ISSN (Print) : 0974-6846
ISSN (Online) : 0974-5645
Indian Journal of Science and Technology, *Vol 12(43), DOI: 10.17485/ijst/2019/v12i43/144730, November 2019*

The Impact of Hydrostatic Pressure Test on the Interstitial Strength of Mild-Steel Pipeline Material

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Abstract

Objectives: This study examined the effect of hydrostatic test practice on the mechanical properties of steel pipeline used in the oil and gas industry. **Method/analysis:** The method involves subjecting a 76.2 mm (3-inch) and 101 mm (4-inch) pipeline spools to predetermined maximum allowable operating pressures and designed hydrostatic pressures at designated data points. Thereafter, the spools were cut and samples prepared for experimental tests and analysis. **Findings:** The results showed that there is a significant change in the mechanical properties like fatigue strength and ultimate tensile strength. The result also showed a progressive increase in the fatigue strength from the control specimens to the hydrostatic pressure-tested specimens. The control specimens also exhibited a reduced fatigue strength compared to the maximum allowable operating pressure (MAOP)-tested specimens. Thus, since the hydrostatic pressure-tested specimens exhibited the highest fatigue strength, this could be reasonably attributed to the strain-hardening behaviour. **Novelty/improvement:** The hydrostatic pressure-testing procedure, at least, is not detrimental to the integrity of the pipeline. At best, it is beneficial since it increases the strain-hardening of the material.

Keywords: Hydrostatic Testing, Service Pressures, Near Point, Far Point, Mechanical Properties, Integrity

1. Introduction

Hydrostatic pressure testing is a common practice in the oil industry that is used to ascertain the structural integrity of a pipeline after the completion of construction and especially when a major repair is carried out in the oil and gas industry.[1] It is also used during the operational phase for the same purpose. However, the operational disturbances caused by retesting make use of less disruptive methods such as intelligent pigging preferable. In[2–3] this process, the pipeline material is subjected to pressures as high as 108% of their SMYS,[4] and the implication of this high pressure is that there may be a change in the overall properties of the pipeline material, such as the strength, creep characteristics, crack propagation properties, as well as the total service life expectancy of the pipeline installations.

In view of the factors highlighted previously, the present study aims to investigate the impact of hydrostatic pressure testing on the interstitial strength of mild-steel pipeline materials. This is, therefore, carried out in order to determine the impact of hydrostatic pressure testing on the tensile strength, fatigue strength, and hardness of pipeline materials and also to establish the basis for continuity or otherwise of hydrostatic testing of pipeline systems from micro-structural impact approach.

Despite the dearth of literature on previous works on hydrostatic testing, there has been a prima facie study that showed that the hydrostatic pressure testing of a pipeline material subjected to pressure as high as 1.5 times the

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maximum allowable operating pressure (MAOP) likely has an evident effect on the micrographic configuration of the pipeline material.[2] However, this study failed to predict the extent of the impact on the pipeline on the interstitial strength of the material. Early attempts by[5] showed that hydro testing affects the plastic deformation of the material. Similarly,[6] also showed that the process affects the yield strength of quenched and tempered AISI 4310 and 4330 steels subjected to high-pressure testing. In addition, this study will establish the appropriate level of pressure to be applied during high-pressure test required for newly constructed and in-service pipelines.

2. Materials and Method

The materials used in the present study include fabricated pipe spools of 3-inch and 4-inch circumferences, respectively, a hydraulic pump, a Barton 202E pressure–temperature recorder, a fatigue-testing machine, Vickers's hardness indentation-testing machine. The pipeline materials were selected based on specific criteria that included the following: product popularity in the pipeline industry, the extent of its usage in transporting liquid hydrocarbons, cost, and availability. The pipe material selected was ASTM A106 Grade B Carbon Steel. The flanges were located at the ends of the pipes. The system incorporates safety valve to safeguard the system against rupture. The valve opens as soon as the pre-set test pressure is exceeded and closes when the excess pressure has been relieved. The pump used is a manually operated hydraulic pump with pressure capacity up to 10,000 psi as shown in Figure 1.

The fatigue-testing machine was used to test the fatigue of the material. The procedure involved the machining of the specimens to fit the fatigue-testing equipment using appropriate tools and machinery. The Vickers micro-indentation hardness test machine was used for the hardness test.

Figure 1. Pressurising the spool using the Enerpac hand-operated pump.

The testing and recording were done at the Petroleum Training Institute (PTI), Warri in Delta State. The pressure readings for the duration of the test are recorded on a standard graphic chart (see Figure 2).

The Barton 202E pressure–temperature recorder (shown in Figure 3) was used to measure the pressure and temperature, respectively. The machine has a 12-inch diameter as shown in Figure 3.

3. Experimental Setup and Procedure

Treated water was introduced into the pipe spool through the nozzle close to the head flange. The water was poured

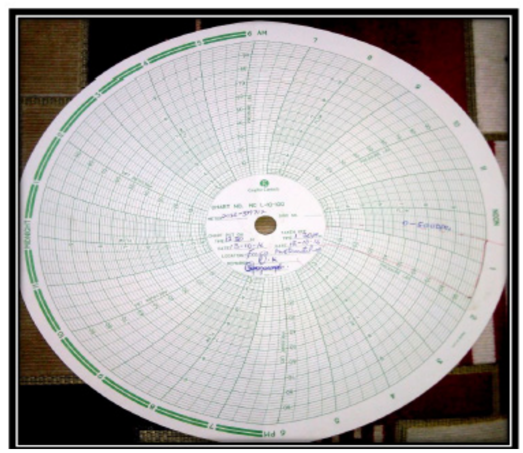

Figure 2. Pressure-recording chart.

Figure 3. Barton 202E pressure–temperature recorder.

into the pipe manually until it was filled up. The pipe spool was inspected all around to find any possible location for leakage, especially around the flanges. After confirmation that all areas were water-tight at atmospheric pressure (see Figure 4), the filling process was stopped. More water was pumped into the vessel in order to pressurise it up to the desired test pressure. The system was allowed to remain at that pressure for more than 4 hours. The system was depressurised at the end of the test period.

A small section of the pipe spool (12 inches) was cut out from the parent spool and labelled according to the pressure test to which it was subjected (hydrostatically tested or service-pressure-tested) as shown in Figures 5 and 6.

The cutting process was carried out by certified technicians in an isolated work area. The cut samples of the spools were cleaned and packaged for transportation to the material-testing facility. The spools were prepared for use as different test specimens as shown in Figure 6. The specimens prepared were consequently subjected to the various tests outlined using the appropriate instruments. Subsequently, the dimensions of the labelled specimens were measured and recorded. The bending stress was calculated using the distance from the load end to the minimum diameter of the specimen. The bending stress, σ, was calculated using the following formula:

$$\sigma = \frac{L_s N \times 32}{\pi \times D^3} \tag{1}$$

where, L_s = Active length of the specimen

N = Load applied to the specimen

D = Diameter of specimen.

The fatigue test was conducted at room temperature using the fatigue-testing machine as shown in Figure 7.

In the same manner, the hardness test was carried out using the Vickers micro-indentation hardness-testing machine. The procedure used for the test was in full alignment with the industry best practices. In general, all the tests were carried out at ambient temperature, between 10°C and 35°C. There are about 32 different experiments that can be used to determine the impact of hydrostatic testing on the interstitial strength of the mild-steel pipeline materials used in the present study. The preceding section outlined the results of the tests conducted.

Figure 4. The experimental setup for the hydrostatic testing.

Figure 5. The cutting of the spools for machining.

Figure 6. Finished specimens ready for fatigue test.

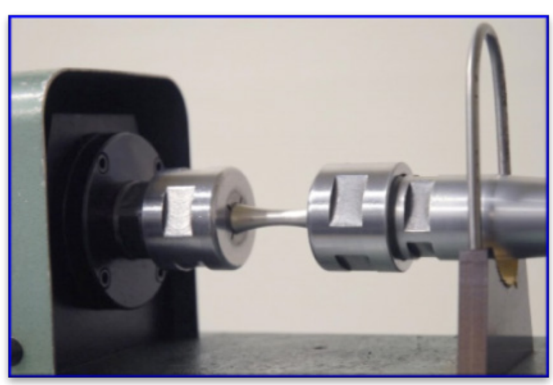

Figure 7. Fatigue test setup.

4. Results and Discussions

The results obtained in the present study revealed that the hydrostatic testing has a remarkable effect on the interstitial strength of the pipeline materials. In view of the above, this section presents the results obtained from the experiments as shown from Figures 8 to 15 and Tables 1 and 2.

Figures 8 to 15 indicate the results of the interstitial strength experiments. Figures 8 and 9 show the Vickers hardness test results for the 3-inch and 4-inch pipe specimens, respectively. The percentage elongation for the 3-inch and the 4-inch specimens, respectively, are shown in Figures 10 and 11. Similarly, the stress–strain curves of the 3-inch and 4-inch pipe specimens are shown in Figures 12 and 13, respectively. Finally, Figures 14 and

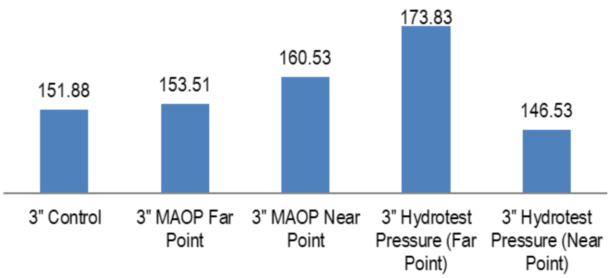

Figure 8. Bar chart showing Vickers hardness relationships between the 3-inch specimens.

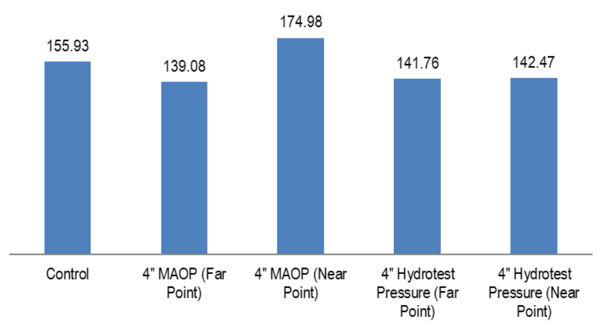

Figure 9. Bar chart showing the Vickers hardness relationships between the 4-inch pipe specimens.

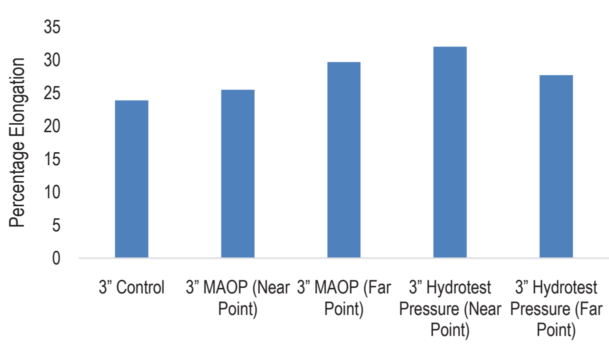

Figure 10. Percentage elongation for the 3-inch pipe specimens.

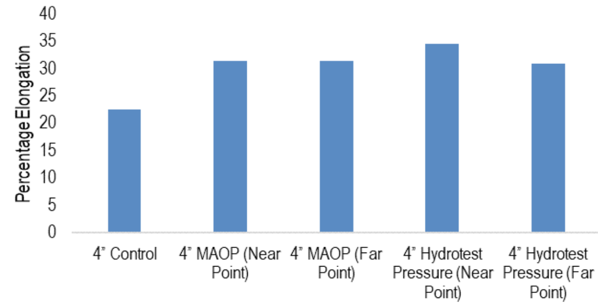

Figure 11. Percentage elongation for the 4-inch pipe specimens.

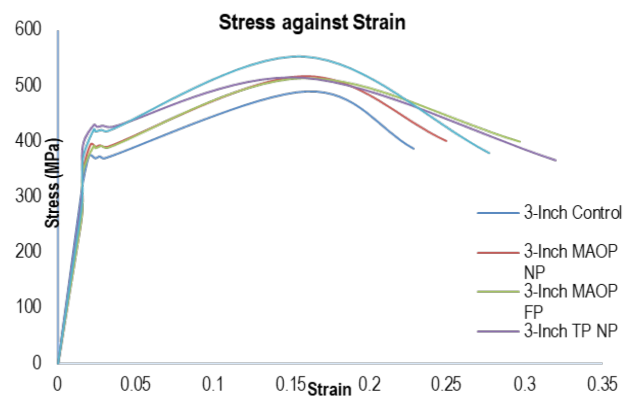

Figure 12. Stress–strain curves of the 3-inch pipe specimens.

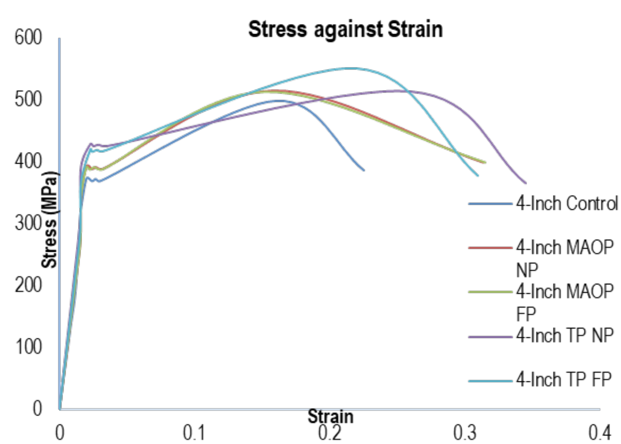

Figure 13. Stress–strain curves of the 4-inch pipe specimens.

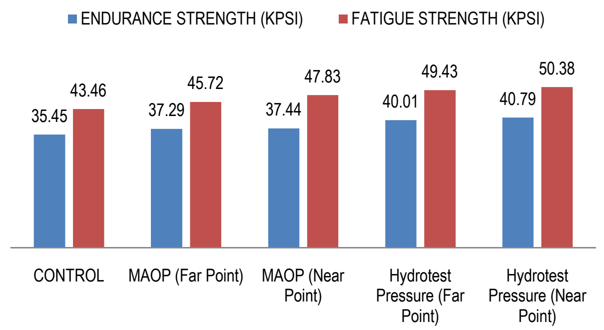

Figure 14 Relationship between Fatigue Strength & Endurance Limit in 3-inch Pipe Specimens

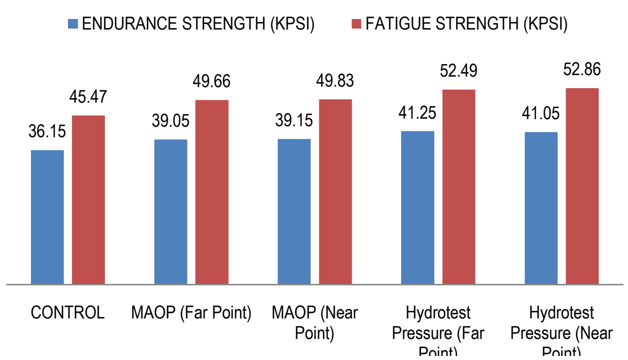

Figure 15 Relationship between Fatigue Strength and Endurance Limit in 4-inch Pipe Specimens

15 show the relationship between fatigue strength and endurance limit in the 3-inch and 4-inch pipe specimens.

Tables 1 and 2 show the summary of the pipe specimen results for the 3-inch and 4-inch pipes, respectively.

4.1. The Vickers Hardness Test Results

The Vickers hardness test results for the 3-inch pipe specimens, as shown in Figure 8, indicated that the control specimens have the least Vickers hardness value when compared to the average hardness of the other specimens, which is 151.88 compared to MAOP specimens of 157.02; hydrostatic pressure-tested specimens had 160.18. Thus, the MAOP specimens taken from far point are less hard than the specimens taken from the near point.

For the hydrostatic pressure-tested specimens, the opposite result was noticed. The far-point specimens were considerably harder than the near-point specimens. The average Vickers hardness of the hydrostatic pressure-tested specimens are higher when compared to the average Vickers hardness of the MAOP-tested specimens. This simply means that the higher the imposed pressure in the pipeline, the higher the Vickers hardness value, until the material ruptures.

Similarly, the Vickers hardness test results for the 4-inch pipe specimens as shown in Figure 9 indicated a similar trend with the 3-inch specimens. The hardness of the control specimens was less than the hardness of the MAOP-tested specimens but not less than that of the hydrostatic pressure-tested specimens. For the MAOP-tested specimens, the near-point specimens were harder than the far-point specimens. For the hydrostatic pressure-tested specimens, the results were similar to the MAOP-tested specimens; the near-point specimens were harder than the far-point specimens. However, the hardness of the control specimens and the average hardness of MAOP-tested specimens were higher than the average hardness of the hydrostatic pressure-tested specimens. This simply implies that the higher the pressure imposed on the pipeline, the higher the Vickers hardness value.

Table 1. The summary of 3-inch-pipe specimens results

Specimen	Control	MAOP		Design hydrostatic pressure-tested	
		Far point	Near point	Far point	Near point
Average grain diameter (μm)	8.19	6.89	6.89	6.64	6.34
ASTM grain size numbers	11.33	11.47	11.4	11.53	11.47
Average grain density (x1000 per sq. mm)	19.96	21.95	20.95	22.95	21.95
Vickers hardness	151.88	153.51	160.53	173.83	146.53
Yield strength (MPA)	379.37	394.16	392.52	429.43	421.22
Ultimate tensile strength (MPA)	489.01	516.36	514.22	562.59	551.8
Endurance strength	244.42	257.11	258.14	275.86	281.24
Fatigue strength	299.65	315.23	329.78	340.81	347.36

Table 2. The summary of the 4-inch pipe specimen results

Specimen	Control	MAOP		Design hydrostatic pressure-tested	
		Far point	Near point	Far point	Near point
Average grain diameter (μm)	7.44	6.78	6.55	8.02	6.14
ASTM GRAIN size numbers	11.10	11.26	11.18	11.00	11.40
Average grain density (x1000 per sq. mm)	16.96	18.96	17.96	15.96	20.95
Vickers hardness	155.93	139.08	174,98	141.76	142.47
Yield strength (MPA)	399.00	412.23	411.29	432.07	434.27
Ultimate tensile strength (MPA)	498.56	540.02	538.79	566.01	569.89
Endurance strength (MPA)	249.25	269.24	269.93	284.41	283.03
Fatigue strength (MPA)	313.50	342.39	343.56	361.91	364.46

4.2. Percentage Elongation Test Results

The phenomenon of percentage elongation gives an idea of the extent the material will respond when subjected to load before reaching its elastic limit. The results obtained from the present study are shown in Figures 10 and 11. The results for both specimens showed a similar trend. At the various data points, a close similarity was seen between the 3-inch and 4-inch specimens. However, it was observed that the hydrostatic pressure-tested near-point 3-inch and 4-inch pipe materials experienced the highest elongation at 32.0% and 34.5%, respectively. This could be attributed to the fact that the ductility of the material increased with hydro test, and this effect is more pronounced at the near point (the near-point specimens presumably experienced the greatest amount of pressure during the experiment) as shown in the Figures 10 and 11.

4.3. Stress–Strain Test Results

From the stress–strain diagram as presented in Figures 12 and 13, it can be seen that the curves for both the 3-inch and 4-inch pipe specimens indicate a higher ultimate tensile strength at the near points than at the far points. This could be explained as follows: as the two pipes are subjected to hydro test, they get stressed beyond the point where a permanent setting takes place, thereby entering into the regime of plastic deformation. In the plastic deformation regime, the pipe does not recover completely from the initially imposed strain, even after the removal of the causative load. As the force is increased further, a point is reached where the test specimen stays stretched even when the stress is not proportionately increased. This point is called yield point.

There were two yield points obtained, namely, upper and lower yield points. With further straining, the effect of a phenomenon called strain-hardening or cold work-hardening takes place. The pipe material became stronger and harder, and its load bearing capacity increased. Therefore, the pipe specimens were able to sustain increased stress. The conclusion, therefore, is that the strain-hardening effect was more noticeable at the nearest-points scenario of the tested pipe specimens than the farthest-point pipe specimens.

4.4. Fatigue Strength Test Results

The results of the fatigue tests of the specimens are discussed in this section. It was clearly observed in the figures prepared that the fatigue strength of the specimens increased with the increased hydrostatic pressure.

For the 3-inch-pipe test specimens there was a progressive increase in fatigue strength from the control specimens to the hydrostatic pressure-tested specimens, ranging from approximately 43 to 51 psi. However, the control specimens exhibited a lower fatigue strength compared to the MAOP-tested specimens. In overall consideration, the hydrostatic pressure-tested specimens exhibited the highest fatigue strength. A reasonable deduction is that due to strain-hardening they are able to withstand more fatigue test cycles before the eventual failure.

Similarly, the 4-inch pipe test specimens also showed a progressive increase in fatigue strength from the control specimens to the hydrostatic pressure-tested specimens, ranging from approximately 45 to 53 psi. The control specimens also exhibited a reduced fatigue strength compared to the MAOP-tested specimens. Overall, the hydrostatic pressure-tested specimens exhibited the highest fatigue strength, which can be reasonably attributed to the strain-hardening behaviour.

5. Conclusions and Recommendation

The following conclusions have been drawn from the study:

- Hydrostatic pressure testing of mild-steel pipeline materials has a very significant impact on the interstitial strength of the material.
- The mechanical properties of a mild-steel material are altered by hydrostatic pressure-testing activities, namely:
  - The hardness property of a mild-steel pipeline material is altered by hydrostatic pressure-testing operation. There is a strong indication that this is a result of the strain-hardening of the material.
  - The tensile strength of a mild-steel material is altered by hydrostatic pressure testing. There is an increase in the overall tensile strength of mild-steel pipeline material after it was subjected to hydrostatic pressure test.
  - The endurance and fatigue strengths of a mild-steel pipe material are affected by the hydrostatic pressure test. The ASTM A106 material has improved the fatigue and endurance strengths after it was subjected to the hydrostatic pressure test.
  - There is a pseudo-linear relationship between the tested mechanical properties of mild-steel pipe material and the hydrostatic test pressure applied to the material. The mechanical properties increase with an increase in the test pressure. The limit of this relationship is suspected to be close to the burst pressure of the pipeline material.
  - The effects of the test pressures at the far-point and the near-point scenarios of the hydrostatic pressure-tested mild-steel material are significant; it has, therefore, been established that hydrostatic pressure-testing of pipelines, at least, is not detrimental to the integrity of the pipeline material. At best, it is beneficial since it increases tensile strength, endurance limit, fatigue strength, and strain-hardening of the pipeline material.

The following are the few recommendations made from this research:

- The limits of the near-direct linear relationship between the test pressure and the mechanical properties of mild-steel material should be followed up.
- The effect on the creep property of the pressure-tested specimens should be investigated.
- Further research should consider replicating the methodology of this research on other material types, such as the stainless steel materials.
- A mathematical equation should be derived to correlate the atomic packing factor (APF) with the strength of the material after it is subjected to different levels of pressures.

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