no longer reach 30 years, actually only a year less. This happens because the fluids used are acidic, so it is easy to form erosion corrosion which can make the pipe thickness wear out, and become thin, if the thickness is no longer strong, hold the load, there will be overload. Based on discussions with field people who studied this case, the first elbow in the pipe was installed, the fluid was still neutral, so ASTM A234 was chosen, but the more fluid the fluid turned acidic, so it seems the material is no longer suitable with the needs of acidic environmental conditions [12].

A series of tests were carried out on elbow pipes as material verification. Several types of tests are carried out between chemical composition and tensile test. All material testing refers to the 2000 5L Specification API standard. The sample tested refers to the sub-section of the visual inspection, namely the ASTM A234 pipe that has ruptured and piped.

5. 2. Mechanical test and analysis

Tensile strength testing was also carried out to determine the suitability of pipe material specifications. The test results can be seen in Table 3.

The tensile test results for two specimens in different areas in the rolling direction are shown in Table 3, showing that all test results are by the ASTM A234 material specifications, according to ASTM A234 for tensile strength (TS) is 416 MPa (min), while the results are 476 MPa and 483 MPa, According to ASTM A234-2015 for Yield Strength (YS) is: 240 MPa (min), while the results are 426 MPa and 435 MPa, In addition to tensile strength, the elongation obtained such as According to ASTM A234-2015 for Elongation (El) is: 30 % (min), while the results are 46.2 % and 44.4 %. All retest results of tensile testing show values much higher than the ASTM A234-2015 standard. These results can increase the toughness of the pipe material.

Table 3

Results of tensile testing of the elbow pipe used, compared with the standard

No. of specimen	Sample 1	Sample 2	ASTM A234
Tensile Strength kg/mm^2 (MPa)	49.2 (483)	48.5 (476)	Min. 416
Yield Strength kg/mm^2 (MPa)	43.4 (426)	44.3 (435)	Min. 240
Elongation (%)	46.2	44.4	Min 30

The design life of a component is the life set by the manufacturer/user based on certain criteria by considering the aspects of yield strength, tensile strength, and elongation by entering a safety factor at a certain value because deformation and cracking do not depend on time. As long as the existing stress does not exceed the design stress divided by the safety factor, the component can last indefinitely, although the practice of various factors can reduce the design life.

5. 3. Hardness testing

The Vickers hardness test was performed on position 1 using a 0.5 kg load. The primary goal of this test is to ascertain the hardness value in the decarburization region, as indicated by Fig. 5.

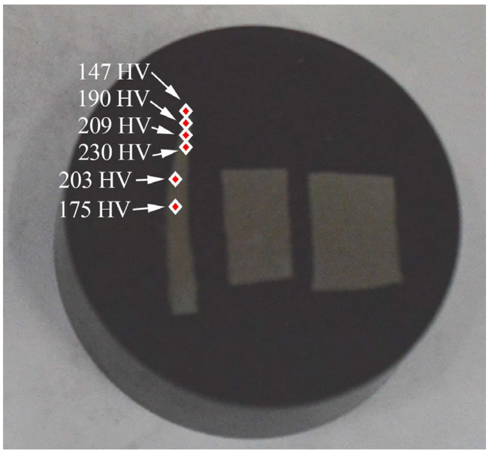


Fig. 5. Results and location of Vickers hardness test

The test findings show that the hardness is still at 230 HV in the ferrite pearlite area but is extremely low in the decarburization structure area, particularly in the vicinity of the fracture edge of 147 HV. Hardness has decreased by nearly 1.6 times. The aforementioned findings suggest that the microstructure has changed in a way that affects the hardness results similarly. The microstructure will largely not change if there is no fluid heat influence for an extended length of time. The pipe will burst as a result of erosion-corrosion occurring more quickly due to changes in the material's microstructure.

5. 4. Metallographic examination

A metallographic examination was carried out on the damaged elbow pipe according to the location listed in the visual inspection (position 1, in Fig. 2). The microstructure photos of the elbow pipe at the broken end position and the outer and inner areas can be seen in Fig. 6. From the microstructure in the inner area, two microstructure phases are visible, namely ferrite and pearlite, where the pearlite composition is larger, according to the carbon content listed in Table 1, which is 0.206 % carbon. However, in the outer area, the percentage of pearlite is less, because decarburization occurs and the ferrite grain size is relatively larger, this is due to the long heat on the pipe elbow and contact with the environment around the elbow pipe, so the carbon content decreases. In the broken end area (edge), relatively larger ferrite grains are visible with pearlite and ferrite phases that also appear to have undergone decarburization. The results of the hardness test show that the area that has undergone decarburization has a relatively softer hardness compared to the area that is still in the ferrite pearlite structure. In the edge area, namely, the edge area where the fracture will occur, an elongated microstructure is found, meaning that the material is still ductile, with the presence of large pressure on the thin material, there is a fairly large deformation so that the structure changes from equiaxial to elongated, this also indicates a fairly strong erosion mechanism on the elbow pipe. From the results of the external and internal microstructures, it can be seen that the outer microstructure is still in the form of ferrite pearlite because the heat carried by the fluid is not too large, while decarburization is formed on the outside. This is because the area inside the pipe is more exposed to heat from the fluid for a long time but no material reduces carbon from the steel, compared to the outer area which is related to the reduction environment. The hardness of the microstructure that has undergone decarburization is much lower than the hardness of the original microstructure in the form of pearlite ferrite. However, the most significant cause of elbow rupture is erosion corrosion, with a very fast corrosion rate, namely a corrosion rate of 14.03 mm/year or 702 times faster than normal conditions. The very rapid erosion-corrosion is exacerbated by the formation of decarburization in its microstructure so that its hardness and tensile strength are far below standard and the elbow pipe rupture occurs. As a result of erosion corrosion on the surface of the pipe elbow which when installed was 14.27 mm thick and is now only 0.8 mm thick, decarburization on the elbow makes its hardness lower, which worsens the mechanical properties of the elbow pipe, so that it is no longer able to withstand the load on the elbow, a rupture occurs.

Based on the place indicated in the visual inspection, a metallographic test was performed on the used elbow pipe that was damaged (position 1, in Fig. 2). Fig. 6 (position 2, in Fig. 2) shows the microstructure photos of the elbow pipe at the broken end position, as well as the outside and inner areas. In Fig. 7, the microstructure is essentially the same as in Fig. 6. Based on Table 1 carbon content of 0.206 %, two microstructure phases ferrite and pearlite are discernible from the inner area's microstructure. The composition of pearlite is higher in this phase. On the other hand, the outer region has a lower percentage of pearlite due to decarburization and a comparatively bigger ferrite grain size. This is because the elbow pipe is exposed to prolonged heat and interacts with the surrounding environment, reducing the carbon content. Relatively bigger ferrite grains with pearlite and ferrite phases that also seem to have undergone decarburization are observed in the broken end area (edge). The portion that has undergone decarburization has a comparatively softer hardness than the area that is still in the ferrite pearlite structure, according to the hardness test results. An elongated microstructure is found in the edge area, specifically the edge area where the fracture will occur, indicating that the material is still ductile. When there is significant pressure applied to the thin material, there is a significant amount of deformation, causing the structure to change from equiaxial to elongated.

This also suggests that the elbow pipe has a fairly strong erosion mechanism. The results of the exterior and interior microstructures show that decarburization is generated on the outside, but the outer microstructure is still in the form of ferrite pearlite because the heat delivered by the fluid is not too great. This is because, in contrast to the outer portion, which is connected to the reduction environment, the area inside the pipe is more exposed to heat from the fluid for a longer period, but no material lowers carbon from the steel. When compared to the original microstructure, which was pearlite ferrite, the decarburized microstructure's hardness is significantly reduced.

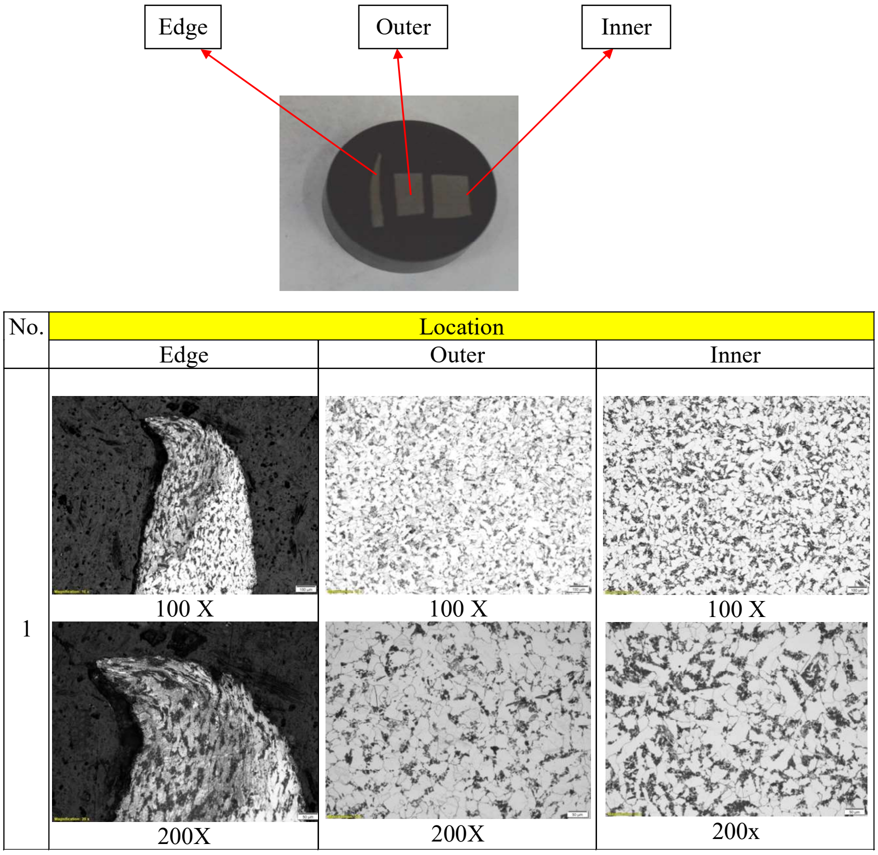


Fig. 6. Microstructure of elbow pipe used in position 1

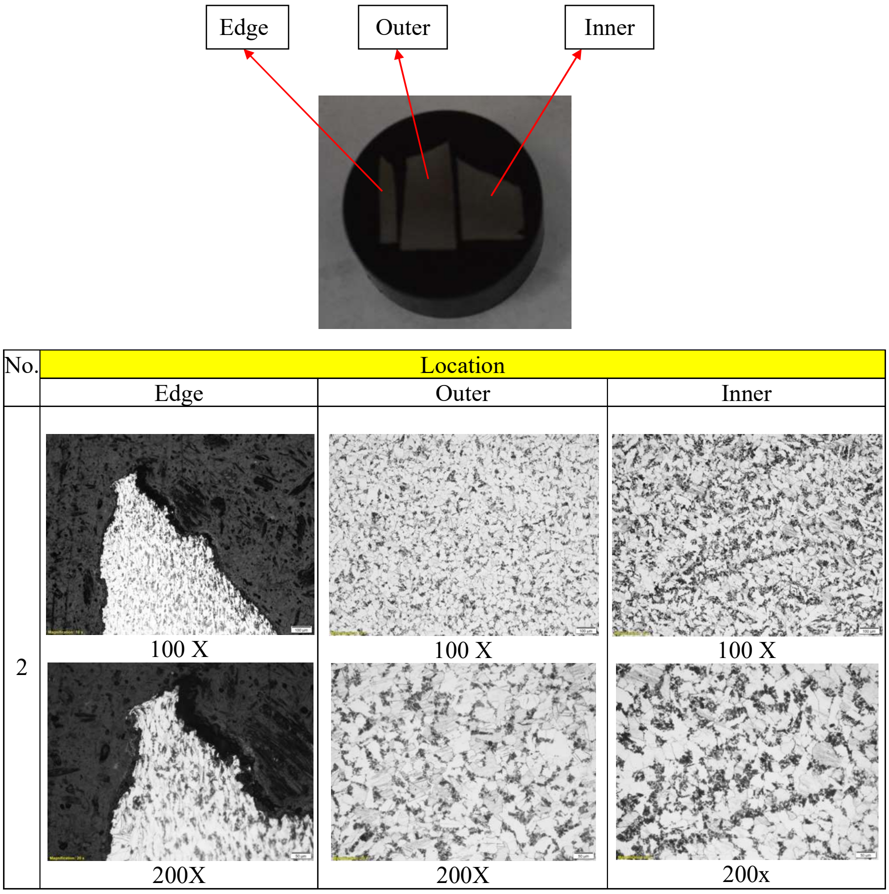


Fig. 7. Microstructure of elbow pipe used in position 2

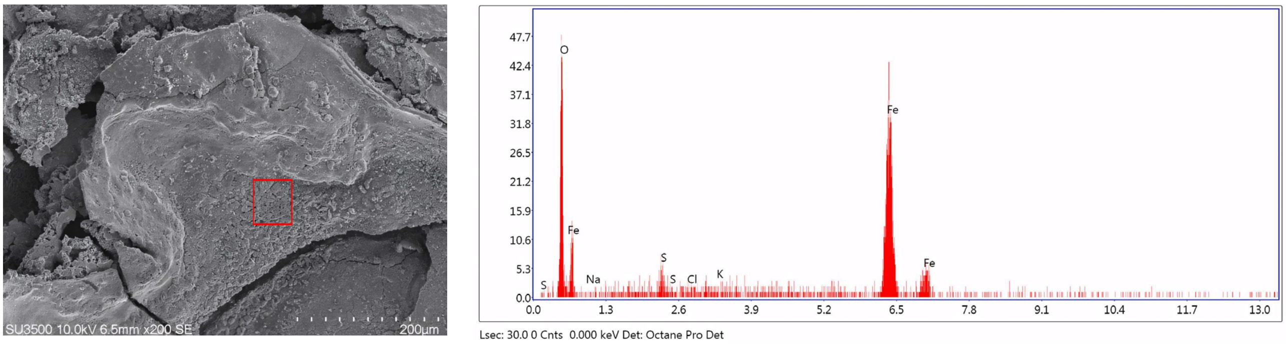
5. 5. Scanning electron microscope and energy dispersive X-ray spectroscopy examinations

Using a scanning electron microscope, the erosion and corrosion-prone sample pieces were inspected. The primary goal was to examine the corrosion surface's micromorphology close to the notch tip, as seen in Fig. 8. The SEM picture magnified 200 times revealed fine cracks in the erosion-corrosion area, with a width of approximately 50–200 µm. The direction of the cracks is not uniform. Regarding Fig. 9, the scale surface showed no cracks according to the SEM data in the non-defective area.

The elbow pipe was intended to channel water vapor and liquids with a normal pH. However, after six months of operation and measuring the gas and liquid's chemical composition, acidic fluids with a pH of 2.67–2.91, were created. The fractured pipe product depicts a sizable, naturally occurring depression as a hill. Erosion-corrosion is another term for the occurrence of big hills and valleys.

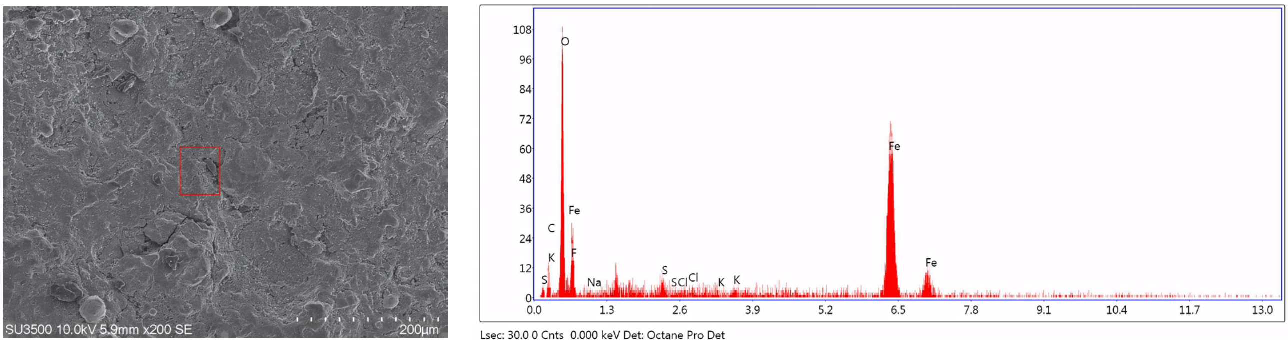
As can be observed in the SEM image, the examination was done at two specific spots, specifically in the erosion-corrosion defect area. Fig. 8, 9 display the two areas that are free of flaws together with the EDS results. SEM and EDS analysis using a mapping model revealed essentially the same chemical composition at both sites. Generally speaking, the elements that predominate are oxygen (O), iron (Fe), carbon (C), Cl, and S in that order. At both sites, the components Cl- and S are present; their presence indicates that the fluid being conveyed contains both elements. It is well known that the presence of chlorine can facilitate the occurrence of erosion and pitting corrosion. The presence of Cl- and S causes holes in the metal, which leads to erosion and corrosion attacks. Although deep, the hole's diameter is rather tiny. Erosion corrosion is the result of pitting corrosion mixed with friction between the corrosive fluid and the metal surface. Fig. 10 displays the mapping results using X-ray pictures. It displays the amounts of Na, Cl-, K, O, Fe, and S in rust that are uniformly distributed across the rust surface in the elbow pipe sample. It is known that the fluid in the elbow pipe is made up of 25 % steam and 75 % liquid geothermal energy, which powers electric generators. Renewable energy is heat energy derived from within the earth that can be replenished, and heat energy is trapped in rocks or fluid fractures beneath the surface of the earth. By using this energy, less of the increasingly scarce fossil fuels can be consumed. Hot water, two phases (brine), dry steam (superheated steam), or saturated steam can all be produced using geothermal means. In Indonesia, brine – a two-phase fluid with a liquid predominance – is the most commonly utilized geothermal source. Brine is mostly composed of 80 % NaCl solution, with additional major components including carbonate, potassium, calcium, and silica. Because there is NaCl in the fluid, erosion, and corrosion will happen more frequently.

Erosion and corrosion are accelerated by the gas and water produced by geothermal energy, which also contains sulfate (1410 mg/kg) and a rather high Cl concentration (1290 mg/kg). Given that the gas and water coming out of the well have an acidic pH range of 2.67 to 2.91, this indicates that the gas and water are aggressively attacking the inner surface of the elbow pipe, forming pitting corrosion defects and erosion-corrosion, which can lead to material failure in less than a year as opposed to the 30-year standard service life.



a *b*

Fig. 8. The results of the EDS examination on location 1 of the surface: *a* — the red mark is position 1 of the chemical composition test shooting with energy dispersive X-ray; *b* — the results of the energy dispersive X-ray examination on location 1 of the surface



a *b*

Fig. 9. The results of the EDS examination on location 2 of the surface: *a* — the red mark is position 2 of the chemical composition test shooting with energy dispersive X-ray; *b* — the results of the energy dispersive X-ray examination on location 2 of the surface

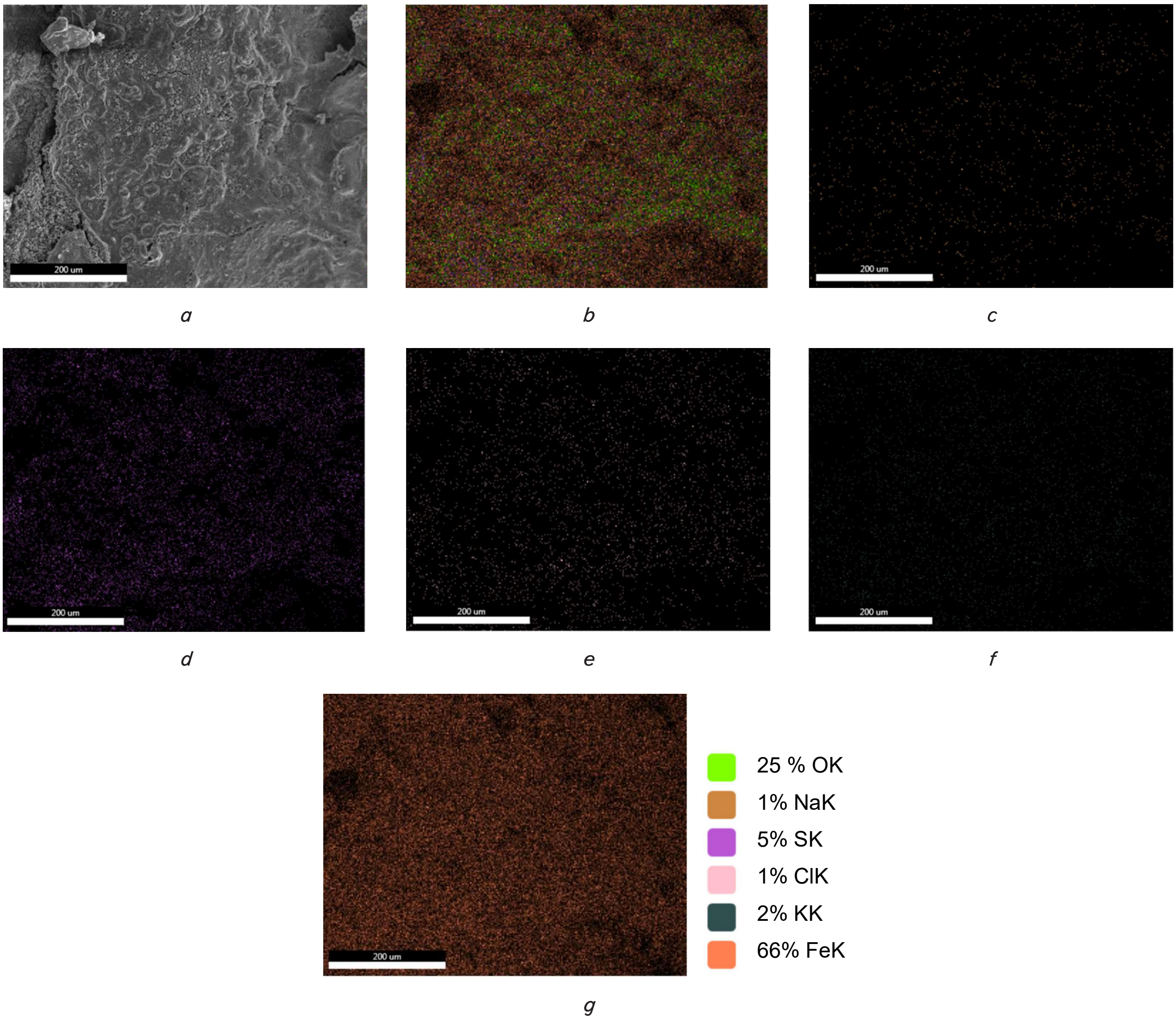


Fig. 10. Results of corrosion erosion mapping on the elbow surface using a scanning electron microscope (SEM): *a* – secondary electron image of steel; *b* – 25 % of the oxygen element's surface in a steel X-ray image; *c* – 1 % of the natrium element's surface in a steel X-ray image; *d* – 5 % of the sulfur element's surface in a steel X-ray image; *e* – 1 % of the chloride element's surface in a steel X-ray image; *f* – 2 % of the kalium element's surface in a steel X-ray image; *g* – 66 % of the ferrum element's surface in a steel X-ray image

The choice of materials is one of the most crucial elements of engineering design. According to the design, the pipe must be safe to use in the field and long-lasting example, 20 years. Mechanical and corrosion-resistant qualities are two material requirements for gas pipe elbows in geothermal power plants that must be taken into account. Low carbon steel pipe manufactured by ASTM A234 specifications is the most extensively used and well-liked elbow pipe in various industries, including oil and gas. This is because low-carbon steel pipes have consistently shown to be high-quality, safe, and dependable.

To solve the issue of inadequate corrosion resistance and internal erosion. Nevertheless, this pipe has drawbacks since it is vulnerable to erosion and corrosion attacks from substances that contain carbonate (K_2CO_3), salt water (NaCl), and sulfuric acid (H_2SO_4). In acidic geothermal fluid conditions, high-pressure ASTM A234 low-carbon steel is no longer appropriate for usage. The corrosion rate, which is 702 times faster than under neutral fluid conditions, further supports this. Therefore, it is necessary to choose the appropriate material – that is, material that is resistant to erosion and corrosion – to accomplish the service life that the designer had intended.

6. Discussion of corrosion erosion in the elbow of pressurized steam water pipe of geothermal power plant

Numerous industrial systems, including centrifugal pumps, sludge handling equipment, and piping accessories in pressurized steam water pipelines of geothermal power plants, are susceptible to corrosion erosion. This is especially true for the pressed steam water pipe of the geothermal power plant, which needs to have extraordinary mechanical and corrosion resistance due to its harsh and acidic surroundings. The fluid being cycled has a pH of 2.67–2.91, which increases the corrosion erosion rate due to the exceptionally high Cl^- of 1290 ppm. The elbow pipe experiences significant turbulence in the working fluid flow, which is correlated with the elbow pipe's high corrosion erosion experience. The elbow-shaped pipe's bend angle is probably to blame for the increased turbulence, which hastens the elbow pipe's collapse. The macroscopic image of the damaged area in Fig. 1 illustrates the typical corrosion erosion on the inner diameter of the pipe due to the presence of tubercles. In the last several years, much research has been done to increase our knowledge of how corrosion erosion interacts in these systems. Materials can degrade more quickly as a result of the intricate mechanical and electrochemical mechanisms involved in wear and corrosion processes, can be seen from the mechanical properties in Table 3, and the hardness test results in Fig. 5. Thinning occurs and the microstructure results in Fig. 6 and Fig. 7, decarburization occurs in the failed area. The damage that occurred at the pipe elbow occurred at the same position with operating conditions containing H_2S gas (123 ppm) and solid silica particles SiO_2 (1.7 ppm). From the fluid flow modeling [3], it was confirmed that the failure occurred at the same position.

When the 12" ASTM A234-2015 elbow pipe sample, intended for pressurized steam, was delivered, it displayed material rupture in the form of a straight longitudinal line. The elbow pipe had a nominal diameter of 304.8 mm and a thickness of 14.27 mm. The fracture's longitudinal shape and orientation were demonstrated by the broken pipe, and the macrostructure's results indicated that the rupture began in an already extremely thin region. This fracture is fibrous since the pipe's surface area has thinned and is no longer able to support the load. As a result, a rupture occurs in the thinnest section, indicating that the material is still ductile despite the overload, can be seen in the microstructure of Fig. 5–7. The elbow pipe's thickness is thinning, which suggests that substantial corrosion erosion has taken place. This type is more common in components where the fluid flows quickly and is acidic than in fluids that are stationary against the elbow wall's surface. Corrosion erosion rust forms on the inner surface of the elbow when the fluid runs across it and the hydrodynamic pressure drops in particular areas, allowing the fluid to escape and form bubbles. The bubbles burst with sufficient force because the mechanical impact that causes the pressure to decrease in certain areas also causes the pressure to increase in other locations. Thus, the rough surface becomes a more favorable location for the formation of new bubbles, causing the corrosion erosion process to reoccur more quickly and widely. It is evident from a visual inspection of the aforementioned image that the elbow pipe manufactured by ASTM A234-2015 is seamless. The pipe was 14.27 mm thick when it was first placed by the norm; nevertheless, corrosion erosion revealed a very sharp thinning. Except for the rupture area, where it occurs quite quickly, the uniform corrosion rate is somewhat quick.

About the usage of ASTM A234-2015 steel, specifically for boilers with steam and water fluids with a reasonably neutral pH, this elbow pipe's life is unable to attain its design life in the geothermal well field because the steam and water there are extremely acidic circumstances. The first design for installing elbow pipes for fluids was neutral, so ASTM A234-2015 material was chosen, based on conversations with field personnel who examined this case. However, in the field, the fluid changed from neutral to acidic, making the material used no longer appropriate for the environmental conditions.

The correct material must always be used for design-related operations. The final product should fulfill the requirements. Selecting the appropriate material is a critical component of engineering design. When doing design operations, some material qualities that need to be taken into account are as follows: Mechanical properties include creep, fatigue, hardness, ductility, elasticity, and strength. Physical attributes include electrical and magnetic characteristics, specific heat, density, thermal expansion, conductivity, and melting point. Chemical properties: flammability, toxicity, corrosion, and oxidation.

Formability, castability, machinability, weldability, and heat-treated hardenability are examples of manufacturing properties.

If a material is chosen incorrectly, the following outcomes may occur: Components that are either harmful to use or cannot function at all; Components that can function but have a short service life (not in line with the intended service life), and Components that exhibit anomalies. The most popular and extensively utilized type of pipe in industry, including the oil and gas sector, is carbon steel pipe, ASTM A234-2015. This is so because detailed information about the dependability of low-carbon steel pipes already exists, together with design guidelines in the form of standards and norms.

Low-carbon steel pipes can also solve the issue of having a poor level of internal and external corrosion resistance. especially by including a coating of anti-corrosion. For everything about pipes, low-carbon steel pipes are therefore quite effective. Out of all the steel pipe types, this one is also the least expensive. This pipe is very durable, weldable, ductile, and strong. Its vulnerability to corrosion attacks from sulfuric acid (H_2SO_4), carbonate (K_2CO_3), and seawater (NaCl) is what makes it weak. This can be seen from the results of the examination using a scanning electron microscope and X-ray mapping in the corrosion area, where a number of Na, Cl-, K, O, and S were found in Fig. 8–10. This kind of pipe is typically utilized in utility sections, such as those with steam generators, water treatment units, power plants, condensate treatment units, and some processing facilities that need specific coatings to prevent corrosion.

Due to the occurrence of corrosion-erosion damage in this case, as we all know. Caused by turbulence that causes high friction on the elbow pipe wall associated with high fluid corrosivity (pH; 2.67–2.91) and the presence of solid particles [3], then the mitigation that can be done is to enlarge the elbow radius to reduce friction, reduce corrosivity by applying the use of inhibitors, in addition to trying to filter the flowing fluid to reduce the solid particle content. Other efforts if it is not possible for the above efforts, then it can be considered to update the material. Elbow pipe failure can be avoided by implementing daily predictive maintenance procedures. This can be achieved by giving employees access to a daily check sheet, which they must fill out and execute with precision. The tasks include monitoring temperature, vibration, noise, dirt, cleaning, calibration, and running operation tests on all components. Every morning during the daily meeting, the results are presented. periodic preventative maintenance should be carried out by NDT, replacement of malfunctioning spare components, and ongoing periodic overhaul. It is necessary to put all standard operating procedures into place and to regularly update them as new techniques are discovered. A quality control group must be run by each department to stop elbow pipe problems from happening again.

Since the elbow pipe failed on a field scale, the limitation of this study is to see in detail the mechanism of erosion corrosion. To find out in detail, it is necessary to conduct laboratory-scale research that is similar to field conditions. This can predict when the elbow pipe will thin and break by extrapolating from simulation conditions in the laboratory.

7. Conclusions

1. Both macroscopic and visual investigations indicate that the fracture location starts in an already extremely thin region. It was discovered that the mechanism of surface area thinning and severe load on the thinnest surface caused a fibrous fracture to occur in that location. This is because severe erosion and corrosion thin the material and cause it to fracture under high loads. Reddish brown deposits were discovered in the core of the pipe elbow and gray deposits on the inner surface in the shape of grouped tubercles. This thinning results from hydrostatic pressure instability in specific pipe elbow segments caused by high-speed fluid flow. Hydrostatic pressure will cause bubbles to form on the elbow's surface, causing corrosion erosion.
2. The tensile test results on the two specimens with rolling direction are 476 MPa and 483 MPa. The ASTM A234 standard states that the tensile strength (TS) is 416 MPa (min), the yield strength is 426 MPa and 435 MPa, the elongation is 46.2 % and 44.4 %, and the extension (El) is 30 % (min). All of the tensile test results show values that comply with the ASTM A234-2015 standard. These outcomes may increase the pipe material's toughness.
3. In the hardness test, the ferrite pearlite area still had a hardness of 230 HV, but the decarburization structure area had a relatively low hardness, particularly along the fracture edge at 147 HV. The hardness is now nearly 1.6 times lower. These results suggest that similar changes in the microstructure have an impact on the hardness outcomes. For an extended duration, the absence of fluid thermal impact will mostly preserve the microstructure. Because of the material's altered microstructure corrosion-erosion, corrosion-erosion will occur more quickly, causing the pipe to fail.
4. The metallographic results in the area of the broken end pipe (edge), the pearlite composition is lower and the ferrite grains are larger than the normal area, decomposition occurs due to prolonged heat exposure and interaction with the surrounding environment so that it has a relatively softer hardness compared to the normal area. A significant amount of deformation structure was also found, this also shows that the elbow pipe has a fairly strong erosion mechanism.
5. Through the use of scanning electron microscopy, the erosion-corrosion-prone sample section revealed small, non-uniform cracks that ranged in width from 50 to 200 μm. Together with the EDS data, scanning electron microscopy analysis revealed two areas free of flaws. The mapping model's use of SEM and EDS data showed that the chemical composition of the two places was nearly identical. Generally speaking, the elements that predominated were oxygen (O), iron (Fe), carbon (C), sulfur (S), and chlorine (Cl). Cl- and S components were found at both sites, indicating that both elements were present in the fluid being channeled. Chlorine has a documented ability to promote erosion and pitting corrosion. Holes are created in the metal by the presence of Cl- and S, which promote erosion and corrosion attacks. The holes are deep, but their diameters are not very large. Pitting corrosion and friction between the corrosive fluid and the metal surface combine to produce corrosion-erosion.

Conflict of interest

The authors declare that they have no conflict of interest about this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data cannot be made available for reasons disclosed in the data availability statement.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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