Journal
Teknologi

Full Paper

DEGRADATION ASSESSMENT OF NUCLEAR POWER PLANT EXTRACTION STEAM PIPING AFTER LONG TERM SERVICE

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Article history
Received
2 March 2016
Received in revised form
30 April 2016
Accepted
15 August 2016

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Abstract

Degradation due to ageing in a Nuclear Power Plant's Extraction Steam Piping has been assessed. Samples of twelve years old seamless carbon steel SA 106B pipe have been taken and subjected to metallographic examination, hardness testing, radiographic examination and ultrasonic thickness measurement to investigate and analyze ageing in piping material. Metallographic examination of aged sample revealed irregularly distributed graphite nodules in ferrite grains and on grain boundaries as well, the reduction in pearlite phase has also been observed from 40% to 25%. This Transformation in microstructure has reduced hardness of steel. Reduction in hardness has found 20.4% and 0.7% on inner and outer layer of the pipe material respectively. Corrosion pits having average depth of 0.07 mm have been found on external surface. Radiograph of aged pipe revealed material removal and wall thinning due to erosion on inner surface of pipe. The extent of erosion had been checked, which has found 8.7%.

Keywords: Degradation, extraction steam piping, SA 106B, carbon steel, NDT

Abstrak

Degradasi akibat penuaan sistem perpaipan pada tempat pengekstrakan wap di Pusat Kuasa Nuklear telah dinilai. Sampel untuk paip karbon keluli lancar SA 106B yang berusia dua belas tahun telah diambil dan pemeriksaan metalografi, ujian kekerasan, pemeriksaan radiografi dan pengukuran ketebalan ultrasonik telah dijalankan untuk menyiasat dan menganalisa tahap penuaan dalam bahan paip tersebut. Pemeriksaan metalografi untuk sampel tersebut telah mendedahkan bahawa nodul grafit telah diedarkan secara tidak sekata dalam bijian ferit dan sempadan bijian, serta pengurangan dalam fasa pearlit juga telah diperhatikan iaitu dari 40% kepada 25%. Transformasi dalam mikrostruktur ini telah menyebabkan kekurangan kekerasan keluli. Pengurangan kekerasan telah didapati iaitu masing-masing sebanyak 20.4% dan 0.7% pada lapisan dalaman dan luaran bahan paip. Lubang karat yang mempunyai purata kedalaman sebanyak 0.07 mm telah ditemui pada permukaan luar. Radiograf paip berusia telah mendedahkan bahawa penyingkiran bahan dan penipisan dinding adalah diakibatkan oleh hakisan pada permukaan dalam paip. Tahap hakisan telah diperiksa dan ianya telah didapati sebanyak 8.7%.

Kata kunci: Penuaan, degradasi, perpaipan pengekstrakan wap, SA 106B, keluli karbon, ujian tanpa musnah

1.0 INTRODUCTION

Carbon steel SA 106B has found various applications in the nuclear power plant industry. Seamless pipes of SA 106B are being used in main steam piping and feedwater pipings. Steam outlet nozzle and condenser structure is also fabricated from the same steel grade [1]. SA 106B is a plain carbon steel, 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 [2]. Replacement of such material is not feasible, so assessment of degradation has become essential [3].

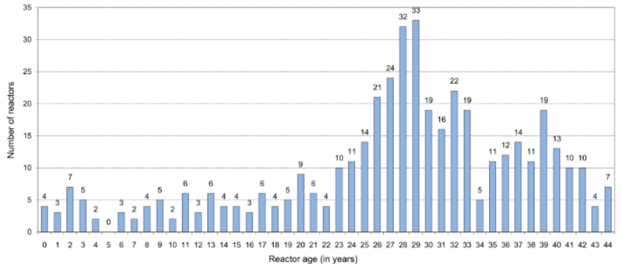

Figure 1 Number of reactors in operation by age (as of 31st Dec 2013) [4]

In order to remain economically effective and financially profitable, the modern industries have to take their safety culture to a higher level and consider production losses in addition to simple accident prevention techniques. Provisions for Safety Instrumented Systems (SIS) is highly recommended, both for conventional and nuclear industries [5]. A Multi-State Physics Modelling (MSPM) approach is also proposed for degradation modelling and failure probability quantification of Nuclear Power Plants (NPPs) piping systems recently [6]. Methods on the durability evaluation in nuclear power plant concrete structures was also investigated thoroughly and reported elsewhere [7]. Nuclear power plants have proved themselves as an economic option for fulfilling the continuously increasing demand of power. Most nuclear power plants operating today have been in operation for decades, Figure 1 [8]. Due to long operation, in the recent past, several failures, including piping, have been reported worldwide in nuclear power plants (NPPs) [9-14]. EPRI (Electric Power Research Institute) summarised 4064 nuclear piping failures in USA from 1961 to 1997 [12]. For the intensive collection of piping failure data in NPPs, OECD/NEA initiated the OPDE (OECD Piping Failure Data Exchange) project from 2002 in which 12 OECD/NEA countries participated. There are about 3600 piping failure data in the OPDE database version 2009-1 [13]. SKI database of Sweden also listed about 4100 piping failures from 1970 to 1997 in 29 countries [14]. The piping failure database can be used in the aging management programme for the intermittent safety review and continued operation, the probabilistic safety assessment, the screening criteria of the leak before break application, and the in-service inspection including the augmented inspection and the risk-informed in-service inspection.

The specific design life of aged nuclear power plants was based only on fatigue life calculation instead of age related material degradation [8]. The materials in nuclear power plants endure hard conditions, and degrade as a result of creep, corrosion, phase changes and emerging of micro-defects. The harmed material can initiate any failure by lowering mechanical properties [15].

Managing the safety aspects of nuclear power plant (NPP) ageing requires implementation of effective programmes for the timely detection and mitigation of ageing degradation of plant systems, structures and components (SSCs) important to safety, so as to ensure their integrity and functional capability throughout plant service life. General guidance on NPP activities relevant to the management of ageing (operation maintenance, surveillance, and inspection of SSCs) is given in the IAEA Safety Standards on the Safety of NPPs, Operation Requirements [15] and associated Safety Guides on in-service inspection, maintenance [17] and surveillance [19].

Integrity assessment of engineering components and structures are becoming increasingly important for both economic and safety reasons. Until recently, Non-Destructive Evaluation (NDE) was relegated to detecting physical flaws and estimating their dimensions. These data were used to determine if a component should be scrapped or repaired, based on quality-acceptance criteria, hence proving defect assessment a way to control structural integrity reliably [20].

Since the interrogating field and the interactions are different, the minimum detectable defect sizes are different in different NDE techniques and mainly depend on the instrumentation. There are many non-destructive test (NDT) techniques based on various physical principles [21]. The interaction of a medium (like electromagnetic radiation, sound waves) with various types of anomalies present in a material under study are used to quantitatively assess structural integrity. NDE procedures involve establishing correlations between non-destructively measured physical/derived parameters and quantitative information about anomalies. The knowledge of microstructural variations in a component is also very important to ensure the desired performance. In addition to the information about defects and microstructures, knowledge of residual stresses in a component is also essential for reliable assessment of structural integrity. Since the discovery of X-rays by Rontgen [22], the use of X-ray radiography for NDE, medicine, materials research, archaeology, quality control or homeland security has increased gradually in the recent years. Ultrasonic Testing (UT) is among other NDE methods, used widely for the detection and characterisation of defects in structural welds [23].

In this paper, a brief description of the physical concepts of various NDT methods and the physical/derived parameters which are used for assessing the above mentioned anomalies, namely defects/stresses/microstructure, are given.

2.0 METHODOLOGY

The nuclear power plant in study has been in service for more than for 40 years now. A 2.76mm thick SA106B carbon steel pipe (OD: 21.34mm), cut from extraction passage (high pressure turbine to deaerator) was provided to assess the ageing effects of nuclear power plant's extraction Steam Piping. A sample from the same material in the as-received state was also studied. Metallographic examination was then carried out using NIKON Metallurgical Microscope as per ASTM E3. Section of an aged pipe was subjected to radiographic testing (RT) using smart 225 KV X-Ray machine to examine any disturbance in the uniformity during plant operation. Exposure time was 60 seconds. Image quality indicator (IQI), 0.25mm, was used following ASTM 1A-6. Ultrasonic testing (UT) was also performed using DM4 DL ultrasonic thickness gauge to record any reduction in the thickness due to erosion. Both RT and UT were performed as per ASME SEC-V. Hardness measurement was performed using Rockwell Hardness Scale B according to ASTM E-18.

3.0 RESULTS AND DISCUSSION

3.1 Corrosion

Visual examination shows no disturbance in the uniformity of as received pipe (Figure 2). Whereas, aged pipe shows marked surface corrosion (Figure 3), confirming the long term service in sea shore environment. Corrosion has the potential to reduce a product's design life by premature degradation [23]. Examination of corroded surface under metallurgical microscope (Figure 4) revealed formation of 0.07 mm deep corrosion pits.

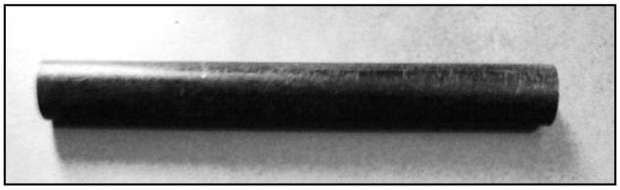

Figure 2 SA 106-B Seamless Pipe (As received)

Figure 3 SA 106-B Seamless Pipe (Aged)

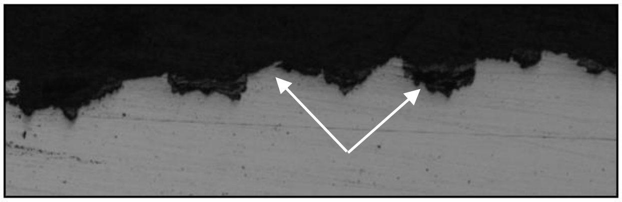

Figure 4 Diamond Polished External Surface of Aged Pipe Sample Showing Corrosion Pits (arrows), 100X

3.2 Erosion

Section of an as-received pipe was subjected to radiographic testing (RT) which revealed no material degradation (figure 5). Radiographic examination of aged pipe revealed the material removal on the internal pipe surface (figure 6). This has occurred due to mechanical rubbing of steam [25] which was being supplied from middle stage extraction of high pressure turbine to deaerator at 0.1 MPa pressure and 250 ^{0}F temperature.

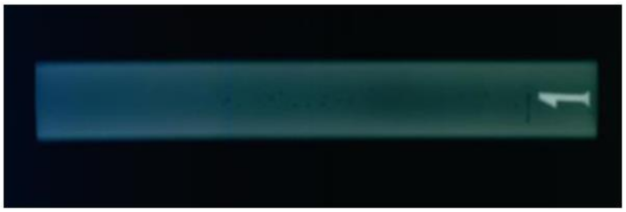

Figure 5 Radiograph of as received (AR) Sample

Figure 6 Radiograph of Aged Pipe

3.2 Thickness Reduction

Impinging of high pressure steam causes the material removal from internal pipe surface [25]. Ultrasonic testing has been performed to determine the intensity of erosion; results have been summarised in figure 7. On average; 8.7 % reduction in thickness has taken place from 2.76 mm to 2.52 mm after 12 years of service.

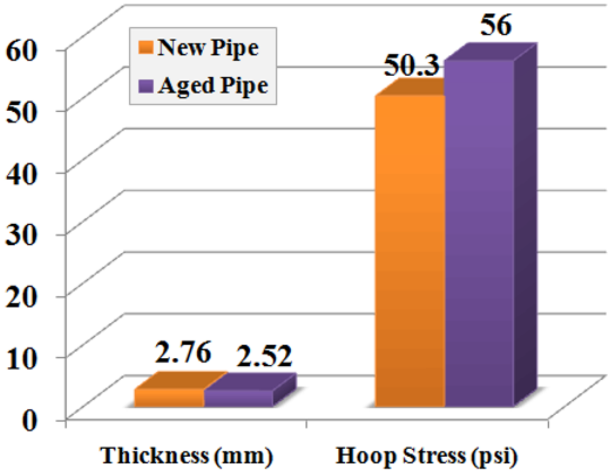

Figure 7 Reduction in Thickness and Increase in Hoop Stress

The hoop stress which acts in tangential direction to the axis of pipe because of the pressure inside the pipe depends upon thickness of pipe [25]. As the pipe degrades and thickness reduces, the probability of pipe failure increases due to increase in hoop stress [25]. Reduction of 8.7% in thickness has increased 11.3% hoop stress upto 0.39MPa, which is very lower than the yield strength of SA 106B (240 MPa) [24] and can not cause any significant deformation.

3.3 Microstructure Transformation

Microstructure of new carbon steel pipe exhibits bands of pearlite and ferrite (see Figure 8); which is typical of the extruded material [27]. Inner surface layer of new pipe is showing decarburized layer up to 0.1 mm occurred during cooling of steel to room temperature after hot extrusion [28]. This anisotropic structure shows poor resistance to impact load.

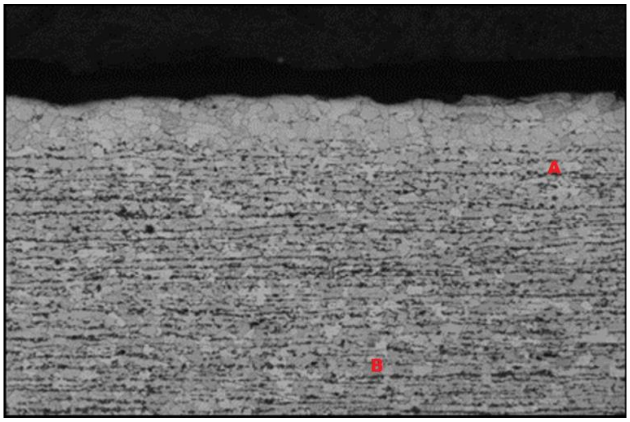

Figure 8 Nital Etched Microstructure of New Seamless SA 106B Pipe, 100X (A= Pearlite, B= Ferrite)

Abrasive action of steam has removed the inner decarburized layer in aged carbon steel pipe (see Figure 9). Prolong exposure to high temperature has distributed pearlite uniformly throughout the matrix and no bands of pearlite and ferrite are present now. Mixture of ferrite and pearlite is more resistant to impact load.

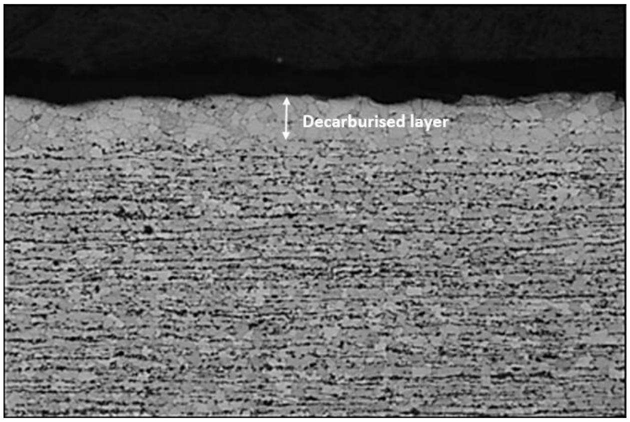

Figure 9 Nital Etched Microstructure of Aged Seamless SA 106B Pipe, 100X

Amount of pearlite and ferrite was 40% and 60% respectively in new carbon steel, which has changed to 25% pearlite and 75% ferrite (Figure 10). Softness is induced with increment of ferrite content, which eventually leads to failure.

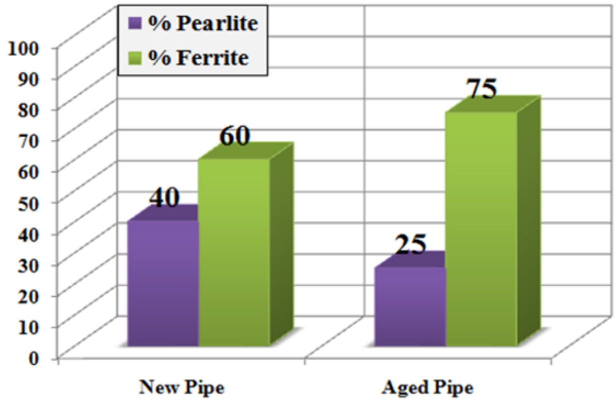

Figure 10 Change in Amount of Pearlite and Ferrite Phase after Prolong Service

Reduction in pearlite has occurred due to the formation of graphite nodules (see Figure 11) and it is more near inner layer of the pipe, as it has been in direct contact with steam for 12 years. Decrease in amount of pearlite decreases strength and hardness of steel.

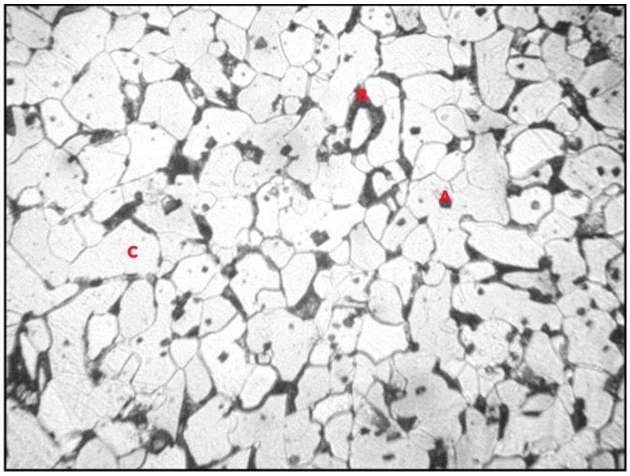

Figure 11 Nital Etched Microstructure of Aged Seamless SA 106B Pipe, 400X (A=Graphite nodules, B=Pearlite, C=Ferrite)

3.4 Hardness

Hardness of the pipe samples has been measured on inner and outer surfaces. Results have been shown in Figure 12. Reduction in hardness of inner pipe surface has found 20%. But on outer surface, it has found 0.7% only. Reduction in hardness is more on inner layer of pipe material because this layer has been directly exposed to hot and pressurized steam.

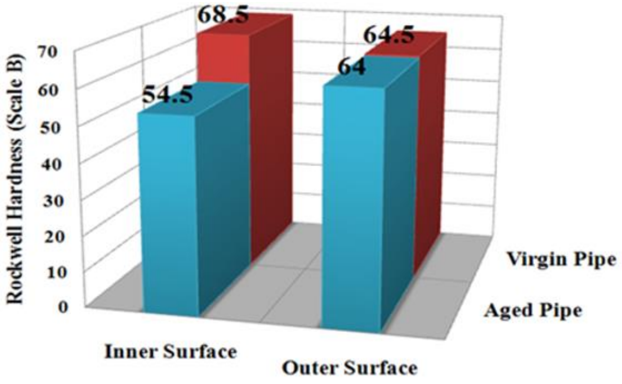

Figure 12 Difference in Hardness of Virgin and Aged Pipe on Inner and Outer Surface

4.0 CONCLUSION

Piping used in high temperature pressure application degrades with time, so is the case with nuclear power plant's extraction steam piping. Corrosive environment formed 0.07 mm deep pits, whereas mechanical rubbing and impinging of hot and pressurized steam has scratched the internal surface. Reduction of 8.7% in thickness has also occurred due to erosion. This deterioration due to erosion and corrosion can be minimised by using Chrome-Molybdenum-Copper steel pipe with protective coating.

Initially present bands of pearlite and ferrite have been eliminated due to prolong exposure to high temperature and microstructure of aged steel has uniform mixture of both phases. Graphite nodules has also been formed by detachment of carbon from iron in pearlite, this has reduced pearlite content from 40% to 25%, the reduction in pearlite is more in internal surface of steel as this layer had been facing hot and pressurized steam directly. This Transformation in microstructure reduces hardness and strength of steel.

The internal surface of steel has faced 20% reduction in its hardness. This much reduction hardness can not cause any harm as the pressure of steam inside the pipe is below the high level pressure of 0.8 MPa.

Acknowledgement

The authors acknowledge the support and are most grateful of UTM, Malaysia and HITEC University, Taxila, Pakistan for their significant efforts and commitments in conducting experiments throughout research period.

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