Investigation of Mechanical Properties for Carbon Steels Tubes Serviced at High Temperature after Long Time of Operation

Ahmed Naif Al-Khazraji, Samir Ali Amin, Husam Ahmed Al-Warmizyari

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ABSTRACT

This paper aims to study the behavior of mechanical properties (impact, hardness, yield strength, and tensile strength) of reformer furnaces tubes made from carbon steel and working at maximum service temperature. Samples of tubes made from carbon steel (A-106 Gr.B) were taken from furnace serviced in reformer unit for long time which is more than the design life (100000 hr). The properties are compared with non-used tubes samples of the same materials. These samples were investigated to have supportive techniques to estimate the remaining safe working life of furnaces operated in high temperature for long time or for furnaces exceed their design life. Charpy v-notch impact tests were performed for each furnace tube material (carbon steel) and also for its similar tube material as non-used one. Tests for each material type were first done at room temperature, then at the maximum tube wall temperature in service (285 °C), to find out the amount of energy absorbed before fracture and the behavior of tube material under such operating conditions during the stages of operation life. Hardness for samples classified as [Carbon Steel (C.St.)-Non-Used, and Carbon Steel (C.St.)-Used] was measured. Standard hot tensile test experiments were performed at different test temperatures [25 °C, 200 °C, 300 °C, 400 °C] for the non-used and used samples. It was found that the samples have the same behavior of increasing hardness and impact energy at service temperatures after their operational age. Hardness is increased by percentage (15.57%) as the material aged, while the impact energy for the two types of materials are increased by percentage (20.86%) at room temperature test and (10%) at 285°C test temperature. Tensile properties of carbon steel A-106 Gr.B, such as yield decrease as temperature increases, while tensile strength increases as temperature increases up to the blue region of temperature range (around 200 °C), and decreases after that.

KEYWORDS: Carbon Steel; Mechanical Properties; Tensile Strength; Hardness; Impact; Tube Furnace

INTRODUCTION

Parts of equipment such as tubes furnaces in different engineering fields running under elevated operating conditions as temperature for a working life more than what design to, may produce different types of damages. Furnaces are used widely in petroleum industry, especially in refining sector to heat up hydrocarbons up to the required temperature for the process, and can be represented as the heart of the process in such plants. The main equipment in petroleum plants can be designed for a life using many governing code and standards taking in considerations the effects of temperature of operation, the applied load, type of alloy used in equipment and its mechanical properties, and also the importance of this equipment in the plant process with its degree of hazard. Such equipment are designed for nominal life about 100000 hr (11.4 years) on the basis of standard API Recommended Practice 530 [1]. The assessment of mechanical properties is extremely important for safe working life; this is due to the microstructural changes that take place as a result of prolonged exposure to temperature.
Charpy impact test results can be used to evaluate material toughness [2]. Toughness is dependent on temperature and generally increases with increasing temperature [3]. The remaining life based on the measured fracture toughness and the mechanical properties for a furnace tube used to heat hydrogen, which had serviced for 100000 hr, was predicted [4][5]. Decrease in tube metal ductility as a result of excessive impact during starting up and unit shutting down should be paid more attention [4][5].

Metallurgical changes in metals which are serviced in elevated temperature can be detected using hardness measurements [6][7]. Measurements of hardness for materials in practice are observed with a high degree of scatter [8]. However, the technique of hardness measurement has been developed recently to be used in remaining life estimation [9][10].

A comparison between the used and non-used metals for the mechanical properties at different temperatures to figure out their roles to resist creep, can be useful to have better view on internal damage due to prolonged exposure to temperature, when these comparisons are made [2].

The objective of this paper is to make a comparison between the impact energy, hardness, and the tensile properties of aged tube made from carbon steel serviced at elevated temperature beyond the life design with a non-used tube of the same material and dimension; the results of this work can be used to support the remaining safe life estimation. Samples of tubes investigated in this work are extracted from Stabilizer Reboiler furnace belongs to Reformer unit at Daura Refinery; this unit is in operation since 1981 and still running. Subsequently, this unit exceeded its design life which is 100000 hr. The design pressure and design wall temperature are 20.2 MPa and 300 oC, respectively, tube diameter is 168.3 mm, and tube thickness is 7.11 mm, where the tubes are made from carbon steel material A-106Gr.B.

2. Experimental Work:
2.1. Material Composition:
Tubes of Stabilizer Reboiler furnace made from carbon steel material with designation A-106 Gr.B, and a non-used tube of the same designations above are compared with standards. The chemical compositions for these tube materials are listed in table 1.

Table 1: Chemical compositions of carbon steel tube samples in comparison with standard

<table>
<thead>
<tr>
<th>Materials</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Ni(^a)</th>
<th>Cr(^a)</th>
<th>Mo(^b)</th>
<th>Cu(^a)</th>
<th>V(^a)</th>
<th>P</th>
<th>S</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-106Gr.B</td>
<td>0.3(^a)</td>
<td>0.10(^b)</td>
<td>0.29-1.06</td>
<td>0.4(^b)</td>
<td>0.4(^b)</td>
<td>0.15(^b)</td>
<td>0.4(^b)</td>
<td>0.08(^b)</td>
<td>0.035(^b)</td>
<td>0.035(^b)</td>
<td>Rem.</td>
</tr>
<tr>
<td>(standard)(^1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. St. Non Used</td>
<td>0.18</td>
<td>0.21</td>
<td>0.47</td>
<td>0.04</td>
<td>0.045</td>
<td>0.008</td>
<td>0.13</td>
<td>&lt;0.002</td>
<td>0.009</td>
<td>0.009</td>
<td>Rem.</td>
</tr>
<tr>
<td>(experiment)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C. St. Used</td>
<td>0.14</td>
<td>0.23</td>
<td>0.59</td>
<td>0.094</td>
<td>0.14</td>
<td>0.039</td>
<td>0.22</td>
<td>0.003</td>
<td>0.009</td>
<td>0.007</td>
<td>Rem.</td>
</tr>
<tr>
<td>(experiment)</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\): Elements [Ni, Cr, Mo, Cu, and V] combined shall not exceed 1 %.  
\(^b\): Maximum.  
\(^c\): Minimum.

2.2. Mechanical Tests:
Specimens of Charpy v-notch impact test were prepared according to the American Standard ASTM E23[12]. Due to tube thickness restriction (thickness below 10 mm) specimens were prepared with sub size dimensions (10x5x55 mm), see Fig. 1. A universal impact test machine (Brooks – Model IT3U) was used in this work; this machine has a maximum impact energy 300 J, striking velocity 5.35 m/s, and effective weight of pendulum 21 Kg. The impact tests for specimens of each type of material were performed in two different temperatures, at room temperature and at operating temperature, as shown in Fig. 2.

Fig. 1: Specimen Dimensions for Impact Test [12].
Hardness tests of Vickers scale according to ISO-6507-1 [13] standard were done for samples of tubes (used and non-used carbon steel) using device (Nemesis 9000) with load 10 Kgf. Samples of these tubes were cut and prepared according to the requirement of adopted standard, these samples were mounted in plastic mounts for surface preparation. Surfaces of samples were prepared by grinding and polishing for hardness measurements.

Changes in strength between used and un-used material at a temperature range (from room temperature up to 400°C) can be found by performing a hot uniaxial tensile test. The aim of these experiments is to record the yield strength, tensile strength, and elongation for each type of materials. Standard tensile test experiments were performed at different test temperatures (25°C, 200°C, 300°C, 400°C), using a universal tensile testing machine type Shimatzu AG-25TC which uses a cylindrical electric heater surround the test specimen and the fixtures during hot tensile test, as shown in Fig. 3. The lower end of testing machine which holds the specimen through pin joint is stationary, and the upper end is moving at a constant speed up to fracture. Flat dog bone type specimens with thickness 3 mm for this purpose were prepared according to the standard ASTM E8 [15], see Fig.4.

Three thermocouples wires (type R) were attached to the specimens at top, middle, and the bottom of the reduced section in the specimen to ensure that the specimen has reached the equilibrium and that the temperature maintained within the specified limit. During the period of the test, the difference between the measured temperature at each one of the three measured zones and the set temperature is maintained within the acceptable limit (±3 degree Celsius) according to the standards ASTM E21[8-9].

Fig. 2: Specimen’s classification for Impact test.

Fig. 3: Tensile Test Machine type Shimatzu AG-25TC
RESULTS AND DISCUSSION

3.1. Impact Energy:

The results of impact test at room temperature and at 285°C can be seen in Fig. 5 (a and b) for comparison purposes. These figures also show that, as the service life of material increased, impact energy for carbon steel tubes increased by (20.86%) at room temperature test and increasing by (10%) at 285°C test temperature. It is thought that this increase is due to thermal effect accompanied with the softening mechanism by formation of soft microstructural constituent (decomposition of cementite leads to more ferrite formation) during service time of the tube at these temperatures.

Also, the result of impact test, which is mentioned in reference number [14] for a pipe made from carbon steel material according to standard API-5L was 73 J for standard specimen dimension (10x10x55 mm), this type of steel is comparative to the pipe material according to ASTM standard A-106 Gr.B and the result was 35.5 J for specimen dimension (10x5x55 mm), as shown in Fig. 5 (a). The impact energy is directly related to the cross-sectional area of the specimens, the value of impact energy is two times more than specimen with 50% reduction in cross-sectional area. Both sizes of used and non-used specimens showed similar behavior of increasing at room temperature and also at test temperature 285°C.

![Fig. 5](image)
a. Impact test at room temperature for specimens with dimensions 10x5x55 mm. b. Impact test at temperature 285°C for specimens with dimensions 10x5x55 mm.

Fig. 5: Impact energy comparison between used and non-used Carbon steel tube samples (A-106 Gr. B).
The impact tests results of carbon steel A-106 Gr. B with different test temperatures are illustrated in Fig 6. It can be seen that the impact energy for the non-used carbon steel increased by (15.10%), while that for used carbon steel increased by (4.76%). This increase possibly caused due to the refinement of ferrite grains because of the homogenization effect when the tube treated for a short time at 285 °C.

![Fig. 6: Relation between impact energy and test temperature for carbon steel (A-106 Gr. B).](image)

3.2. Hardness Behaviour:

Any individual of hardness measurement made in the lab will lack perfect precision that often leads to take multiple measurements at some independent variable. Though no one of these measurements is likely to be more precise than any other, this group of values will cluster about the true value we are trying to measure. This distribution of data values is often represented by showing a single data point, representing the mean value of the data, and error bars to represent the overall distribution of the data. The standard error for hardness measurement which has been done for the material’s samples was calculated (2.2549, and 0.7434) for samples of materials (non-used and used material), respectively.

It can be seen in Fig. 7 that hardness of the used material is increased by a percentage of (15.57%) more than the non-used state. It is believed that this increase, which will happen when heating a carbon steel at 285 °C, is due to the structure which becomes more homogenized accompanied with a slight increase in cementite that resulted in higher hardness.

![Fig. 7: Hardness measurement comparison between non-used and used tubes materials](image)

3.3. Tensile Properties:

The results of uniaxial tensile tests for carbon steel A-106 Gr.B under different test temperatures (25°C, 200°C, 300°C, 400°C) were drawn on the same stress-strain diagram for comparison, the resulted diagram for the non-used material can be seen in Fig. 8, while Fig. 9 shows the resulted diagram for the used material.
Tensile properties of carbon steel A-106 Gr.B, such as yield and tensile strength, generally decrease as temperature increases, but in this case the tensile strength shows an opposite behaviour for this metal in a range of temperature starting from 0 °C up to about 300 °C, it shows an increase and then a decrease in ultimate tensile stress, this state is similar between non-used and used material, see Fig. 10.

Fig. 8: Stress-strain curve under different temperatures for non-used carbon steel A-106Gr.B

Fig. 9: Stress-strain curve under different temperatures for used carbon steel A-106Gr.B for 290000hr

Fig. 10: Yield and tensile strength versus temperature for carbon steel A-106 Gr.B
Using the hot uniaxial tension test to differentiate between the non-aging and aging steels represents an easy method to do that. During those tests for carbon steel material under hot temperatures, a strain aging effect can be developed. Hot uniaxial tension tests performed in the temperature range of blue-heat region (around 200°C) for carbon steel, as shown in Fig. 10 and 11, will lead to decreasing the ductility, on the other hand this will causes strength and hardness increasing due to strain aging. The increasing of tensile strength at temperature 200 °C for the non-used and used samples is attributed to the higher temperature associated with the effect of strain aging embrittlement or the blue-brittleness because this effect happen in the region of blue-heat.

**Fig. 11:** Ruptured specimens of hot tensile tests in different test temperatures for non-used and used carbon steel material

Comparisons were made between the results of uniaxial tensile tests represented by stress-strain curves as shown in figures (12 to 15) for different test temperatures, each diagram compares the tensile properties of carbon steel A-106 Gr.B at specific temperature between the non-used and used samples. In general, the yield and tensile strength of carbon steel A-106 Gr.B shows slight increase for the used material compared with the non-used material, see table 2.

**Table 2:** Properties of carbon steel A-106 Gr.B at different test temperatures

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>25</th>
<th>200</th>
<th>300</th>
<th>400</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen Type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Non-Used</td>
<td>Used</td>
<td>Used</td>
<td>Used</td>
<td>Used</td>
</tr>
<tr>
<td>Yield Strength0.2% (MPa)</td>
<td>283</td>
<td>291</td>
<td>261</td>
<td>267</td>
</tr>
<tr>
<td>Tensile Strength (MPa)</td>
<td>465</td>
<td>472</td>
<td>588</td>
<td>616</td>
</tr>
<tr>
<td>Elongation, % (%)</td>
<td>33</td>
<td>49</td>
<td>19</td>
<td>31</td>
</tr>
</tbody>
</table>

**Fig. 12:** Stress-strain curve at room temperature for non-used and used carbon steel A-106Gr.B
Fig. 13: Stress-strain curve at 200°C temperature for non-used and used carbon steel A-106Gr.B

Fig. 14: Stress-strain curve at 300°C temperature for non-used and used carbon steel A-106Gr.B

Fig. 15: Stress-strain curve at 400°C temperature for non-used and used carbon steel A-106Gr.B
Changes in mechanical properties of material as a result of service life in different conditions from load, temperature, environment, etc., can be provided easily if we adopt usual examination techniques such uniaxial tensile tests to have data or figures aid the estimation of the current internal situation of these materials, or the degree of deterioration may exist.

Conclusions:

4.1 Impact energy of carbon steel tubes A-106 Gr. B increased by a percentage of (20.86%) after service age (290000 hr) and at temperature (285 °C).

4.2 The impact energy for the non-used tubes of carbon steel increased by a percentage of (15.10%) when the test temperature was increased from room temperature up to (285 °C).

4.3 Hardness of this type of steel increased by a percentage of (15.57%) at temperature (285 °C).

4.4 Yield strength decreased as test temperature was increased; on the other hand tensile strength increases in range of temperature around 200 °C, and decreases at a temperature more than the range referred to the blue range of steel.

4.5 Hot uniaxial tension test is the easiest way to differentiate between non-aging and aging steel.

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REFERENCES