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METALLURGICAL EXAMINATION AND LIFE TIME ASSESMENT OF HIGH PRESSURE STEAM PIPES OF A PALM OIL PROCESSING PLANT

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Intisari

Pipa baja sering digunakan untuk menyalurkan uap bertekanan tinggi dari sebuah ketel uap menuju ke unit turbin uap atau ke unit produksi lainnya. Tulisan ini menyajikan penelitian metalurgi yang dilakukan pada sejumlah pipa uap bertekanan tinggi pada sebuah pabrik yang baru dibangun untuk menyalurkan uap bertekanan tinggi dari sebuah ketel uap menuju ke pabrik pengolahan minyak ke-lapa sawit. Tujuannya adalah untuk memastikan bahwa keterpaduan material pipa uap memiliki kesesuaian dengan spesifikasi dan kehandalan yang diinginkan. Disamping itu, tujuannya juga ada-lah untuk memperkirakan umur layan pipa uap tersebut. Pengujian metalurgi dilakukan dengan mempersiapkan sejumlah benda uji yang diambil dari tiga potongan pipa uap yang diterima, yaitu meliputi : analisa kimia, uji metalografi dan uji kekerasan serta uji tarik pada suhu 300 °C. Disamping itu, analisa umur juga dibuat menggunakan persamaan yang diambil dari ASME Boiler dan BPVC (*pressure vessel code*) dan dari data standar API 530. Hasil pengujian metalurgi yang diperoleh menun-jukkan bahwa pipa uap bertekanan tinggi yang dibuat dari material ASTM A-106 Gr. B seluruhnya dalam kondisi baik, baik dari segi struktur mikro maupun dari segi sifat mekanis. Hasil pengujian juga menunjukkan bahwa pada struktur mikro tidak diketemukan adanya cacat yang berarti, dan seluruh (ke tiga) pipa uap yang di uji tersebut diperkirakan dalam keadaan siap untuk dioperasikan. Pada tekanan operasi 70 bar(g) dan temperatur operasi maksimum 300 °C yang direncanakan, diperkirakan bahwa pipa uap tersebut dapat memberikan umur desain hingga 25 tahun atau lebih dengan laju korosi 0,2 - 0,3mm/tahun.

***Kata Kunci**: Ketel uap, pengujian metalurgi dan analisa umur, pipa uap bertekanan tinggi*

Abstract

Steel pipes are commonly used for transporting high pressure steam from a steam generating unit or boiler to a steam turbine or other processing unit. This paper presents a metallurgical examination performed on HP steam pipes of a newly constructed plant for transporting high pressure steam from a boiler to a palm oil processing plant. The aim was to assure that the material integrity of the steam pipes meet the intended specification and reliability. In addition, the aim was also to determine the estimated service life of the steam pipes. The metallurgical examination was conducted by preparing a number of specimens from the as-received three pieces of HP steam pipes. Various laboratory exam-inations were performed including chemical analysis, metallographic examination, hardness testing and tensile testing at 300 °C. In addition, a life-time analysis was also made using an equation based on the ASME Boiler and Pressure Vessel Code (BPVC) and data obtained from the API Standard 530. Results of the metallurgical examination obtained showed that the HP steam pipes which were made of ASTM A-106 Gr. B were all in good condition, either in microstructure or mechanical property. There were no any significant defect observed, and all the three HP steam pipes were assumed being ready to place in service. Under the intended operating pressure and temperature of 70 bar(g) and 300 °C (max), respectively it can be estimated that the HP steam pipes may likely reach some design life up to 25 years or more with the corrosion rate approximately 0.2 - 0.3 mm/year.

***Keywords**: Boiler, metallurgical examination and life-time analysis, high-pressure (HP) steam pipe*

1. INTRODUCTION

High-pressure (HP) steam pipes are commonly used for transporting high-pressure steam from a steam generating plant or boiler to a steam turbine unit or any other pro-cessing plant. Most of the materials used for HP steam pipe are low carbon or low-alloy steels [1]-[2], in which its microstructures containing matrix ferrite phase and some small amount of pearlite phase [3]-[4].

During in its service, the HP steam pipe material which is similar to the boiler tubes usually subjected to various deterioration mechanisms such as softening degradation, creep, thermal fatigue, hot corrosion, erosion, etc., either acting alone or in combination [3]-[10]. These deterioration mechanisms are frequently known as the main cause of material damage or degradation that could reduce the service life of the HP steam pipes or the boiler tubes [11]-[13]. The total service life of the HP steam pipes or other boiler tubes is very much influenced by deterioration rate that may occur, and this is very much dependent on the initial defect and quality of the material being used, such as chemical composition, microstructure and mechanical property [13]-[15], and also the operating parameters being applied [8], [16]. For HP steam pipes and other boiler tubes that are operated below the creep temperature regime, most of the damage occurred are due to corrosion, either by internal corrosion such as under deposit corrosion, pitting corrosion, cavitation, etc., or by external corrosion such as corrosion under insulation, stress corrosion, pitting corrosion, etc. [17, 18]. Corrosion can reduce the pipe or tube wall thickness and could result in leakage when the wall thickness reaches the minimum al-lowable wall thickness (MAWT). According to the ASME BPVC, this MAWT is a func-tion of the operating parameters such as pressure and temperature, pipe or tube outside diameter and the type of material being used [19]. By monitoring the wall thickness of the pipe or tube periodically, it will be possible to determine the corrosion rate that may oc-cur, and eventually it can be used to estimate the service life or remaining life of the steam pipe or boiler tubes [2],[20].

This paper presents a metallurgical assessment performed on a number of HP steam pipes being used for transporting high pressure steam from a boiler to a palm oil pro-cessing plant. These HP steam pipes were just about being ready for commissioning to-gether with the newly constructed boiler and its palm oil processing unit (see Figure 1). Under final inspection prior to commissioning, it was considered to perform some ex-amination and assessment on several HP steam pipes to assure that the overall material integrity of the HP steam pipes were in good condition and reliable before being placed into service. According to the plant site information, all the HP steam pipes being in-stalled were made of material specification of ASTM A-106 Gr. B. The operating pres-sure and temperature being intended to apply to the HP steam pipes were 70 bar (g) and 300 °C (max.), respectively.

The purpose of this metallurgical testing and assessment was to verify the chemical composition, microstructure and mechanical

Figure 1. A newly built boiler construction and its corresponding HP steam piping system, connected to a palm oil processing unit at location approximately on the right hand side (not seen)

property, and to determine whether the ma-terial used for the HP steam pipe met the specification or suitable for its intended oper-ating condition. Furthermore, this metallurgical testing and assessment was also aimed to estimate the useful life-time of the HP steam pipes which will be based on the test re-sults obtained.

2. EXAMINATION DETAILS AND ASSESMENT

In this metallurgical testing and assessment, 3 (three) pieces of new and similar steam pipe of Ø 4," Ø 6," and Ø 10" in diameter shown in Figure 2 were used to represent the HP steam pipes that have already been installed in the newly built boiler construction plant. The three pieces of new steam pipes were then cut into several specimens for la-boratory examination. Chemical analysis on the prepared samples was carried out using optical spark emission spectrometer. The purpose of this chemical analysis was to de-termine whether the material used for the HP steam pipe met the specification. In addition, metallographic examinations were also performed on the vertical tubular furnace. The tensile test specimen was made according to the specification of ASTM A 370 [22]. Finally, a life-time calculation and analysis was made which was based on the test results ob-tained. This life-time calculation and analysis was made using an equation based on the ASME Boiler and Pressure Vessel Code (ASME BPVC) [19] and data obtained from the API Standard 530 [20].

According to the ASME BPVC [19], the minimum allowable wall thickness (MAWT) of the HP steam pipe is as follows:

$$t_{min} = \frac{P.D}{2S + P} + 0.005D ....1)$$

where t_{min} is the minimum allowable wall thickness of the HP steam pipe expressed in millimeters, P is the working pressure = 70 bar (g) = 7.0 MPa = 0.714 kgf/mm^2, D is the outside pipe diameter expressed in millimeters, S is the maximum allowable stress at 300 °C. For material ASTM A-106 Gr.B, S = 117.9 MPa = 12.025 kgf/mm^2 (according to the ASME BPVC Sect.II Part D) [24].

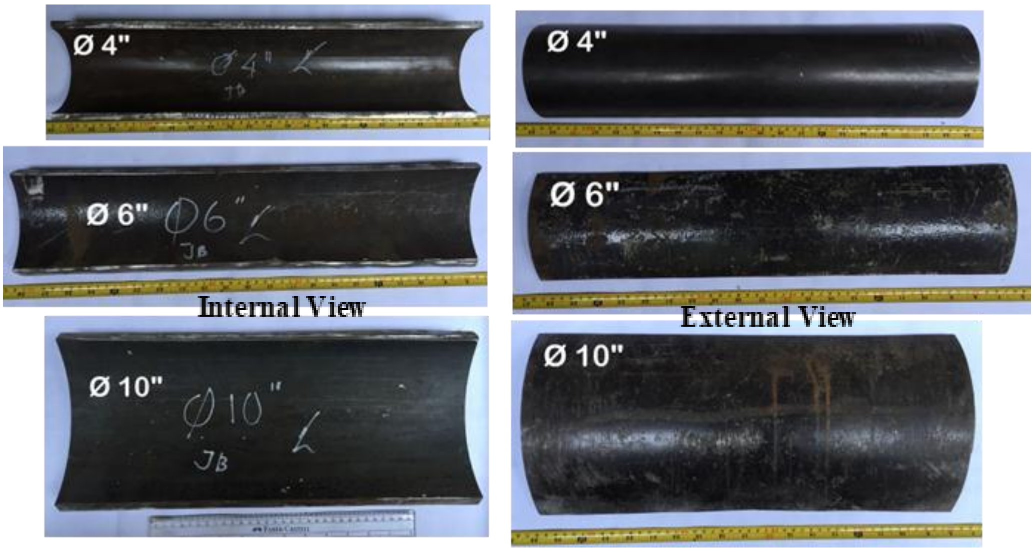

Figure 2. The as received sections of new HP steam pipes of different diameters (Ø 4," Ø 6," and Ø 10") for laboratory examination

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 ap-plied was Nital's solution [21]. A hardness survey was also carried out on the same sam-ple for the metallographic examination using the Vickers hardness method at a load of 5 kg (HV 5). Moreover, tensile testing on the prepared samples was also performed at 300 °C using an universal testing machine equipped with a

3. RESULTS AND DISCUSSION

3.1 Chemical Analysis

Results of chemical analysis obtained from the three different HP steam pipes having the three different HP steam pipes having diameter of 4," 6" and 10" in comparison with the standard material are presented in Table 1. The results obtained indicate that the three diameters of steam pipe closely met to the material specification of ASTM A-106 under the quality of Gr. A or Gr. B [23], typical of low or medium carbon steel having microstructures containing of matrix fer-rite phase with some amount of pearlite as second phase. The carbon steels with such microstructures generally have low to medium level of hardness or strength. From the results of hardness test and tensile test obtained which will subsequently be presented, it is confirmed that all of the HP steam pipes are most likely made in accordance with the material specification of ASTM A-106 Gr. B [24].

3.2 Metallographic Examination and Analysis

Microstructures obtained from HP steam pipe material of 4" diameter in both cross section and longitudinal section are presented in Figure 4, showing matrix ferrite phase (light color) with second pearlite phase (dark color), typical of low to medium carbon steel [21]. In general, morphology of the microstructures are well clearly defined and homogeneously distributed, and no any metallurgical defect such as inclusions or crack is observed [14].

Table 1. Results of chemical analysis obtained from the new HP steam pipe material in comparison with the standard material.

Element	Composition, wt.-%				
	HP Steam Pipe			Standard Materials	
	Ø 4”	Ø 6”	Ø 10”	ASTM A-106 Gr.A	ASTM A-106 Gr.B
Fe	98.3	97.9	98.1	Balance	Balance
C	0.238	0.195	0.207	0.25 (max)	0.30 (max)
Si	0.286	0.225	0.283	0.10 (min)	0.10 (min)
Mn	0.876	0.815	1.04	0.27–0.93	0.29–1.06
P	0.0250	0.0271	0.0327	0.035 (max)	0.035 (max)
S	0.0043	< 0.0030	0.0067	0.035 (max)	0.035 (max)
Cr	0.0531	0.167	0.0353	0.40 (max)	0.40 (max)
Ni	0.0200	0.111	0.0313	0.40 (max)	0.40 (max)
Mo	0.0259	0.0585	0.0194	0.15 (max)	0.15 (max)
Cu	0.0297	0.341	0.0158	0.40 (max)	0.40 (max)
V	0.0087	0.0104	0.0138	0.08 (max)	0.08 (max)
Nb	0.0309	0.0398	0.0423	–	–
Al	0.0127	0.0054	0.0375	–	–
Ti	0.0020	0.0023	0.0014	–	–

Table 2. Results of hardness test obtained from the three different HP steam pipes

Test Point No	Vickers Hardness Number (HV) of HP Steam Pipe Material					
	Ø 4"		Ø 6"		Ø 10"	
	Cross-section	Longitudinal section	Cross-section	Longitudinal section	Cross-section	Longitudinal section
1	148.0	149.5	144.0	145.0	173.5	166.0
2	145.0	152.0	145.0	146.0	170.5	166.0
3	147.0	154.5	145.0	146.0	153.0	154.5
4	151.0	156.0	147.0	152.0	161.0	148.0
5	144.0	149.5	148.0	144.0	165.0	166.0
6	148.0	-	145.0	-	169.0	-
7	148.0	-	141.8	-	162.5	-
8	157.0	-	144.0	-	148.0	-
9	157.0	-	148.0	-	152.0	-
10	158.0	-	143.0	-	172.0	-
Average	**150.3**	**152.3**	**145.1**	**146.6**	**162.6**	**160.1**

However, there are only seen some slight surface defect occurred on some of pipe surface exterior. The occurrence of these surface defects is likely not affecting significantly to the overall strength of the pipe material [25]. These outer surface defects may have been caused by the effect of shipping and handling of the pipes during transportation and/or construction. In addition, there are also seen some slight scale or deposit formation at the internal surface of the pipe and these may have been caused by some internal oxidation occurred during the pipe manufacturing process [14].

Table 3. Calculated Tensile Strength (TS) of HP steam pipe material based on the results obtained from the hardness test shown in Table 2

Pipe Diameter	Average Hardness Measured (HV)	Converted Hardness (HB)	Calculated TS (MPa)
Ø 4”	150.3	143.1	491.0
	152.3	145.0	497.6
Ø 6”	145.1	138.0	473.5
	146.6	141.0	483.8
Ø 10”	162.6	154.0	528.4
	160.1	152.1	521.9

Note:
Calculated TS = 0.35 HB (kgf/mm^2); HB = Brinell Hardness Number

Figure 3. The three broken tensile test specimens after being tested at 300 °C

Table 4. Results of tensile test at 300 °C obtained from the HP steam pipe materials

Pipe Diameter	**Test Temperature: 300˚C**					
	Sample Diameter (mm)	**Ao (mm^2)**	**Fm (kN)**	**TS**		**ε (%)**
				(N/mm^2)	**(kgf/mm^2)**	
Ø 10”	8.58	57.8	29.0	502	51.1	29.0
Ø 6”	6.05	28.7	15.0	522	53.2	32.0
Ø 4”	6.25	30.7	17.0	554	56.5	34.0

Note:
Ao = Cross sectional area; Fm = maximum tensile load; TS = Tensile Strength

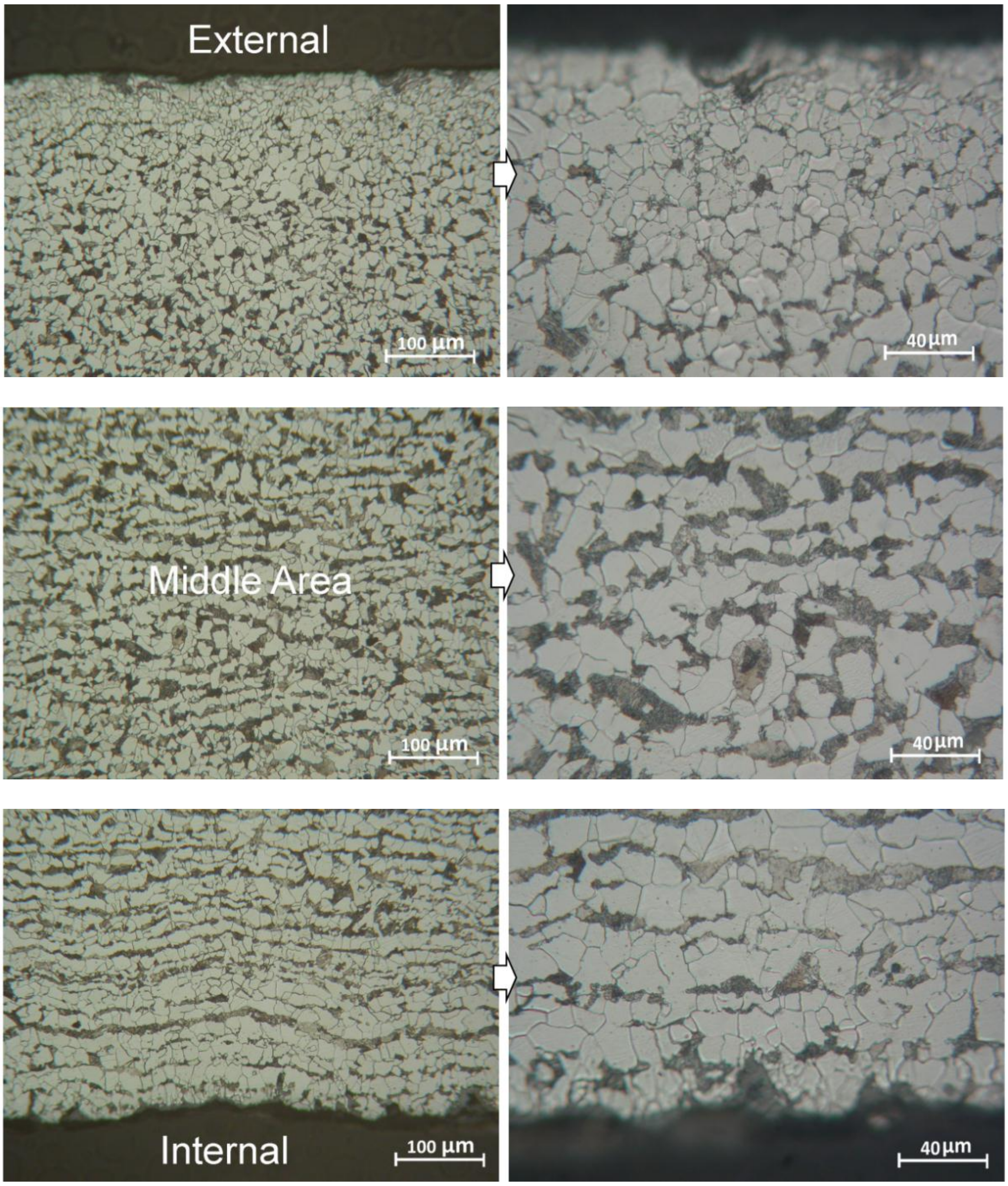

Figure 4. Microstructures obtained from the cross-section of the 4" diameter of HP steam pipe, showing matrix ferrite phase (light color) and second pearlite phase (dark color), typical of low to medium carbon steel. Etched with 5% Nital solution

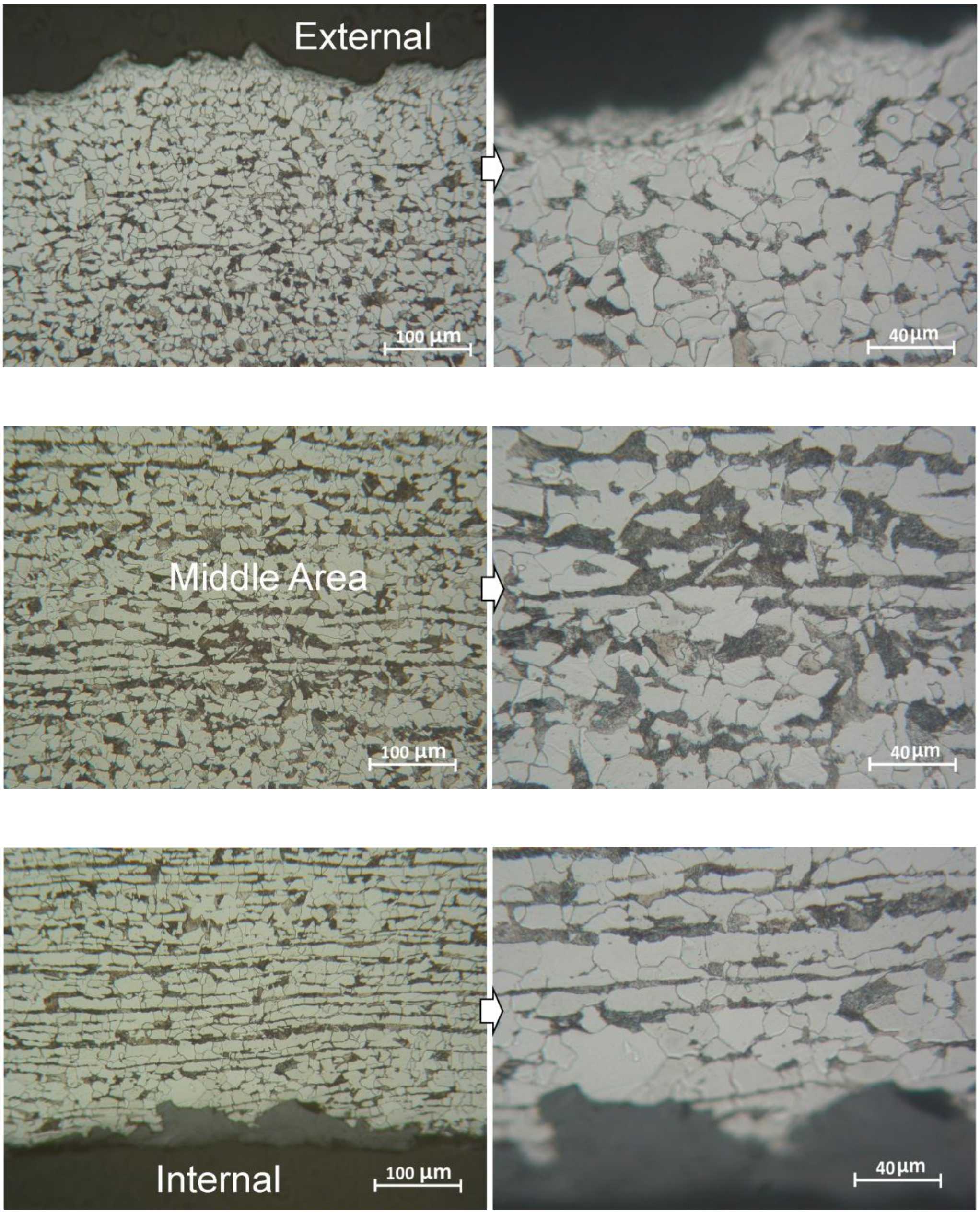

Figure 5. Microstructures obtained from the longitudinal-section (b) of the 4" diameter of HP steam pipe, showing matrix ferrite phase (light color) and second pearlite phase (dark color), typical of low to medium carbon steel. Etched with 5% Nital solution

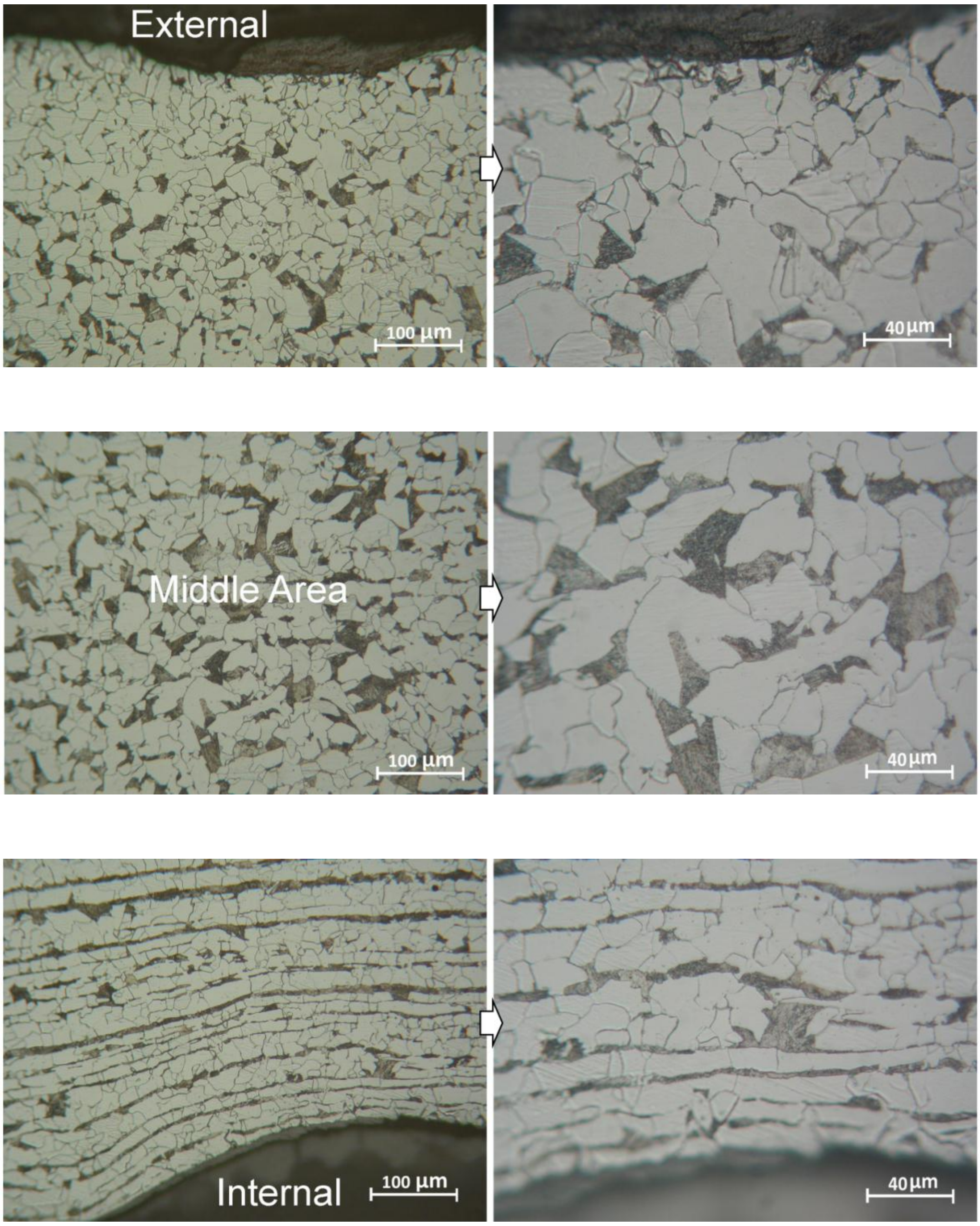

Figure 6. Microstructures obtained from the cross-section of the 6" diameter of HP steam pipe showing matrix ferrite phase (light color) and second pearlite phase (dark color), typical of low to medium carbon steel. Etched with 5% Nital solution

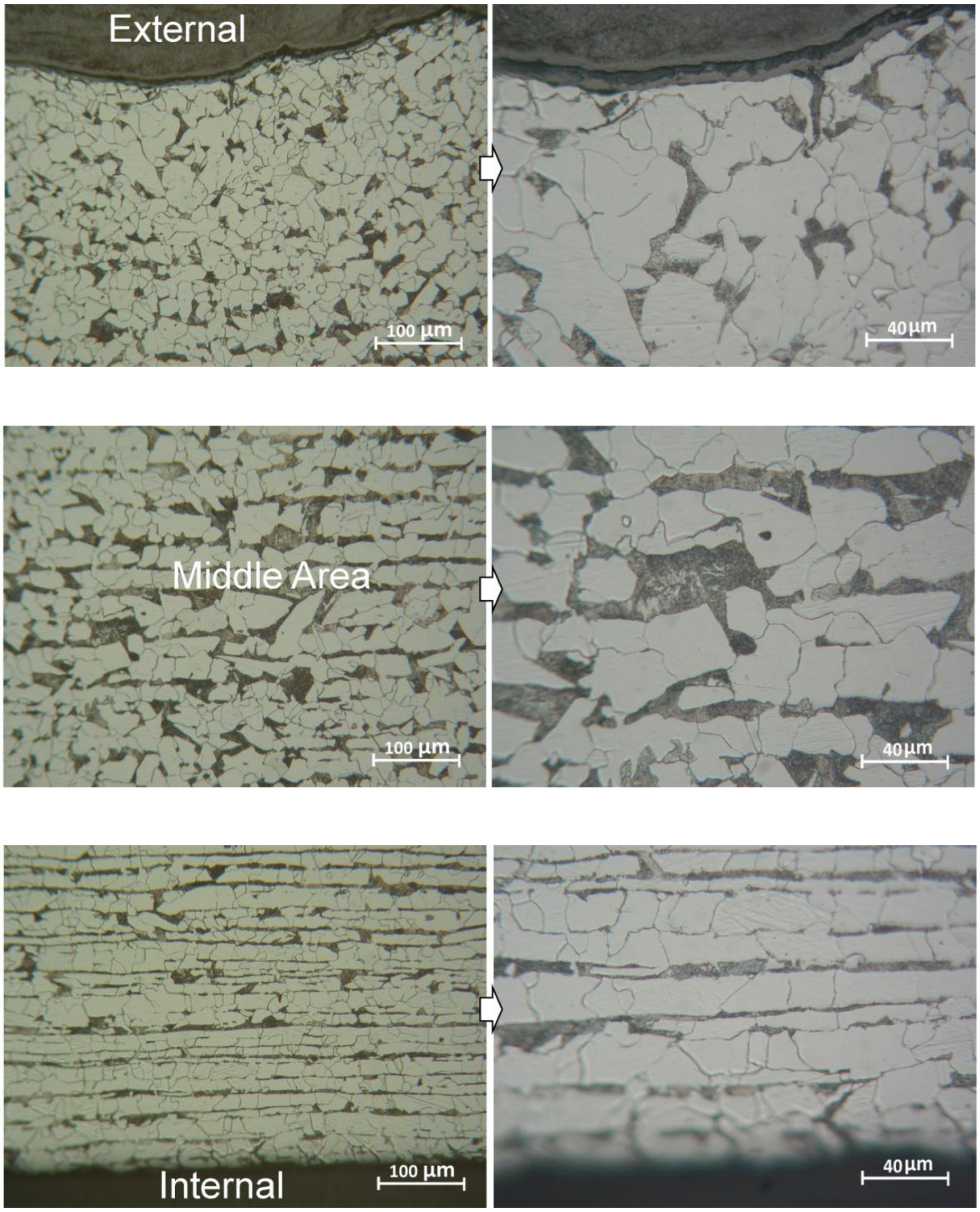

Figure 7. Microstructures obtained from the longitudinal-section of the 6" diameter of HP steam pipe showing matrix ferrite phase (light color) and second pearlite phase (dark color), typical of low to medium carbon steel. Etched with 5% Nital solution

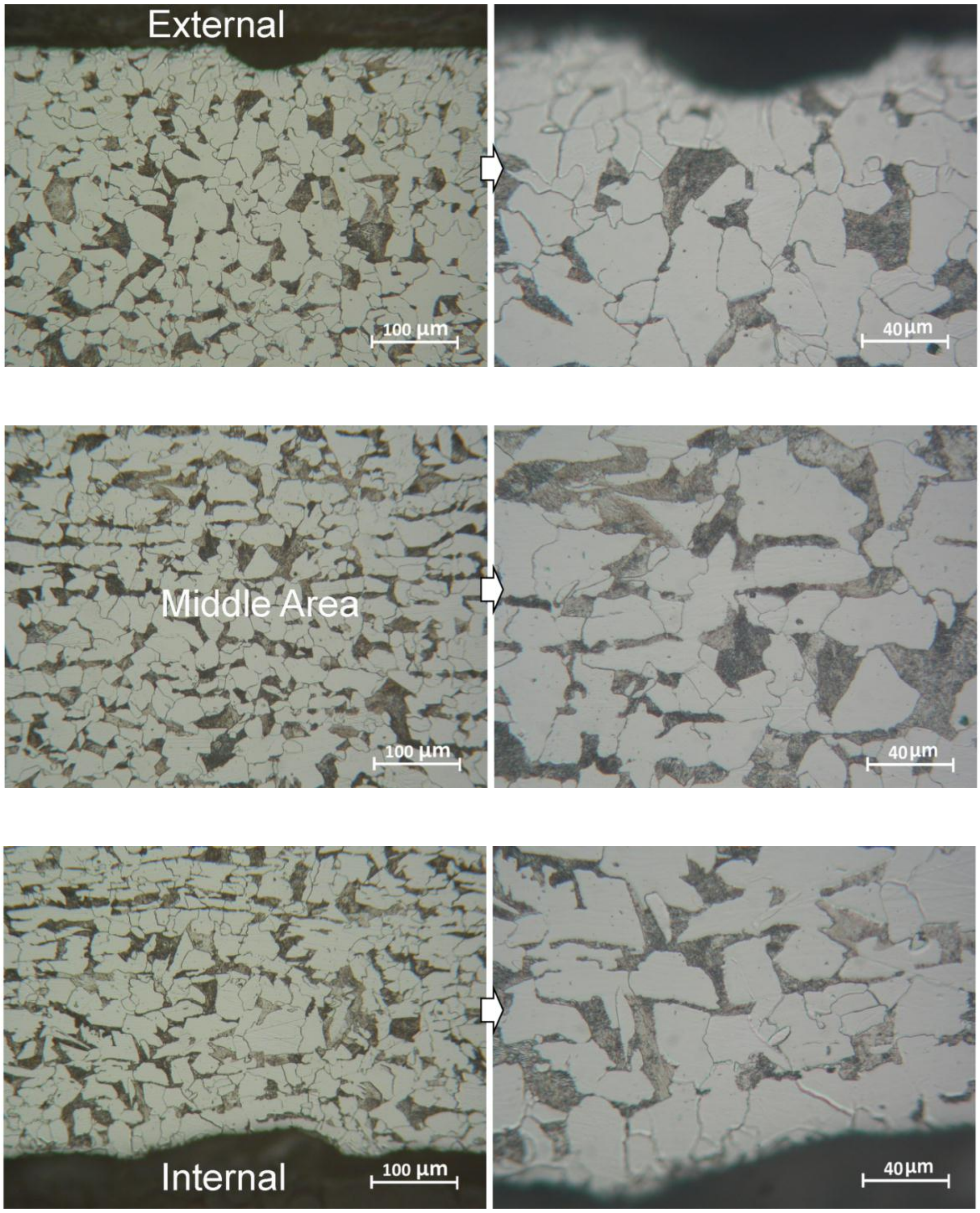

Figure 8. Microstructures obtained from the cross-section (a) and the longitudinal-section (b) of the 10" diameter of HP steam pipe showing matrix ferrite phase (light color) and second pearlite phase (dark color), typical of low to medium carbon steel. Etched with 5% Nital solution

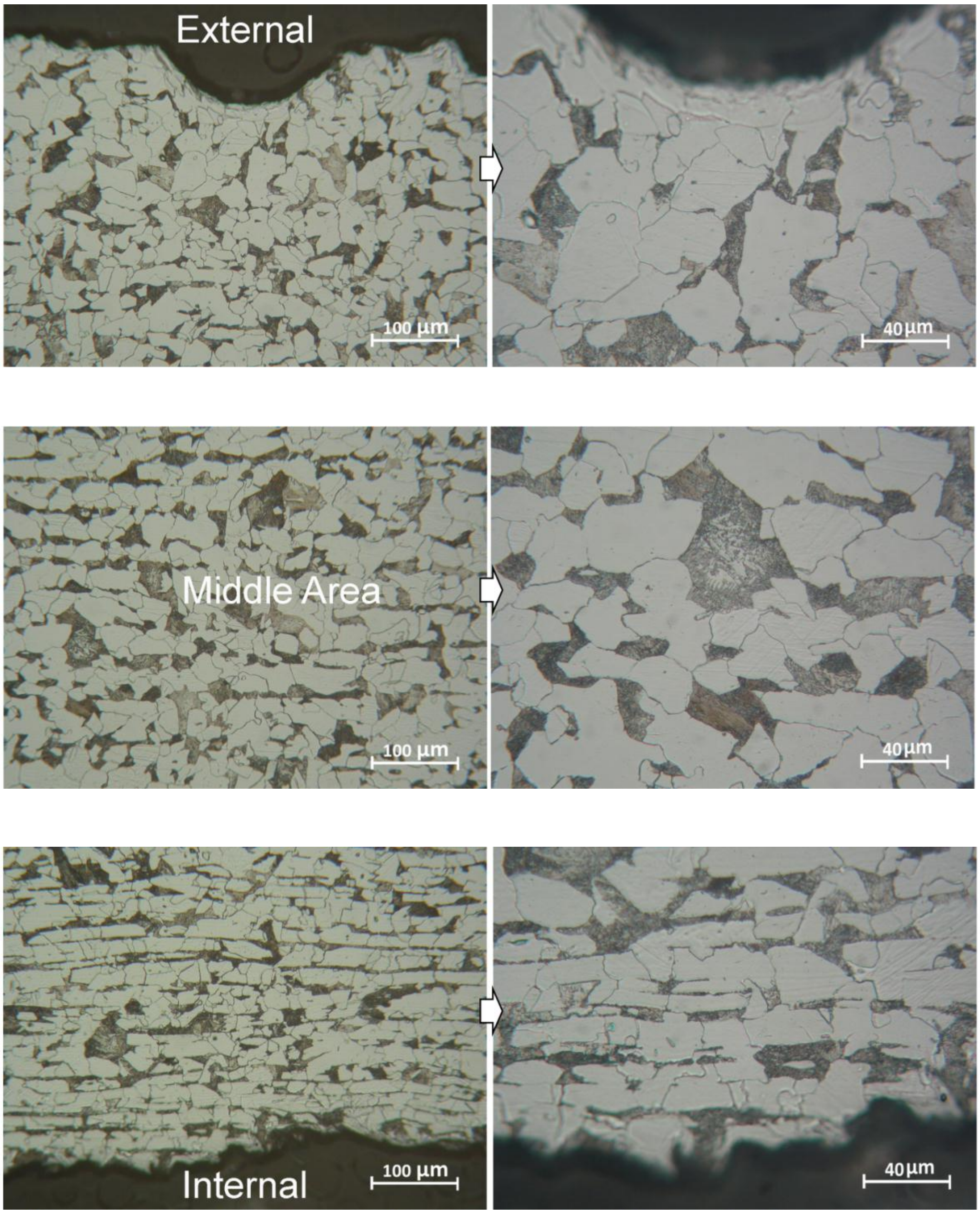

Figure 9. Microstructures obtained from the cross-section (a) and the longitudinal-section (b) of the 10" diameter of HP steam pipe showing matrix ferrite phase (light color) and second pearlite phase (dark color), typical of low to medium carbon steel. Etched with 5% Nital solution

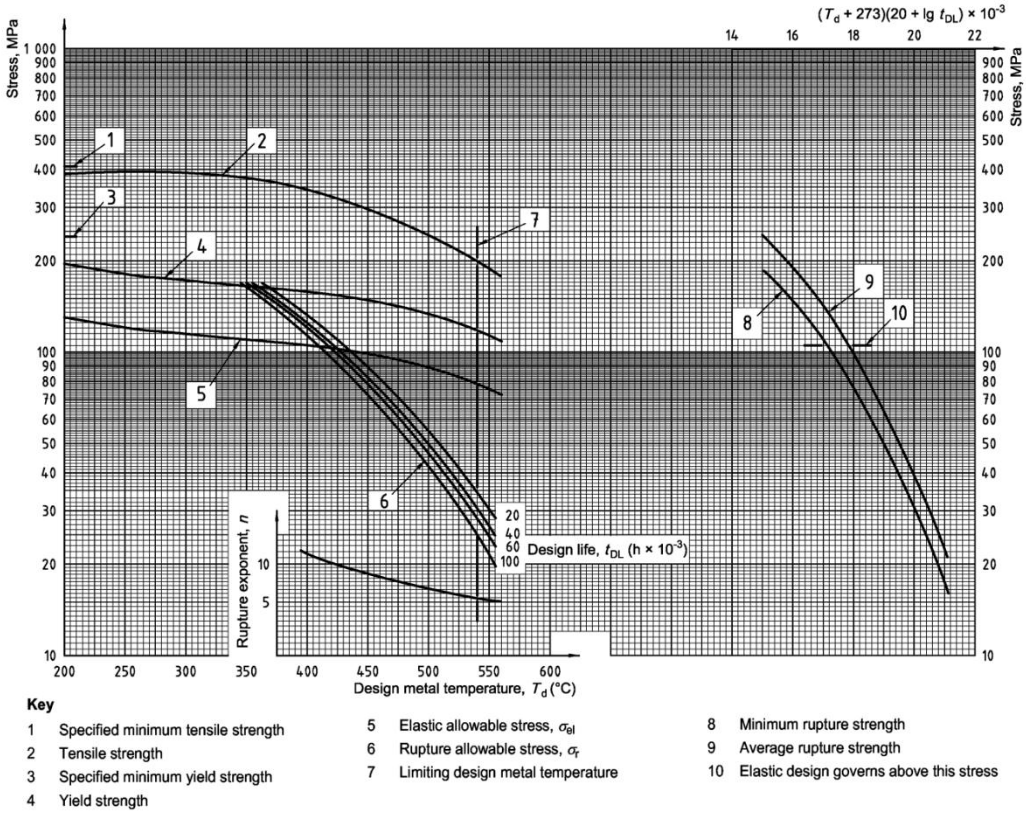

Figure 10. Stress curves (SI units) for ASTM A 53 Grade B (seamless), ASTM A 106 Grade B and ASTM 210 Grade A-I medium-carbon steels (according to API Standard 530) [20]

The microstructures obtained from HP steam pipe material of 6" diameter in both cross section and longitudinal section which are presented in Figure 4 are very much similar to those obtained from the HP steam pipe material of 4" diameter, either in pattern and morphology of the microstructures, or the external and internal formation of surface defects occurred on the pipe. Similar microstructures obtained from HP steam pipe material of 4" and 6" in diameter were also observed in HP steam pipe material of 10" in diameter, either in cross section or in longitudinal section of the specimens (see Figure 6). This further indicated that all the three HP steam pipes were made and manufactured by the same material specification of ASTM A-106 Gr. B [23]. In addition, most of the microstructures obtained from the three HP steam pipe materials are equaxed and/or elongated and this indicated that the HP steam pipes were manufactured by hot rolling and may also have been further subjected to some annealing or normalizing heat treatment [14]. Combination of this rolling and heat treatment process may have resulted and improved the microstructure and mechanical property relationship of the steam pipe material [15].

3.3 Hardness Test and Analysis

Results of hardness test obtained from specimens of the three different HP steam pipes are presented in Table 2. It can be seen that the hardness values obtained were very much close among the three pipes examined, ranging from 145.1 to 162.6 HV. This hardness range obtained indicated that the microstructure-mechanical property rela-tionship of the three pipe materials were about similar and homogeneous [14], [25].

The hardness test results shown in Table 2 can be used to calculate or estimate the value of tensile strength (TS) of the pipe material, see Table 3. It can be seen that the value of all the calculated TS were well above the minimum TS according to the materi-al specification of ASTM A-106 Gr. B (or ASME SA-106 Gr.B) which is 415 MPa (min) [23] –[24].

3.4 Tensile Test at 300 °C

The broken tensile test specimens after they have been tested at 300 °C are seen in Figure 3, and the tensile test data obtained are summarized in Table 4. It can be seen that the TS values of the three pipes of diameter 10," 6" and 4" are well above the min-imum TS value according to the material specification of ASTM A-106 Gr. B, either based on the ASME Boiler and Pressure

Vessel Code (ASME BPVC), or based on the API standard 530 (see Figure 10) [20].

The test results shown in Table 4 indicate that all the HP steam pipe materials are in accordance with the material specification of ASTM A-106 Gr.B. According to the ASME Boiler and Pressure Vessel Code, Section II Part D, for material of ASTM A-106 Gr.B, the tensile strength (TS) at room temperature : 415 MPa (min), while the tensile strength and max. allowable stress at 300 °C are 413.7 MPa (min) and 117.9 MPa, re-spectively [24]. Similarly, according to API Standard 530 (see Figure 10), for material of ASTM A-106 Gr.B, the tensile strength at room temperature: 410 MPa (min), while the tensile strength and the allowable stress at 300 °C are 387.5 MPa (min) and 115 MPa, respectively [20]. In addition to the tensile strength, the elongation obtained as shown in Table 4 is relatively high, and this could improve the toughness of the pipe material.

3.4 Life-Time Analysis of the HP Steam Pipes

a). Life-time estimation based on the ASME BPVC

Life time estimation of all the three diameter steam pipes were calculated based on the equation 1), and the results obtained are summarized as follows :

For HP steam pipe of 4" diameter, the minimum allowable wall thickness is as follows:

$$t\,min = \frac{(0.714).(101.6)}{2(12.025)+(0.714)} + 0.005(101.6),$$

$$\text{or } t\,min = 3.44\,mm$$

For design life is assumed of 25 years, corrosion rate (CR) can be calculated as follows:

$$CR = \frac{t0 - t\,min}{25\,year} = \frac{9.15 - 3.44}{25} = 0.2284\,mm/year$$

where t_0 = 9.15 mm is the initial wall thickness of HP steam pipe of 4" diameter.

For HP steam pipe of 6" diameter, the minimum allowable wall thickness is as follows:

$$t\,min = \frac{(0.714).(152.4)}{2(12.025)+(0.714)} + 0.005(152.4),$$

$$\text{or } t\,min = 5.152\,mm$$

For design life is assumed of 25 years, corrosion rate (CR) can be calculated as follows:

$$CR = \frac{t0 - t\,min}{25\,year} = \frac{10.84 - 5.152}{25} = 0.2275\,mm/year$$

where t0 =10.84 mm is the initial wall thickness of HP steam pipe of 6" diameter.

For HP steam pipe of 10" diameter, the minimum allowable wall thickness is as follows:

$$t\,min = \frac{(0.714).(254)}{2(12.025)+(0.714)} + 0.005(254),$$

$$\text{or } t\,min = 8.59\,mm$$

For design life is assumed of 25 years, corrosion rate (CR) can be calculated as follows:

$$CR = \frac{t0 - t\,min}{25\,year} = \frac{16.10 - 8.59}{25} = 0.3\,mm/year$$

where t0 = 16.10 mm is the initial wall thickness of HP steam pipe of 10" diameter.

b). Life-time estimation based on the tensile test result at 300°C

From the tensile test results at 300 °C shown in Table 4, it can be seen that the average value of TS (Tensile Strength) is about 526 MPa. If the allowable stress of the HP steam pipe material at 300 °C is assumed about 66.7% from its Tensile Strength at 300 °C (see the comparison value of this percentage in Figure 10) [20] , the allowable stress (S) of the HP steam pipe material at 300 °C becomes:

S = 66.7% x 526 MPa = 350.8 MPa, or 35.8 kgf/mm^2.

By using the equation as mentioned above, the minimum allowable wall thickness of the HP steam pipe can be calculated.

For HP steam pipe of 4" diameter, the minimum allowable wall thickness is as follows:

$$t\,min = \frac{(0.714).(101.6)}{2(35.8)+(0.714)} + 0.005(101.6),$$

$$\text{or } t\,min = 1.5\,mm$$

If the maximum corrosion rate (CR) is estimated about 0.3 mm/year, the life-time (LT) of HP steam pipe material of 4" diameter can be calculated as follows:

$$LT = \frac{t0 - t\,min}{CR} = \frac{9.15 - 1.5}{0.3} = 25.5\,year$$

where t0 = 9.15 mm is the initial wall thickness of HP steam pipe of 4" diameter.

For HP steam pipe of 6" diameter, the minimum allowable wall thickness is as follows:

$$t\,min = \frac{(0.714).(152.4)}{2(35.8)+(0.714)} + 0.005(152.4),$$

$$\text{or } t\,min = 2.26\,mm$$

If the maximum corrosion rate (CR) is estimated about 0.3 mm/year, the life-time (LT) of HP steam pipe material of 6" diameter can be calculated as follows:

$$LT = \frac{t0 - t\,min}{CR} = \frac{10.84 - 2.26}{0.3} = 28.6\ \text{year}$$

where t_0 = 10.84 mm is the initial wall thickness of HP steam pipe of 6" diameter.

For HP steam pipe of 10" diameter, the minimum allowable wall thickness is as follows:

$$t\,min = \frac{(0.714).(254)}{2(35.8)+(0.714)} + 0.005(254),$$

$$\text{or } t\,min = 3.78\,mm$$

If the maximum corrosion rate (CR) is estimated about 0.3 mm/year, the life-time (LT) of HP steam pipe material of 10" diameter can be calculated as follows:

$$LT = \frac{t0 - t\,min}{CR} = \frac{16.10 - 3.78}{0.3} = 41\ \text{year}$$

where t0 = 16.10 mm is the initial wall thickness of HP steam pipe of 10" diameter.

Based on the aforementioned test results and life-time assessment, all the HP steam pipes that have been installed are considered to be ready being placed into service. This consideration is made under assumption that all the HP steam pipes that have been tested were representing to all of the constructed HP steam pipes.

In order to assure that the corrosion rate occurred on the HP steam pipes during their future operation is remained within the range of 0.2–0.3 mm/year, it is also important to monitor the wall thickness of the HP steam pipes periodically at least at every major inspection performed in order to monitor any internal oxidation and/or corrosion that may occur on the HP steam pipe internal surface due to any unexpected change in boiler water quality and/or boiler water treatment applied. In addition, it is also required to monitor the external corrosion of steam pipes due probability to any corrosion under insulation [5].

Furthermore, it is also considered to perform in-situ metallographic examination and hardness testing periodically to evaluate any metallurgical and/or mechanical degradation that may have occurred during the utilization of the HP steam pipes in service due to any unexpected change in operating conditions.

4. CONCLUSIONS

From the results of chemical analysis, metallographic examination, hardness test and tensile test obtained, it can be seen that the material used for the HP steam pipes are very much close and met to the material specification of ASTM A-106 Gr. B (or ASME SA-106 Gr.B).

In addition, the morphology of microstructures in combination with the hardness and tensile strength values obtained are all in favor and supporting that the ma-terial of HP steam pipes are all in good condition. Although there are some slight defects and/or scale formation occurred on some of the exterior and interior surface of the HP steam pipes, however, most likely these slight imperfections may not be likely affecting to the mechanical property or performance of the HP steam pipes quite significantly in service.

Based on the present status and condition of the HP steam pipes, it can be estimated that under the intended operating pressure and temperature of 70 bar(g) and 300 °C (max.), respectively, the HP steam pipes may likely reach some design life up to 25 years or more. This estimated design life is made based on the corrosion rate approximately 0.2–0.3 mm/year.

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