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FAILURE ANALYSIS OF PIPES IN A CONSTRUCTION

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ABSTRACT

The high working pressure, temperature, and corrosivity of the fluid flowing in the pipe cause problems in pipe failure in operation. The purpose of the analysis is to obtain information related to working conditions at pressure, temperature, and fluid corrosivity, causes of failure, initial cracking of materials, and types of materials used in a construction. The analysis method includes tracing the results of previous pipe research, studying mechanical properties, composition, hardness, stress concentration, fluid corrosivity, heat treatment, comparison between results, discussion and conclusions. Application of pipe analysis in a construction of production facilities, and factories. The conclusions obtained include: rupture of coal boiler pipes at 1100°C, tensile strength of 48.2 MPa with fluid at 730°C; dezincification and deposits with sulfur content of ~0.60 wt%, and Cl ~9.45 wt% which are corrosive; exposure to hydrogen sulfide concentrations up to 1000 ppm, the presence of localized pitting corrosion due to chloride attack up to 88 °C; erosion rate of 26.77 mm/year and corrosion rate of 1.107 mm/year causing thinning of the elbow wall of 20# steel pipe, diameter 600 mm, thickness 10 mm; working pressure of diesel engine fuel pipe at 637.5 MPa or 63.8 Bar; and so on.

Keywords : *boiler, corrotion, hardness, mechanical properties, pipe.*

1. Introduction

Failure of many pipes of a construction can be caused by various reasons and conditions. Failure of a component can be detrimental and dangerous to the factory or production system, therefore efforts to anticipate and eliminate failures from occurring are very important steps for the success of a production. Failure analysis of pipes is carried out on several previous research results to obtain information about the use of pipes, causes of failure, initial location of failure, and types of materials that fail in the operation of a production.

Previous research results that focus on failure analysis of various pipes are obtained from: the use of pipes including for boilers, for line ducting, for oil refineries, ammonia plants, water pipes, petrochemical plants, methyl ethyl carbonate pipes, crude oil pipes, oil and gas industry, gas wells, LPG desulfurization units, oil and natural gas industry discharge pipes, chemical reaction plant units, diesel engine fuel pipes, reheat furnace pipes, hot fluid transport pipes in solar thermal power plants, aluminum cooling pipes, and metal hydraulic pipes for aircraft.

Previous research results focusing on the causes of failure in various pipes were obtained due to the following reasons: material strength, cracks, creep, corrosion, erosion, brittleness /hardness of the material, stress concentration, stress corrosion cracking, fatigue life, incorrect heat treatment, high temperature, high working pressure, miscommunication, and earthquakes.

2. Literature Review

The average hardness of superheater tube material made of low carbon steel (C=0.148%, SA213 T22) in the area away from the fracture is 200 HB (ASTM A213/A213M) at C=0.15-0.2%, and the hardness near the fracture is 166-167 HB [1]. Superheater elbow tubes made of ASTM A213 T11 material lined with SS304 for boilers operate at 380-480°C, which in reality can exceed 500°C and are at risk of sensitization due to chromium carbide (Cr23C6) in stainless steel 500-900°C which erodes the tube and can cause corrosion [2]. Supercritical boiler pipes made of MG16T10-2 material damaged in the middle wall area have a hardness of 286 HV which is greater than the intact pipe (SA213-TP347H) in the middle wall area which has a hardness of 157 HV which causes fishmouth cracks [3]. The boiler superheater tube pipe made of ASTM A213 T11 material was damaged in 2 parts: part 1 was still intact with a grain diameter of 21.3 μm at 600°C, part 2 was torn with a grain diameter of 23.6 μm at 700°C, and part 3 was extensively torn with a grain diameter of 30.8 μm at 750°C [4]. Water wall tube made of GB 3087-10/SA-192 material in coal boilers operating at 1100°C, its strength is 48.2 MPa with fluid at 730°C exceeds the limit of pipes capable of working with fluid at 550°C with a strength of 12.7 MPa [5]. Steel superheater boiler pipe near the crack zone shows a hardness of 123-130 HV which is lower than ASTM A213 T12 with a hardness of 170 HV due to excess heat as a material-eroding chromium carbide forming [6]. The boiler pipe area on the riser wall tube made of broken steel has a hardness of 179.2 HB which is greater than ASTM A210 A1 worth 143 HB which becomes brittle due to excessive heat [7]. The water tube wall made of ASTM A210 C material for the ruptured boiler had a hardness of 162.5 HV, which was greater than the uninstalled tube which had a hardness of 158 HV [8]. The hardness of the outer wall of the boiler pipe made of SA 210 C material is 200 VHN and the inside of the pipe is 125 VHN, which causes oxidation to increase its hardness [9]. Heat exchanger tubes made of SA 179 material for boilers have pink deposits inside the tube with high copper content and low zinc content, indicating dezincification and deposits nearby with S content of ~0.60 wt%, and Cl ~9.45 wt% as corrosive attacks near the holes [10].

The dust cleaning pipe made of SS400 material broke, due to the accumulation of solid material in the pipe and a decrease in the strength of the material due to corrosion which thinned the pipe wall by up to 70% from 6 mm to 0.8 mm which resulted in a hole [11]. A 20” diameter pipe made of API 5L Grade X52 Standard material, 399 m long, was damaged and broken due to being hit and dragged by a ship's anchor, due to a failure in communication between the ship's guide (speaking English) and the ship's captain (speaking Chinese) located in Balikpapan Bay, on the pipeline between the Lawe-lawe Terminal to the Balikpapan Pertamina Refinery [12]. Welded joints on ASTM A106 pipe-ASTM A105 flange in the steam line of an ammonia plant cracked at 148°C and 7 Bar pressure, due to the average grain size in the coarse grain heat affected zone (CGHAZ) of 36 μm, and the finer grain heat-affected zone (FGHAZ) of 17 μm [13]. Pipes made of ASTM A106 Grade B material are used in boiler feed water pipes, with an average hardness value of 138 HV > the minimum standard value of 130 HV, causing leaks starting at the end of the inhibitor pipe, due to the very high oxygen content of 38.28% (wt) as oxygen concentration cell corrosion [14]. During the 1999 Kocaeli earthquake, the seismic behavior of a 2200 mm welded steel pipe near the Kullar surface fault intersection in Izmit, Kocaeli, experienced a small leak due to the right lateral fault movement of 3.0 m causing local bending and wrinkling of the pipe when crossing the 55° angle fault line [15]. The wall hardness of a boiler tube at a petrochemical plant made of DIN 7175-79 material that broke changed from 73.5 HR_B to 94.5 HR_B and also the area closest to the rupture of the failed tube became the hardest [16]. The deposition of compounds ($CaSO_4$) and corrosion products (Fe_2O_3) formed on the inside of the SA-210 Grade C boiler water-wall tube causes local heat transfer to decrease, resulting in overheating and local softening which thins the wall and eventually causes holes [17]. Pipe cracking becomes leaking at a tensile strength of 730 MPa, a yield strength of 249 MPa, and a ductility of 55%, while the tensile strength and yield strength of SS 30408 material are 520 and 205 MPa, so that its ductility is 35% lower than the standard which causes the pipe to crack and methyl ethyl carbonate liquid to leak [18]. The main cause of leaks in API 5L Grade B pipes for underground crude oil transfer pipes is due to corrosion under deposits (under deposit corrosion/UDC) due to high levels of dissolved oxygen in water which forms corrosive deposits in the form of high concentrations of chloride ions which enter through the gaps in the deposits and significantly accelerate the corrosion rate underneath [19]. An 8.9 cm diameter water pipe made of API 5L, Grade B material damaged during full operation in the oil and gas industry at temperatures between 49 and 88 °C and exposed to hydrogen sulfide (H2S) concentrations of 350-1000 ppm, showed highly localized pitting corrosion due to chloride attack [20].

Elbow pipes made of ASTM A234 WPB steel in gas wells that are passed through by water with a pressure of 4 kg/cm² at 10-30 °C, contain CO_2 in the water which causes corrosion in the welding area due to galvanic coupling between the weld and the steel pipe, resulting in holes and water leaks [21]. The 20# steel pipe elbow, 600 mm, 10 mm thick, and the ratio of length to diameter of the elbow is 1.5, is supplied with LPG through an LPG desulfurization unit with a maximum erosion rate of 26.77 mm/year and a maximum corrosion rate of 1.11 mm/year, causing the thinning of the leaking wall [22]. Industrial discharge hopper pipe made of SS 316 cracked due to stress corrosion cracking (SCC) due to the presence of Cl levels on the outer surface of the hopper pipe which meets oxygen to form chloride, the main source of SCC as the starting point for cracks [23]. In the boiler pipe-flange connection of ASTM A105 failed, due to a pressure surge of 163 Bar and a temperature of 350°C, which exceeded the normal at 27.2 Bar, 308°C, and the presence of weld misalignment defects on the inner surface, 4 mm long, slag inclusions, porosity, and lack of fusion between the weld layers, there were beachmarks indicating fatigue fractures that started from weld defects in the area of high stress concentration that propagated, and finally broke [24]. The ASTM A351 HK-40 pipe in the reaction plant unit flows fluids with high sulfide content which causes accelerated sulfide corrosion at 600oC and leaks that form in the pipe due to erosion of the fluid flow from a mixture of liquid, gas and solids [25].

The crack in a high-pressure fuel pipe with a tensile strength of 850 MPa for a diesel engine was fatigue fractured at the interface between the head and body of the pipe starting from the outer area and propagating inward through 18 test specimens at pressures of 637.5, 595, 552.5, 510, 485, and 467.5 MPa until the specimen cracked, obtaining the fatigue life of 6 pressure levels with a loading frequency of 10 Hz and a pressure ratio of -1 [26]. The slide pipe on the walking beam type reheating furnace from JIS G 3445 Grade STKM 13A cracked and its walls became thinner by up to 47% from the original 25 mm caused by the high levels of Fe oxide-corrosive in the form of wustite (FeO), as well as the elements Ca, Mg, and Si which form crusts causing excessive heat, supported by high water hardness (82.02 mg/liter), which is very aggressive-corrosive, increasing the creep rate and ultimately causing leaks and bulges [27]. AISI 321 SS pipe used in solar power plant to convey hot fluid containing Cl ions at ~400 °C leaked, due to incorrect post-weld heat treatment for laser beam welding (LBW), metal inert gas welding (MIG), and spot welding, it was revealed that leakage occurred near the spot weld joint due to SCC, because the weld had residual stress beyond the threshold limit of early crack formation due to Cl ions [28]. During normal cooling operation, the aluminum chiller pipe (AA6061-T4) operated at -3.9°C and a pressure of 0.103 MPa, with the temperature increasing up to 10°C during the defrost cycle. The pipe had operated 5700 thermal cycles before the explosion, indicating that the fracture was due to fatigue [29]. When a metal hydraulic pipe sleeve for an aircraft was removed, the location of stress concentration in the form of a circular groove with a depth of 35±7 μm, and a radius of 76±2 μm caused the initial crack at the end of the pipe near the metal sleeve that was circular in the groove [30].

The processed results from the analysis of previous research results were obtained as follows: The hardness of the broken superheater tube is 17% lower than the standard and the carbon content is also 0.5% lower than ASTM A213/A213M [1]; The temperature increase can exceed 20°C, so that sensitization is possible in the range of 500-900°C [2]; An increase in hardness of 82.17% causes fishmouth cracks in supercritical boiler pipes because the pipe material becomes brittle [3]; A temperature increase of 150°C is too great, causing the boiler tube to expand by up to 44.6%, which results in the pipe cracking and breaking [4]; A 180°C increase in fluid temperature increases the tube stress by 279.5%, causing tube rupture [5]; The steel material of the superheater boiler pipe softened by 27.65% due to excessive heat causing the formation of chromium carbides which erode the pipe material [6]; The increase in hardness in the fracture area is 25.3% exceeding the ASTM A210 Grade A-1 limit which makes the pipe brittle [7]; The increase in hardness of the boiler water wall tube by 2.84% makes the material more brittle [8]; An increase in the hardness of the outer wall of the boiler pipe by 60% causes the rupture of the water pipe wall [9]; Dezincification attacks cause boiler heat exchanger tubes to become perforated and leak [10; There was no maintenance access in the initial pipe design for routine inspection and cleaning, so maintenance could not be carried out [11]; Communication must use the same language to avoid misunderstandings between the guide and the ship's captain when parking above the 399 m long API 5L Grade X52 Standard pipe area embedded in the seabed [12];

The coarsening of the average grain size in the CGHAZ was 52.8% to 36 μm compared to the fine-grained heat-affected zone which was finer with an average grain size of 17 μm, resulting in low strength causing cracks and fractures in the welded joints between ASTM A106 pipes and ASTM A105 flanges in the steam line of an ammonia plant [13]; The oxygen content of 38.28% in the corrosion product/crust acts as the anodic of the electrochemical cell, the corrosion of which is massively accelerated, and the surrounding area which is rich in oxygen becomes cathodic, so that a galvanic pair is formed which causes a deep depression (gouging) measuring 480 mm x 140 mm, thinning occurs which ultimately results in leakage [14]; A 2200 mm welded steel pipe was damaged during the Kocaeli earthquake whose fixed end condition had higher strain, ~20% and tighter wrinkles, 16.5 m, while its free end had reduced strain and increased distance of 21.0 m whose stress was 10-20% exceeding the standard limit of 0.33-2% as evidence of the cause of leakage [15]; The increase in the hardness of the boiler tube walls made of DIN 17175-79 material by 22.22% causes the material to become brittle and break apart [16]; $CaSO_4$ and Fe_2O_3 deposits on the inner walls of the boiler water-wall tube cause local heat transfer to decrease, resulting in softening which thins the pipe and eventually causes holes [17];

The toughness of SS 30408 pipe is lower than 35% which causes the pipe to crack and methyl ethyl carbonate liquid to leak [18]; Leakage of API 5L Grade B pipes for crude oil, due to corrosive deposits in the form of high concentrations of chloride ions with dissolved oxygen in the water entering through the deposit gaps and accelerating the corrosion rate [19]; The 8.9 cm diameter water pipe made of API 5L, Grade B material is thinning, due to exposure to hydrogen sulfide (H2S) concentrations of 350-1000 ppm which results in the wall segments becoming thin and leaking [20]; Elbow pipes made of ASTM A234 WPB steel in gas wells passing through water with a pressure of 4 kg/cm² at 10-30 °C, contain corrosive CO_2 in the weld area and steel pipe, so that the pipe wall becomes thin, becomes perforated and water leaks occur [21]; The elbow of 20# steel pipe, 600 mm, 10 mm thick, and the ratio of length to diameter of the elbow is 1.5, is flowed with LPG with a maximum erosion rate of 26.77 mm/year and a maximum corrosion rate of 1.11 mm/year, causing the wall to thin and leak [22]; SS 316 hopper pipes crack in the oil and natural gas industry, causing SCC due to the presence of Cl levels on the outer surface of the hopper pipe combining with oxygen to form chloride as the initial crack [23]; racture of ASTM A105 steam boiler pipe-flange joints, due to pressure spikes of 83.3% to 163 Bar and 12% temperature to 350°C, and the presence of weld defects on the inner surface, slag inclusions, porosity, and lack of fusion between weld layers, and beachmarks are indications of fatigue fractures that originate from weld defects that propagate due to stress fluctuations, and eventually fracture [24];

The ASTM A351 HK-40 pipe in the reaction plant unit flows fluids with high sulfide content which causes accelerated sulfide corrosion due to operation at 600oC and leaks formed in the pipe due to erosion of the mixed fluid flow of liquid, gas and solids [25]; Fracture of high-pressure fuel pipe at the interface between the head and the pipe body through 18 test specimens at pressures of 637.5, 595, 552.5, 510, 485, and 467.5 MPa until the specimen cracked, the fatigue life of 6 pressure levels was obtained with a loading frequency of 10 Hz and a pressure ratio of -1 [26]; The JIS G 3445 Grade STKM 13A slide pipe cracked and its walls became 47% thinner due to the corrosive Fe oxide content in the form of wustite (FeO), as well as the Ca, Mg and Si elements which form crusts which cause excessive heat, supported by high water hardness (82.02 mg/liter), which is very corrosive, increases the creep rate and ultimately causes leaks and bulges

[27]; AISI 321 SS pipe in solar power plant carrying hot fluid containing Cl ion at ~400 °C leaked, due to incorrect post-weld heat treatment for LBW, MIG, and spot welding, it was revealed that leakage occurred near the spot weld joint due to SCC, because the weld had residual stress exceeding the threshold limit for early crack formation [28]; During normal cooling operation, the aluminum chiller pipe (AA6061-T4) operated at -3.9°C and a pressure of 0.103 MPa, with the temperature increasing to 10°C during the defrost cycle, the pipe had operated 5700 thermal cycles before the explosion, indicating that the pipe fracture was due to fatigue [29]; and The presence of circular grooves in metal hydraulic pipes for aircraft causes initial cracking of the pipe near the sleeve [30].

3. Research Methods

The analysis method used is to trace the results of previous pipe failure analysis, study the mechanical properties, composition, brittleness/hardness, stress concentration, stress corrosion cracking, cracks, fluid corrosivity, corrosion, erosion, creep, fatigue life, heat treatment, comparison between results, discussion and drawing conclusions.

4. Results and Discussions

The results of the analysis of various pipe failures that have been used by previous researchers in various applications are summarized in Table 1 for the application, cause of failure, initial crack location, and pipe material.

Table 1 - Application, failure causes, crack initiation locations, and pipe materials

No.	Pipe Application	Cause of Failures	Location of crack initiation	Pipe Material
[1]	Superheater boiler pipe of Teluk Sirih steam power plant (PLTU)	Due to the hardness lower than standard (200HB) ~17%	On the elbow of the pipe with diameter of 63.5 mm	SA213 T22
[2]	Superheater tube boiler of steam power plant PT. X	Pitting corrosion on the external side	On the pipe elbow with SS coating 1.6 mm and total thickness 7.1 mm	ASTM A213 T11 coated with SS304
[3]	Superheater pipe in a supercritical boiler of PT. Bhimasena Power Indonesia steam power plant	Fish-mouth cracking due to the overheating, leading to the hardness increase of 82.17% which causing the material to be brittle	MG16-T10 pipe of the final superheater area with internal diameter 31 mm	SA213-T91
[4]	Superheater tube boiler steam power plant	Creep void combined with higher temperature than 750°C	Alongside the pipe	ASTM A213 T11
[5]	Water Wall Tube in Coal Boiler PT Ecogreen Oleochemicals Batam	Coal boiler pipe rupture due to operation at 1100°C, strength 48.2 MPa with fluid at 730°C	Tube damage begins due to overheating in the boiler furnace due to a decrease in fluid flow rate, and the function of the water level control instrument in the steam drum is inaccurate	GB 3087-10/SA-192
[6]	Superheater boiler pipe in palm factory	Due to lower hardness nearby the fractured zone (123-130 HV) due to overheating	Bottom left of cross-section	A213 T12
[7]	Riser wall tube no. 3 in Boiler Unit 2	Due to hardness value that exceeded ASTM A210 A1 standard by 25.3% which indicates overexposure to heat	Fractured section near mid-span of riser tube	ASTM A210 A1
[8]	Water wall Tube inside a Steam Boiler	Due to 2.84% value increase of the failed tubes's hardness which causes possible changes brittleness	around welded area of the pipe elbow	SA 210 C
[9]	Waterwall Tube Boiler at 65MW	Due to increased hardness of 60% by outer oxide layer from corrosion,	External surface of the outer tube wall	SA 210 C

	steam power plant	indicating embrittlement		
[10]	Tube Boiler	Dezincification and deposits near the hole contain sulfur content of ~0.60 wt%, and Cl ~9.45 wt% which is corrosive	At the internal surface of the inner tubes	Outer tube (SA 179 steel) and inner tubes (Al-brass)
[11]	Liquid fertilizer NPK-1 PT Pusri Palembang	Accumulation of solid materials in the pipe and reduction in material strength due to corrosion which thins the pipe walls by up to 70% from 6 mm to 0.8 mm which is perforated	Line ducting 1N-D212 (cooler cyclone) to 1N-D214 (cooler pool scrubber) NPK-1 factory	SA 210 C
[12]	In Balikpapan Bay, on the pipeline between the Lawe-lawe Terminal to the Balikpapan Pertamina Refinery	Miscommunication between the ship's guide (using English) and the ship's captain (using Chinese) resulted in the 399 m long API 5L Grade X52 pipe getting caught on the ship's anchor	In Balikpapan bay, on the pipeline between the Lawe-lawe Terminal to the Balikpapan Pertamina Refinery	API 5L Grade X52
[13]	Steam pipeline welded joint in an ammonia plant	Due to sharp internal corner angles (30°) which are stress risers	Initiated from the weld root on internal surface of pipe	ASTM A106 (pipe) and ASTM A105 90 (flange)
[14]	Boiler feed water pipe	Very high oxygen content 38.28% (wt) as oxygen concentration cell corrosion	At the inhibitor pipe end	ASTM A106 Grade B
[15]	2200 mm diameter welded steel water pipe near Kullar surface fault intersection in Izmit, Kocaeli	During the 1999 Kocaeli earthquake, the seismic behavior of 2200 mm welded steel pipes near the Kullar surface fault intersection in Izmit, Kocaeli	In the area of local wrinkles and bends in the pipe when crossing the fault line at a 55° angle during right lateral fault/plate movement as far as 3.0 m	API Grade B steel
[16]	At a petrochemical plant	Increased hardness of boiler tube walls from DIN 7175-79 material from 73.5 HR_B to 94.5 HR_B	The damaged tube started at a distance of 4 m below the roof of the combustion chamber	Steel grade ST.45.8
[17]	Boiler water-wall tube	The deposition of compounds ($CaSO_4$) and corrosion products (Fe_2O_3) that form on the inside of the boiler water-wall tube causes local heat transfer to decrease, resulting in excessive heat and local softening that thins the tube wall and eventually causes holes	The initial location of the leak was on the fire side of the main burner near the steam boiler	SA-210 Grade C
[18]	Pipe cracking for methyl ethyl carbonate (noncorrosive for metals)	The toughness that occurs is greater than 35% of the standard which causes the pipe to crack and methyl ethyl carbonate liquid to leak, while the toughness that occurs is at 55%	Pipe cracks initiated at 2 locations in the base metal and 1 location in the base metal next to the weld	S30408
[19]	Underground crude oil transfer pipe	Under deposit corrosion due to high levels of dissolved oxygen in water forming corrosive deposits in the form of high concentrations of chloride ions which enter through the deposit gaps and accelerate the corrosion rate	The crack started from a gap under the sediment on the inside of the pipe	API 5L **Grade B** carbon steel
[20]	Oil and gas industry	Exposure to hydrogen sulfide (H_2S) concentrations of 350-1000 ppm, indicates the presence of highly localized pitting corrosion due to chloride attack at temperatures between 49 and 88 °C	The initial crack occurred in the water outlet pipe of the oil-water-gas separator	API 5L, Grade B
[21]	Gas well	Water leakage through the gas well elbow pipe with a pressure of 4 kg/cm² at 10-30 °C, there is CO_2 in the water	45° angle gas well elbow pipe	ASTM A234 WPB

		causing corrosion in the welding area due to galvanic coupling between the weld and the steel pipe		
[22]	LPG Desulfurization Unit	The maximum erosion rate of 26.77 mm/year and the maximum corrosion rate of 1.107 mm/year caused the thinning of the elbow wall of 20# steel pipe, diameter 600 mm, thickness 10 mm, and the ratio of length to diameter of the elbow is 1.5	The initial hole occurred at the elbow next to the outside wall	Steel 20#
[23]	Industrial discharge hopper pipe of an oil and natural gas	Stress corrosion (SCC) is the presence of Cl levels on the outer surface of the hopper pipe which comes into contact with oxygen	Initial cracking occurred in the hopper in the area after the flange	SS 316
[24]	Boiler pipe-flange welding	Pressure surge of 163 Bar and temperature of 350°C, which exceeds the normal (27.2 Bar, 308°C) at the boiler pipe-flange weld and the presence of 4 mm weld misalignment defects, slag inclusions, porosity, and lack of fusion between weld layers, and the presence of beachmarks	Crack initiation originates from weld defects in areas of high stress concentration that propagate due to stress fluctuations	ASTM A105
[25]	Reaction plant unit	Accelerated corrosion of sulfide-containing fluids occurs at temperatures of 600°C and erosion of fluid flows from liquids, gases and solids	Initial crack at the bottom of the longitudinal pipe of ASTM A351 HK-40	ASTM A351 HK-40
[26]	Diesel engine fuel pipe	Diesel engine fuel pipe vibrations are represented by 18 test specimens at 6 pressure levels of 637.5, 595, 552.5, 510, 485, and 467.5 MPa until the specimen cracks at a loading frequency of 10 Hz and a pressure ratio of -1	The initial crack occurred at the end of the pipe right in the middle of the collar thread	The high-pressure fuel pipe with reinforced steel with tensile strength 850 MPa
[27]	Reheating furnace	Thinning of the pipe wall by up to 47% from the original 25 mm due to high levels of corrosive Fe oxide in the form of wustite (FeO), and the elements Ca, Mg, and Si which form crust causing excessive heat, high water hardness (82.02 mg/liter) which is very aggressive and corrosive	The initial crack started from inside towards the outside pipe	JIS G 3445 Grade STKM 13A
[28]	Transport of hot fluids containing chlorine in solar thermal power plants	Incorrect post-weld heat treatment for laser beam welding (LBW), metal inert gas welding (MIG), and spot welding, Cl ion levels at ~400 °C, and residual stresses beyond the threshold limits are causes of SCC	Initial cracking occurs in the weld area	SS AISI 321
[29]	Aluminum chiller pipe	Fatigue life was achieved at 5700 thermal cycles before explosion, which was normally operated at a temperature of -3.9°C and a pressure of about 0.103 MPa, with the temperature increasing up to 10°C during the melting cycle	Initial cracks occur in the weld area due to excessive load	AA6061-T4
[30]	Metal hydraulic pipes for aircraft	The presence of stress concentration from the circular groove near the metal hydraulic pipe sleeve for aircraft as an initial crack with a depth of 35±7 µm, and a radius of 76±2 µm	Initial crack in the circular groove near the metal hydraulic pipe sleeve	Ni-Al-Si alpha-brass alloy, UNS C69100

The use of pipes includes: boilers [1], [2], [3], [4], [6], [7], [8], [9], [10], [14], [17], [24], line ducting [11], oil refineries [12], ammonia plants [13], water pipes [15], petrochemical plants [16], methyl ethyl carbonate [18], crude oil [19], oil and gas industry [20], gas wells [21], LPG desulfurization units [22], oil and natural gas industry discharge pipes [23], chemical reaction plant units [25], diesel engines [26], reheat furnaces [27], hot fluid transportation in solar thermal power plants [28], aluminum cooling [29], and metal hydraulic pipes for aircraft [30].

The largest use group is for boilers [1], [2], [3], [4], [6], [7], [8], [9], [10], [14], [17], [24], followed by use for other specific uses including: NPK liquid fertilizer [11], oil refineries [12], ammonia plants [13], water pipes [15], petrochemical plants [16], methyl ethyl carbonate [18], crude oil [19], oil and gas industry [20], gas wells [21], LPG desulfurization units [22], oil and natural gas industry discharge pipes [23], chemical reaction plant units [25], diesel engines [26], reheat furnaces [27], transportation of hot fluids containing chlorine in solar thermal power plants [28], aluminum cooling pipes [29], and metal hydraulic pipes for aircraft [30].

The majority of pipe usage is related to corrosive and hot and pressurized materials. The highest corrosivity is achieved for deposits near holes with sulfur content of ~0.60 wt%, and Cl ~9.45 wt% [10], the highest temperature is achieved for boiler tube rupture due to operation at 1100°C [5], and the highest pressure in fuel pipes is achieved for diesel engines of 63.8 Bar [26].

Pipes are used for the flow of chemical materials such as liquid fertilizers [11], ammonia [13], petrochemicals [16], gas wells [21], LPG desulfurization units [22], oil and natural gas industry discharge pipes [23], chemical reaction plant units [25], reheat furnaces [27], and the transportation of hot fluids containing chlorine in solar thermal power plants [28], while relatively non-corrosive uses are in oil refineries [12], water pipes [15], methyl ethyl carbonate [18], crude oil [19], the oil and gas industry [20], diesel engines [26], aluminum coolant pipes [29], and metal hydraulic pipes for aircraft [30].

5. Conclusion

The conclusions that can be drawn from the discussion include:

1) The rupture of coal boiler pipes at 1100°C, tensile strength of 48.2 MPa with fluid at 730°C; dezincification and deposits with sulfur content of ~0.60 wt%, and Cl ~9.45 wt% which are corrosive; exposure to hydrogen sulfide concentrations up to 1000 ppm, the presence of localized pitting corrosion due to chloride attack up to 88 °C; erosion rate of 26.77 mm/year and corrosion rate of 1.107 mm/year causing thinning of the elbow wall of 20# steel pipe, diameter 600 mm, thickness 10 mm; working pressure of diesel engine fuel pipe at 637.5 MPa or 63.8 Bar; and
2) Other pipes of a construction that broke during operation are shown in Table 1.

Follow-up suggestions for the conclusions include:

a) The standard value provisions must be attempted to be maintained in operating conditions with periodic checks to anticipate that the working pipe does not experience failure, the level of corrosive elements should be controlled as much as possible, so that it does not exceed the threshold value of the standard, the selection of component materials or spare parts should be chosen as much as possible in accordance with the recommended standards,
b) The occurrence of pipe failure due to miscommunication in areas where pipe installations are installed on the seabed must be given buoy instructions and signs in easy-to-understand language or can contact the contact person from the authorized company in the seabed pipe area.

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