Thermal Mechanical Fatigue of Coke Drum Materials

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Abstract Coke drums are vertical pressure vessels used in the delayed coking process in petroleum refineries. Significant temperature variation during the delayed coking process causes damage in coke drums in the form of bulging and cracking. There were some studies on the fatigue life estimation for the coke drums, but most of them were based on strain-fatigue life curves at constant temperatures which do not consider simultaneous cyclic temperature and mechanical loading conditions. In this study, a thermal-mechanical material testing system is successfully designed and implemented. A selected set of base and clad materials of coke drums are investigated under isothermal cyclic loadings. In addition, a comparative study between isothermal and thermal mechanical fatigue lives of clad materials is conducted. Some of these fatigue tests are similar to the actual loading scenario experienced by the coke drums. The experimental findings lead to better understanding of the damage mechanisms occurring in coke drums and more accurate prediction of fatigue life of coke drum materials.

Keywords: Coke drums, Low cycle fatigue, Isothermal mechanical fatigue, Thermal mechanical fatigue

1. Introduction

Coke drums are vertical pressure vessels used in the delayed coking process in petroleum refineries and oil sands plants. They are normally constructed of carbon or low carbon alloy steels and internally clad with SA 240 Type 410S or Type 405 stainless steel to protect the coke drums from corrosion. They range in size from 4 to over 9 meters in diameter and 25 to over 40 meters in height. The maximum shell thickness varies from 14 to 42 millimeters. The maximum operating temperature ranges from 427 to 482°C [1].

First, heavy residual is imported into a coker heater and heated to approximately 482°C. Before direct the heavy oil into the coke drum, the drum is preheated by flowing vapour from the bottom of the drum to the top. (Temperature rises from approximate 150 °C to 360 °C). Then, the hot heavy oil is directed into the coke drum to begin the fill cycle. The fill cycle usually takes 14-18 hours. When the filling is completed, light hydrocarbon from the coke produced during the thermal cracking process is removed by steam stripping. (Temperature drops from 450 °C to 250 °C approximately) After that, high rate of quench water is injected into the coke drum cooling the vessel and possibly extracting the solid coke. After soaking, the solid coke is cut by applying the high-pressure water steams. After all the coke is removed from the drum, the coke drum is reheated and checked in order to prepare for a new operation cycle. [1]

The severe cyclic thermal-mechanical load makes coke drums susceptible to damage. It is also found that shell bulging is one of the causes contributing to cracking and failure in the vessel shell of coke drums. There are studies on the fatigue life estimation for the coke drums [2-4], these are based on base metal under uniaxial isothermal fatigue lives which do not consider cyclic temperature conditions. Xia et al. [5, 6] conducted a finite element study on heat transfer and stress analysis of coke drum for a complete operating cycle. It is found that significant stress and strain values are observed at the clad of the coke drum, which can exceed the yield limit of the material. Therefore, the fatigue life evaluation of coke drum based only on base material is not sufficient. The more accurate evaluation of the fatigue life behavior should be carried out under loading conditions similar to the operational condition, such as under thermal-mechanical cyclic loading.

In this paper, a successfully-developed thermal-mechanical fatigue testing system is presented. A selected set of base and clad materials of coke drums are investigated under isothermal cyclic loadings. In addition, in addition, a comparative study between isothermal and thermal mechanical fatigue lives of clad materials is conducted.

2. Experimental Setup

In order to experimentally investigate fatigue life of coke drum materials under thermal-mechanical cyclic loading, a thermal-mechanical fatigue (TMF) testing system has been successfully installed in our lab. The system mainly consists of a closed-loop servo-controlled hydraulic MTS testing machine which is used as a principal loading frame, a heating device, a control system, and gripping fixtures.

2.1. Heating Device

The TMF testing involves a temperature cycling. Therefore, a relatively fast heating and cooling is essential for conducting a fatigue test. There are various techniques including induction, direct resistance, radiant, or forced air heating. By evaluating the scope of this research and the interested regime of fatigue life, an induction heating with power rated at 5 kW is selected as a effective heating source. The induction unit mainly consists of a power unit, a working coil, and a cooling system. By positioning the conductive material such as metal specimen inside the working coil, the specimen can be heated up at adjustable rate. Because the working coil provides an open environment, this approach also offer an opportunity to install active specimen cooling (for example, forced air) to achieve desired cooling rate.

One of the difficulties using this system is to minimize the dynamic thermal gradient along the axial-direction of the specimen. The configuration of working coil plays an important role affecting the thermal gradient along the axial direction. Variables such as number of coil turns and patterns can have significant effect on the thermal gradients. There are several researchers [7-10] investigated the effect of working coil configuration on the thermal gradient of the specimen. In reference [7] it was found that by using ten-turns one direction helical configuration of the working coil, the thermal gradient along the gauge length of a solid cylindrical specimen could be within ±10°C at 800°C. In reference [9] an investigation on the effect of working coil configuration on solid flat specimen was carried out. It concludes that an elliptical coil with its centre axis perpendicular to the middle axis of the specimen gives a smallest thermal gradient on the solid flat specimen. In addition, it was recommended in [10] that a longitudinal opposite direction working coil is for better axial temperature gradients. An experimental investigation of effect of working coil configurations on thermal gradient along a flat specimen was first carried out, as shown in Fig. 3-3.

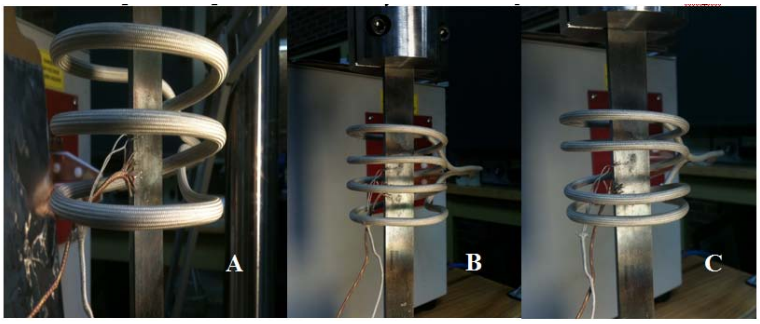

Figure 1 Configuration of working coil on flat specimen

Fig. 1 A-C shows the one direction longitudinal configuration with different turns. The temperature increases up to 500°C, and the dynamic temperature was recorded. The results shows that the working coil configuration C (4 turns with 25 mm gap in the middle) gives the minimal thermal gradients (10°C) at 500°C.

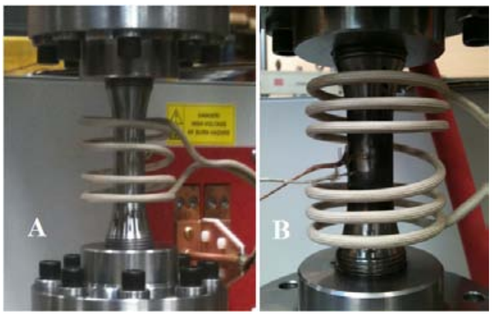

Figure 2 Configuration of working coil on thin-walled tubular specimen

Fig. 2 shows the two different working coil configurations on thin-walled tubular specimen. The temperature increases up to 500°C, and the dynamic temperatures were recorded. The results shows that the working coil configuration A (4 turns with gap in the middle) gives larger thermal gradients (50°C) at 500°C. If the number of turns increases to 6 with gap in the middle, the thermal gradients greatly reduced to 10°C at 500°C.

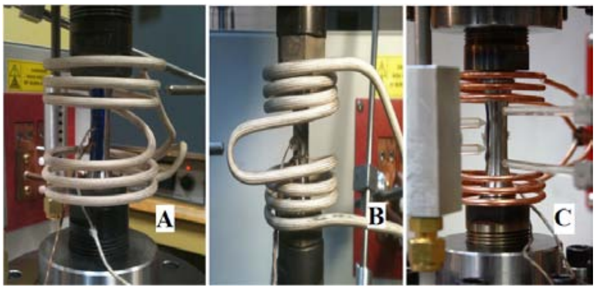

Figure 3 Configuration of working coil on cylindrical solid specimen

Figure 3 shows the three different working coil configurations on cylindrical solid specimen. The results showed that the working coil configuration A (6 turns with gap in the middle) gives larger thermal gradients (30~40°C) at 500°C. A configuration of longitudinal opposite-direction working coil (Fig. 3-5 B) was then tested, the result showed oppose thermal gradient (500°C in the center, 520~530°C at 12.7 mm away from the center). After several trial and error experimentations, the third configuration C was designed. Two separate working coils were attached on the power unit, and each with three turns. From the experimental result of this configuration, the dynamic thermal gradient almost disappears (within 5~10°C) along the axial direction at 500°C. Therefore, through this series of experimentations of working coil configuration, two separate working coil gives the minimal thermal gradient in axial direction.

2.2. Control System

To conduct in-phase strain-controlled TMF test, a program was written in the control system to accurately manage all the components. The dynamic temperature of the specimen is measured by the spot-welded thermocouple in the center of the gage length, and the temperature controller sends the measurement to the signal controller synchronistically. The signal controller send the commands to the heater and air jet during the heating and cooling phases, and it also controls the axial strain to feedback the hydraulic piston to apply the load. All the data is stored by the data acquisition on timed-basis. The strain is controlled by the dynamic temperature signal as shown in Fig. 4. The thermal cycling is carried out at beginning of each test, and thermal strains at T_{max} and T_{min} are recorded. The total strains at T_{max} and T_{min} are calculated:

$$\varepsilon_{Tot}^{T_{\max}} = \varepsilon_{Thermal}^{T_{\max}} + \varepsilon_{mech} \tag{1}$$

$$\varepsilon_{Tot}^{T_{\min}} = \varepsilon_{Thermal}^{T\min} + (-\varepsilon_{mech}) \tag{2}$$

A strain-temperature range ratio δ is defined as:

$$\delta = \frac{\Delta\varepsilon}{\Delta T} = \frac{\left(\varepsilon_{Tot}^{T_{\max}} - \varepsilon_{Tot}^{T_{\min}}\right)}{\left(T_{\max} - T_{\min}\right)} \tag{3}$$

both ε and T in voltages.

The ratio of input to output voltages of the gain amplifier and attenuator is then adjusted to the ratio of δ. The temperature cycling between T_{max} and T_{min} will also generate a voltage which is equal to total strain at the corresponding temperature. After the test, thermal strain is fitted as a function of temperature in a polynomial equation. The mechanical strain can be obtained by subtracting the thermal strain from the total strain.

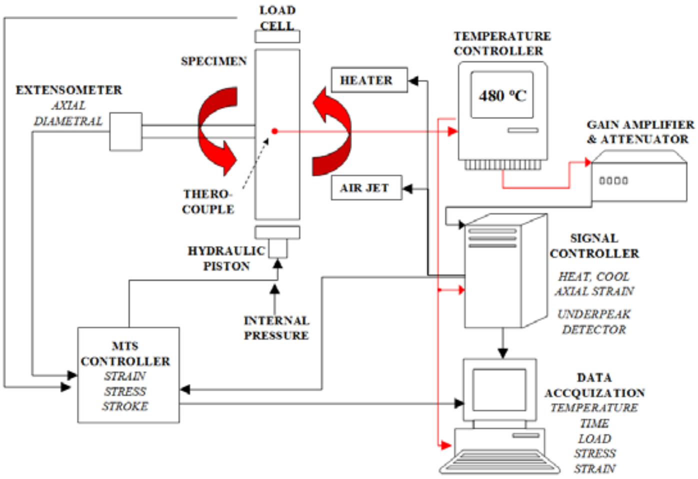

Figure 4 Demonstration of temperature-dependent strain-controlled mode

2.3. Strain Control and Measurement

A new strain control and measurement technique is introduced for high temperature fatigue testing. For high temperature strain-controlled fatigue tests, implementation of punching dimples or knife-edges within gauge length of specimen are common practices for mounting extensometers. Premature failure on the test section of the specimens were introduced at the punch dimple or knife-edge contact area by implementing these techniques as shown in Fig. 5 A and B, respectively.

Figure 5 Photos of premature failure caused by dimple and knife-edge

Alternatively, a pair of dimples is punched outside the gauge length of the specimen as shown in Fig. 6. The punched dimples are located on the thicker cross sections which are outside the effective gauge length of the test sections. Therefore, the premature failure will not be introduced by these dimples. However, since the controlled strain is from outside of gage length, a correlation between measured strain and strain within gauge length should be carefully calibrated and verified. The correlation coefficient is defined as (in this case):

$$C = \frac{\varepsilon_{0.6''}}{\varepsilon_{1''}} \tag{4}$$

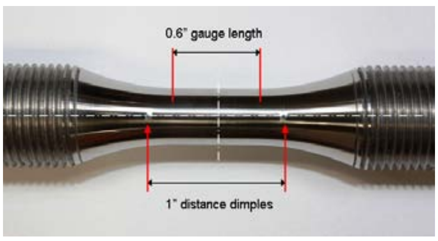

Figure 6 Picture of the specimen with dimples

Two approaches, analytical analysis and finite element analysis are implemented to establish the strain correlation at elevated temperature for each material. The results are then compared with the experiments to verify the established correlations at each temperature.

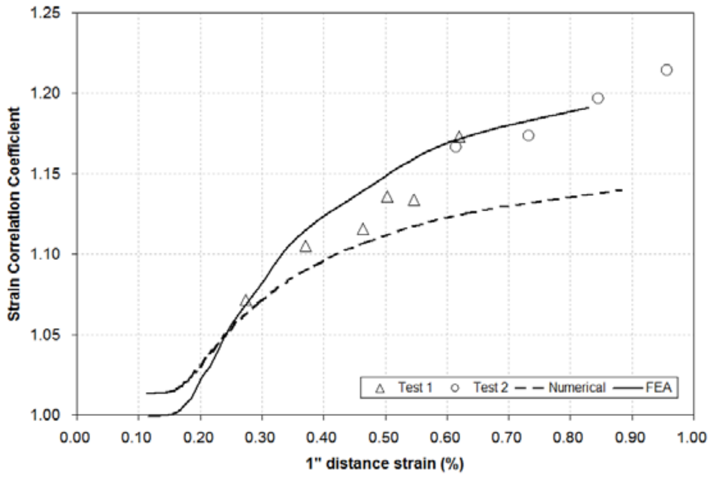

Figure 7 Comparison of room temperature correlation coefficients

The correlation coefficients between the experiment and the two analysis methods are shown in Fig. 7. It can be seen that the experimental points are mainly fallen in the range between the two correlation curves by the analytical and FEA methods. At higher strain range, those points are closer to the FEM correlation curve. However, the difference of the correlation coefficients predicted by the analytical and FE methods is about only 4% when the strain is up to 0.8%. Therefore, a mean curve of the two predictive curves is suggested to be used. In addition, the strain correlation technique can also be applied to thermal-mechanical fatigue tests.

2.4. Materials and Test program

Table 1 Tested coke drum materials

Name	Nominal Chemical Comp.	Plate
SA387 Gr. 22 CL2	2 ¼Cr-1 Mo	Base
SA 240 TP410S	13Cr	Clad

In this paper, low cycle fatigue tests conducted for the following materials: SA387 Gr. 22 CL2 and 410S. Uni-axial isothermal low cycle fatigue tests were carried out as benchmark tests. The tests are under strain-controlled condition at rate of 0.005/Sec. The tests were conducted at fully-reversed cyclic loading condition ($R=\varepsilon_{min}/\varepsilon_{max} = -1$) at both 100 and 480°C. In addition, TMF tests were conducted on 410S. The tests are under temperature-dependent strain-controlled condition, and in-phase thermal-mechanical loading was applied.

3. Results

Isothermal fatigue lives of SA387 Gr.22 CL 2 at 100 and 480^{o}C are shown in Fig 8. From the results, it is shown that as the temperature increases, the fatigue life decreases. One also see that the linear lines can fit the data points quite well, in addition the two fatigue lines at two different temperature are almost parallel to each other in the log-log scale graphs. Therefore, the isothermal fatigue data can be fit by the following equation:

$$\frac{\Delta\varepsilon}{2} = A(T)(N_f)^c \tag{5}$$

where Δε/2 is the strain amplitude (mechanical strain), N_f is the number of cycle to failure, c is a constant and *A* is a temperature dependent constant,

where $$A(T) = A_{T_{\max}} - \frac{(T_{\max} - T)(A_{T_{\max}} - A_{T_{\min}})}{(T_{\max} - T_{\min})} \tag{6}$$

T_{max} = 480°C and T_{min} =100°C in this case.

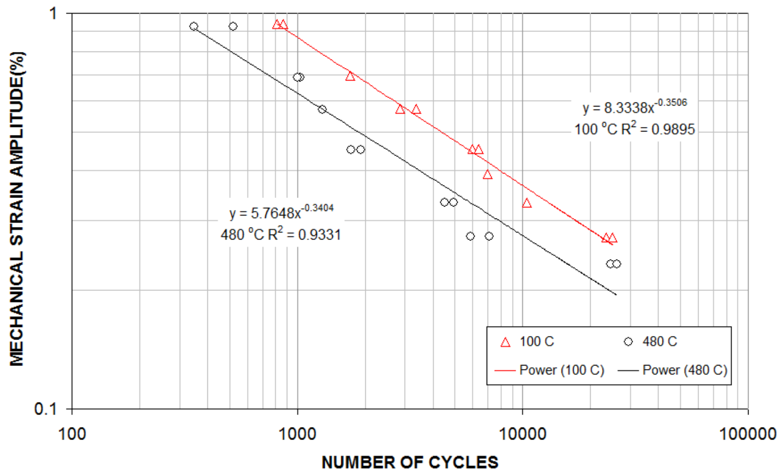

Figure 8 Isothermal fatigue Lives of SA387 GR.2 CL2 at 100 and 480°C

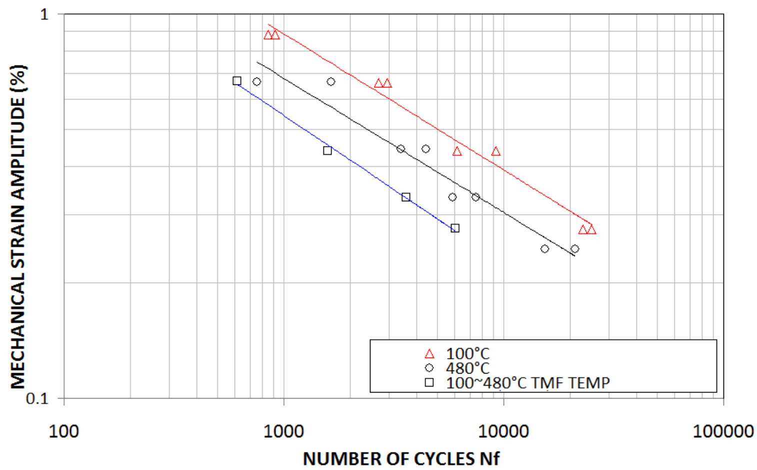

Figure 9 Isothermal and TM fatigue lives of 410S

Isothermal and thermal-mechanical fatigue lives of 410S are shown in Fig 9. From the results, it is shown the same trend as that of the isothermal fatigue tests for the material SA387 Gr. 22 CL2. Therefore the same form of the above equations (5) and (6) can be used to fit the fatigue life data for the material 410S. In Fig. 9, four data points from the in-phase TMF tests with temperature cycling between 100 and 480°C are provided. It is found that the fatigue life of 410S under TMF loading is even shorter than the life at constant temperature of 480°C, though in the TMF loading the maximum temperature is 480°C. Due to the insufficient amount of data conducted, more data points are required to verify the trend of this observation.

4. Summary

In this paper, newly-developed thermal-mechanical fatigue testing system is presented. The developed system can successfully simulate in-phase thermal-mechanical loading which is similar to the loading experienced by the coke drums. Some key developments of this system are introduced such as heating device and control system. In addition, an alternative strain control and measurement technique was developed for both isothermal and TMF fatigue tests Furthermore, some preliminary fatigue tests results were presented. For isothermal fatigue tests, it is shown that as temperature increases, the fatigue lives of SA387 and 410S decrease significantly. Additionally, by comparing lives between isothermal and thermal-mechanical fatigue, it is found that the fatigue life of 410S under TMF loading is shorter than the life at 480°C. Therefore, it is inaccurate to estimate the service life of coke drums based on isothermal fatigue data. Due to the insufficient amount of experimental data, this trend need to be further verified and the mechanisms of this observation need to be explored. More tests are still carrying on in our lab. Based on the comprehensive experimental investigation, reasonable fatigue life models will be developed for the coke drum materials.

Acknowledgements

This research is supported by a Collaborative Research and Development (CRD) Grants of The National Science and Engineering Research Council (NSERC) of Canada (CRD #350634-07 and CRDPJ 403054-10).

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