



## Degradation due to ageing in extraction steam piping of a nuclear power plant

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### ABSTRACT

Ageing assessment of extraction steam piping, which was limited to wall loss and corrosion, has been extended to microstructural degradation in this paper. Metallography, radiography, ultrasonic thickness and hardness measurements have been carried out for examining the virgin and twelve years old Seamless Carbon Steel SA 106B pipe in this study. In addition to commonly observed degradation mechanisms i.e. pitting and wall thinning, microstructural degradation has also been observed. The transformation of bands of pearlite and ferrite phases, present in virgin microstructure, into uniformly distributed pearlite and irregularly distribute graphite nodules have been observed due to ageing. The depletion of pearlite phase from 40% to 25% and consequent reduction in hardness up to 20.4% maximum has been observed. The more reduction in hardness of internal surface has been observed as it comes in direct contact with steam. Due to microstructural degradation with simultaneous pitting, wall thinning and reduction in mechanical properties, frequent inspection has been suggested.

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## 1. Introduction

Industrialization have prompted the world to get more economic and reliable source of power i.e. Nuclear Power Plants. Currently installed nuclear power plants have been in operation for decades. The specific design life of older nuclear power plants was based only on fatigue life calculation, whereas age related material degradation was ignored (IAEA Nuclear Energy Series, 2009). The materials in nuclear power plants endure hard conditions (Umer et al., 2016; Waseem and Ryu, 2016) and degrade as a result of creep, corrosion, phase changes and emerging of micro-defects. The degraded material can initiate any failure by lowering mechanical properties (Ivanova et al., 2012). Carbon steel SA 106B is extensively utilized in high temperature piping of nuclear power plants. Such as seamless pipes of SA 106B are used in main steam and feed water systems. Steam outlet nozzle and condenser structure is also fabricated from the same steel grade

(Hänninen, 2009). It is a plain carbon steel; its structure is composed of pearlite phase in ferrite matrix. Extended exposure to high temperature and pressure conditions causes degradation in this steel, consequently threatens the safe operation by reducing strength (Mansoor and Ejaz, 2009). Replacement of such material is not considered feasible, therefore assessment of age related degradation becomes essential (Furtado and May, 2004). Material ageing has been a critical issue therefore much research work has been done regarding material ageing assessment of critical components of the nuclear power plants such as reactor pressure vessel, pressure tubes, steam generators, pressurizer, main steam piping and pipe line corrosion etc. Ageing assessment of piping has been a topic of particular interest for researchers, various studies have been published such as Ossai et al. (2016) observed increasing degradation due to prolong service of pipelines (Ossai et al., 2016), Bai et al. (2016) observed negligible effect of solution treatment on degradation of austenite steel used in piping of power plants (Bai et al., 2016) and Deng et al. (2009) found the effect of microstructure on ageing (Deng et al., 2009). To the best of our knowledge, the ageing analysis of piping is still limited to loss of material, general corrosion, crevice and pitting corrosion and wall thinning (U.S.NRC,

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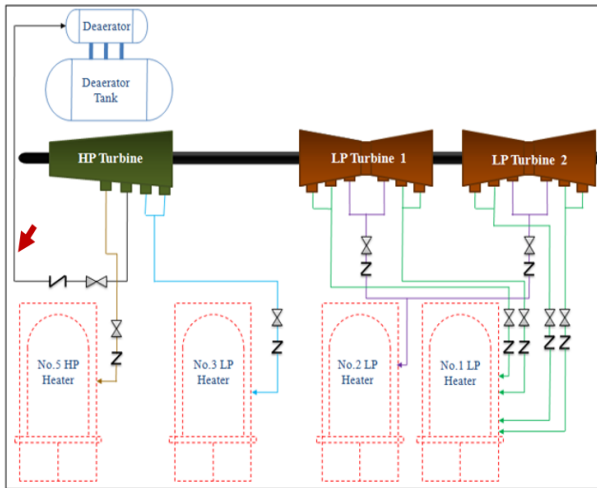
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2009), but this paper extends this very important to microstructural degradation.

**2. Materials and methods**

The nuclear power plant under study has been in operation for 40 years. The pipe samples of extraction steam passage way were taken, which had been carrying steam from high pressure turbine to deaerator for twelve years. The location, from where pipe samples were obtained, is shown by a red arrow in Fig. 1.



**Fig. 1:** Schematic diagram of extraction steam piping system

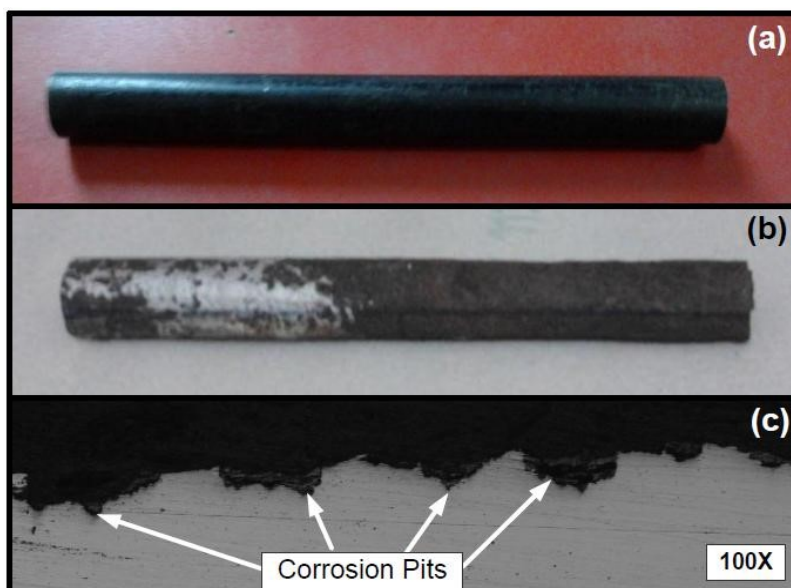
The ageing effects on extraction steam piping’s material were investigated. The test sample (i.e. aged pipe of carbon steel SA 106B) having 21.34 mm outside diameter (OD) and 2.76 mm thickness was cut and subjected to thorough examination. A virgin pipe of same size, type and material was also subjected to the same analytical protocol for comparison of results. Metallographic examination

was carried out using metallurgical microscope. Samples were prepared for metallography according to standard procedure as given in ASTM E3. Image software was used to determine the content of different phases. Radiographic examinations were carried out by Smart 225 KV X-ray machine according to ASME SEC-V guideline. Samples were exposed for 60 seconds. The image quality indicator (IQI) having 0.25 mm diameter was used as per ASTM 1A-6. Ultrasonic tests were performed to measure the reduction in thickness due to erosion according to ASTM E-18. DM4 DL ultrasonic thickness gauge was utilized. Hardness measurement was done in Rockwell Hardness Scale B according to ASTM E-18. Hardened steel sphere by applying 100 Kg load using ZHR Rockwell Hardness Tester; 10 Kg minor load was also applied initially to hold the sample firmly by an initial penetration and to enhance the accuracy of results.

**3. Results and discussion**

Aged, (c) Cut-off View of External Surface of Aged Pipe Showing Corrosion Pits at 100X magnification.

Visual examination shows no disturbance in uniformity of virgin pipe, See Fig. 2(a). Whereas, aged pipe surface as shown in Fig. 2(b) shows corrosion, as it has been in sea shore environment which is highly corrosive. Corrosion has the potential to reduce a design life of the component by premature degradation (Ginzel, 2002). Examination of corroded surface under metallurgical microscope, as shown in Fig. 2(c), reveals formation of corrosion pits, maximum depth of pit is 0.07 mm, which causes non-uniform reduction in thickness and reduces the ultimate strength of the material (Sidharth, 2009).



**Fig. 2:** SA 106B seamless pipe, (a) virgin, (b)

Radiographic examination of virgin pipe exhibits no sign of erosion, as shown in Fig. 3(a). Whereas

material removal is evident on the internal surface of aged pipe, see Fig. 3(b) which shows mechanical

rubbing of steam on internal surface of service exposed pipe (Callister and Rethwisch, 2007). Steam is supplied from middle stage extraction of high

pressure turbine to deaerator at 15 psi pressure and 250 °F temperature conditions.

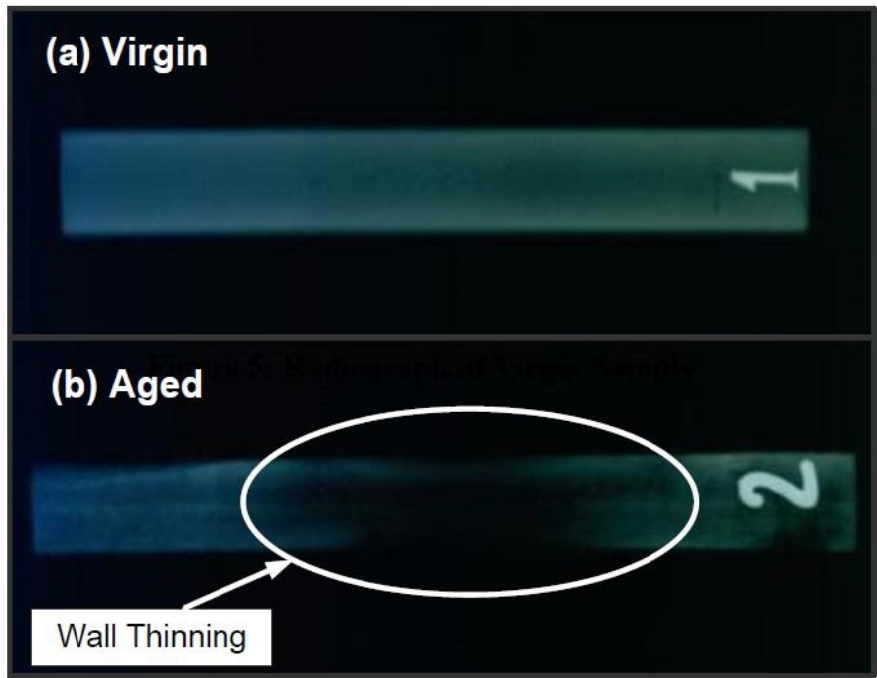


Fig. 3: Radiographs of (a) virgin pipe and (b) aged pipe

Ultrasonic testing has been performed to determine the intensity of wall thinning due to material removal. On average; 10.46% reduction in thickness is observed from 2.77 mm to 2.48 mm due to 12 years of service. Consequently, the average hoop stress which acts in radial direction because of the pressure inside the pipe and depends upon

thickness of pipe, increases up to 13 % from 50.29 psi to 56.87 psi. As the pipe degrades and thickness reduces, the possibility of pipe failure increases due to increase in hoop stress (Braverman et al., 2005). Fig. 4 shows the increase in hoop stress due to reduction in wall thickness on the pipe.

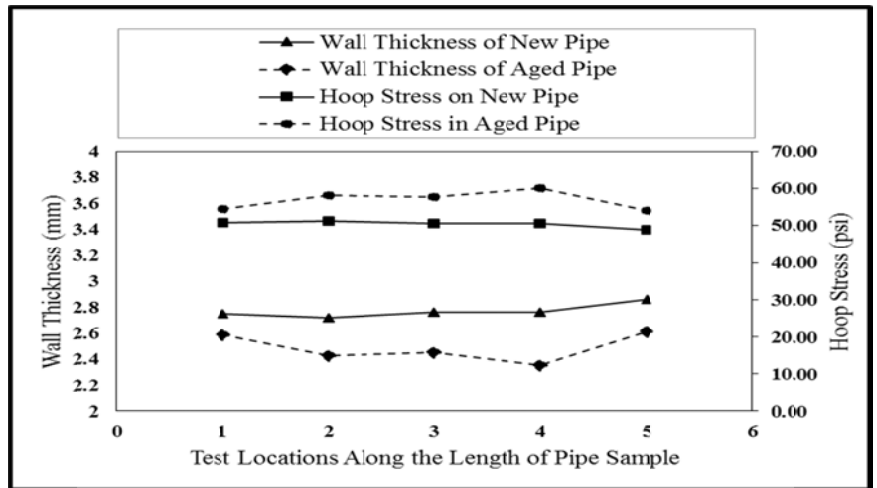


Fig. 4: Increase in hoop stress due to reduction in wall thickness

Microstructure of new carbon steel pipe exhibits bands of pearlite and ferrite, see Fig. 5. These bands are typical of the extruded material (Misiolek and Sikka, 2006). Inner surface layer of virgin pipe shows decarburized layer up to 0.1 mm. This decarburized layer forms during cooling of steel to room temperature after hot extrusion (Callister and Rethwisch, 2007) this anisotropic structure shows poor resistance to impact load (Caballero et al., 2006). Abrasive action of steam removes the inner

decarburized layer in aged carbon steel pipe. Prolong exposure to high temperature distributes pearlite uniformly throughout the matrix and no bands of pearlite and ferrite are observed in aged pipe, see Fig. 6. Mixture of ferrite and pearlite is more resistant to impact load. Amount of pearlite and ferrite, determined by image analyzing software ImageJ, was 40% and 60% respectively in new carbon steel, which changes to 25% pearlite and 75% ferrite due to twelve years of service in high

temperature and pressure conditions. Reduction in pearlite occurs due to formation of graphite nodules, see Fig. 6 and Table 1. Decreasing amount of pearlite

has deleterious effects as it decreases strength and hardness of steel (Gonzaga et al., 2009).

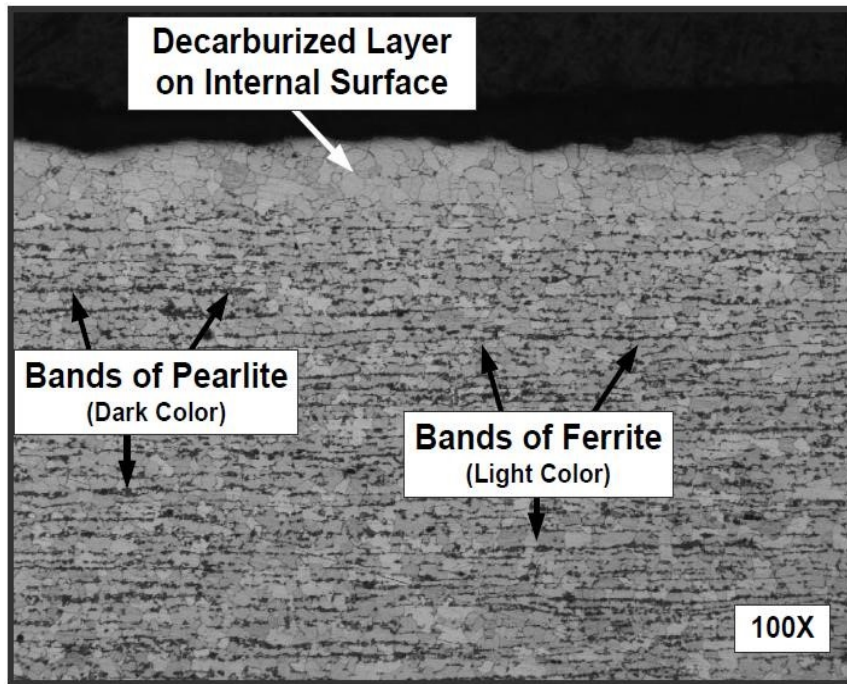


Fig. 5: Nital (1-10% Nitric Acid in Ethanol) etched microstructure of new seamless SA 106B pipe at 100X

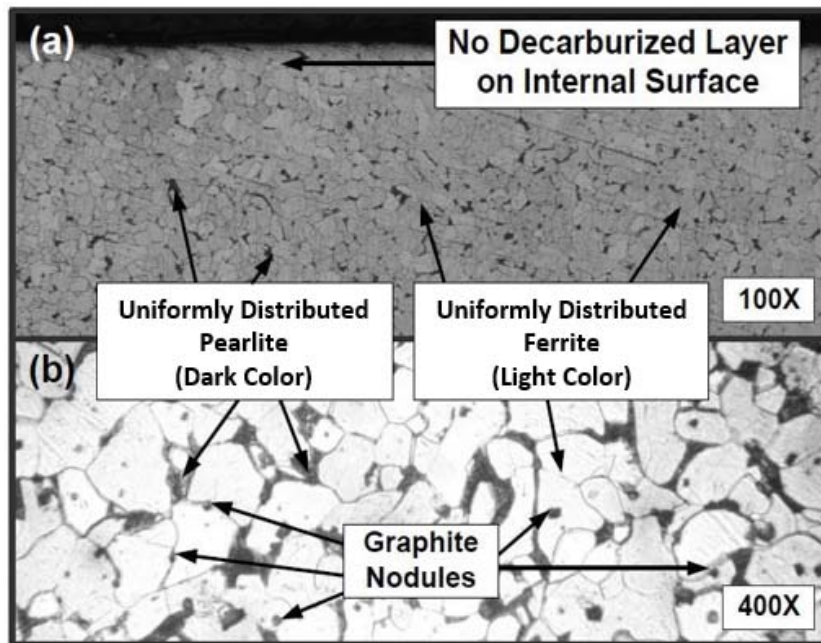


Fig. 6: Nital etched microstructure of aged seamless SA 106B pipe at (a) 100X and (b) 400X.

Table 1: Reduction in hardness due to ageing

Rockwell Hardness Scale B (HRB)			
Pipe Surface	Virgin Pipe	Aged Pipe	Reduction (%)
Internal	68.5	54.5	20
External	64.5	64	0.7

Hardness of the pipe samples was measured on internal and external surfaces. Reduction in hardness of internal pipe surface is observed 20%. However, external surface experiences only 0.7% reduction in hardness. Reduction in hardness is 29 times more on internal layer of pipe material

because this layer has been directly exposed to hot and pressurized steam.

#### 4. Conclusion

Age related degradations have been observed in extraction steam piping of a nuclear power plant. Corrosion pits, which cause non-uniform reduction in thickness and reduce ultimate strength, have been observed with maximum depth of 0.07mm. 8.3% reduction in wall thickness has been observed due to mechanical rubbing and impinging of hot and



pressurized steam on internal surface. The hoop stress, acting in radial direction has been increased due to reduced wall thickness. Initially present bands of pearlite and ferrite have been eliminated due to prolong exposure to high temperature which changes the mechanical properties. Microstructure of pipe material has been transformed into uniform mixture of pearlite and ferrite. Graphite nodules have also been formed by detachment of carbon from iron in pearlite, which has reduced pearlite content from 40% to 25%. The reduction in pearlite is comparatively higher on internal surface layer of pipe as this layer faced hot and pressurized steam directly. The strength and hardness of the carbon steel SA 106B has been reduced due to this microstructural transformation. The need to frequent examination has been revealed by this study as the combine effect of microstructural degradation and pitting on internal surface of the piping may lead to fracture.

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