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Study on Sizes Limit of Coiled Tubing under Internal Pressure and Bending Cyclic Complex Loads

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Abstract: The size of the pipe body of coiled tubing would change applied by internal pressure, cyclic bending complex loads. CT fatigue was accompanied by the sizes of the pipe body, namely diameter, circumference, ellipse degree increasing. When the sizes got to some degree, the CT's mechanism would decreased, when it passed the guide arch, injection and other equipments, it could lead to incompatibilities with deployment equipment which could cause severe mechanical damage and the several sticking accidents. Therefore, grasping the change law and an accurate prediction for CT sizes limits growth was necessary for both safety and reliability in CT operations. In this study, the full-scale fatigue and sizes testing on the CT fatigue machine were investigated under 25MPa internal pressure and bending cyclic complex loads. The data from the testing experiment of size of the pipe body was analysed and the relationship between sizes limits, namely, diameter, circumference, ellipse degree and the cycle (Residual Life) was found. And according to the curve fitting equation, the increasing laws of sizes for CT was established under the internal pressure of 25 MPa. The sizes of CT were accurately and timely predicted and the sizes limits were controlled and monitored which could provide reliable method for the safety service for CT.

Key words: Diameter, circumference, ellipse degree, severely plastic deformation, coiled tubing

INTRODUCTION

Coiled tubing (shortened asCT) was thin walled steel tubes wrapped on the reel and thousands meters long, used in the oil industry with its special advantage for production and maintenance services in the oilfields (Luft, 2001; Walton, 2001; Walker, 1992; McClatchie, 1999; Leniek, 2000; Portman, 2004). It was well known that CT worked under the severely plastic deformation which is suffered to complex loads. Fatigue damage was the main failure form which was typically low-cycle fatigue (Tipton, 1996; Wang and Zhang, 2001; Gao and Xiao, 2012; Wang, 2008).

CT worked under the plastic deformation during the process of reel unwinding, passing through a gooseneck arch guide (bending) and an injector unit (straightening). It would go through 3 times bending and 3 times straightening procession in one lift and downhole operation and it passed through the gooseneck arch guide for 4 times. So, the gooseneck arch guide was the important objective for CT. When CT works, it would be full of high internal pressure inside. Under the internal pressure, the diameter would grow (Elliott, 1994). The thickness would decrease and the circumference, ellipse degree would increase too when fatigue cycle increased. If the sizes of the CT reached some degree, when it passed through the gooseneck arch guide which could cause severe mechanical damage based on the incompatibilities with deployment equipment and mechanism decrease (Wang, 2008). It would affect greatly the remaining life of CT. It was necessary for the shape of cross-section and the sizes of the CT to control and monitor, as well as assured the safety reliable service to CT (Shan *et al*., 2011; Guo *et al*., 2010; Wei *et al*., 2010).

At present, there was no reliable plastic theory to calculate the remaining life of CT. there was also no mature rejection criterion. Cutting-off method based on the experience was mainly used in the oilfield. But this method was easy to make an error judgment and cause to waste and the accident. Yang and Gao (1999) established the diametral growth model according the data from the experiment and three-dimensional curve fitting. But the parameters of their model were too many and uncertainty. Tipson established the growth mode of diameter for CT, but the hypothesis of the mode had limit. Tipson (1998) gave the case of diameter growth based on stress and the strain. But the study on circumference and ovality was less. In this study, Based on the work principle of Coiled

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Tubing, the fatigue-testing machine of CT was developed. The full-scale sample of CT was loaded on the fatigue-testing machine (Newman *et al.*, 1991, 1993). Under 25 MPa internal pressure and bending fatigue load, along the straightening and bending boards, the sample was moving cyclically and the most displacement was 300 mm. Every 100 cycles, stopped the fatigue-testing and tested the geometry sizes of the pipe at every key points. The relationship between the diameter, circumference, ellipse degree and the fatigue remaining life along the bending board was studied. The size of the bending board was the same as the gooseneck arch guide. And the variation laws of maximum diameter, circumference and ellipse degree were found. According to the experiment data, the growth of the limit sizes of pipe were fitted which could predict the limit sizes to CT during operation and the remaining life was gained.

MATERIALS AND METHODS

Experimental equipment

Fatigue-testing machine of CT: The experiment consisted of loading experiment machine, hydraulic driving mechanism, control station and pump. The loading experiment machine was made up of clamp, straightening board, bending board and the head. Hydraulic driving mechanism was the unit of providing power.

Figure 1 was the fatigue-testing machine of CT.

Experiment condition and the sample mechanism: The tested material was CT80 steel, high intensity low carbon alloy steel with good ductility, used widely in the fields of oil field. The mechanical properties of specimen was followed: The yield strength σ_S was 482.3 MPa, the tensile strength σ_S was 551.2 MPa, the elongation δ was 30% and the hardiness (HRC) was 22.The maximum journey which was the displacement that moved from the straightening board to the bending board loaded by the head was set by three sensors. The first moving direction was downward. When the sample got to the lowest down position which was the maximum journey, the counter recorded one cycle. The loading frequency of the fatigue-testing machine was 2.5S/T. One cycle (or T) was the cycle from the straightening to the bending then to the straightening. The internal pressure was from 0 to the 100 MPa which could be controlled by the pump. The media was water, oil and some mixture such as oil and water. The maximum load was 10t. In this study, water was filled in the pipe.

Measurement scheme: The measurement scheme is followed as Fig. 2. The fatigue experiment with the full-scale sample was established according to simply supported beam method. The sizes of the sample were followed: The outer diameter was 38.1 mm, the thickness was 3.2 mm and the length was 2000 mm. The distance from the clamp and the head is 1200 mm which was the

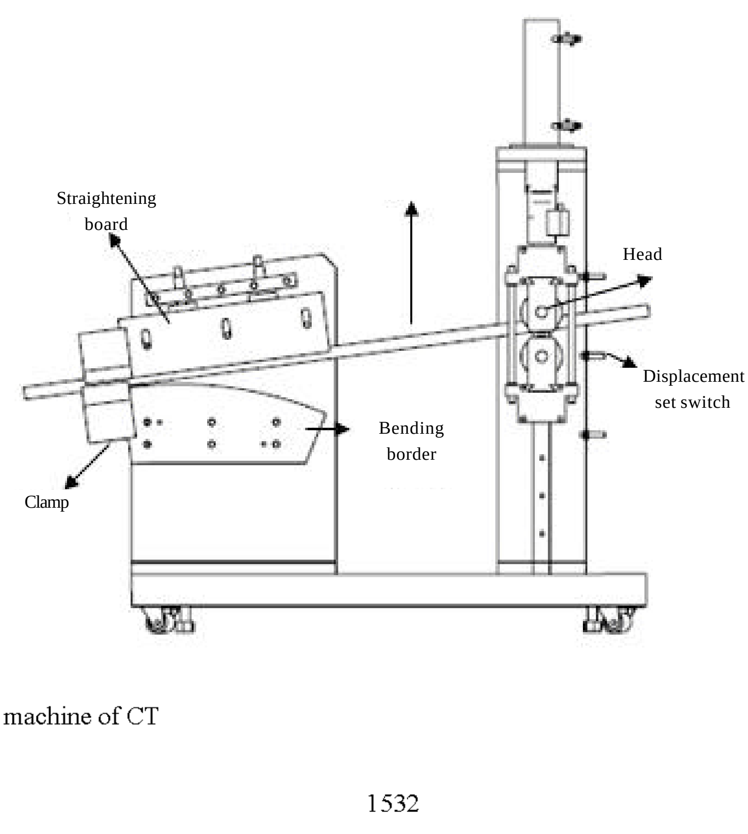

Fig. 1: Fatigue-testing machine of CT

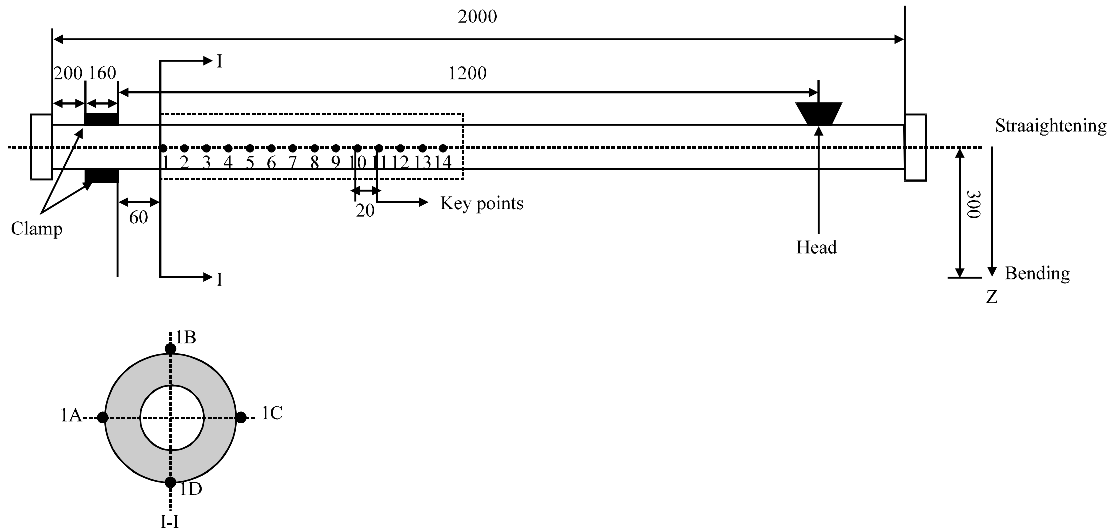

Fig. 2: Schematic diagram of key points and the loads

main portion to be forced. One side was limited by the clamp and the other side was forced by the head. The sample cyclically moved along the straightening board down to the bending board then up to the upper straightening board. And one bending-straightening process is a cycle (T).Z was the down direction and the maximum displacement was 300 mm which could be set by displacement set switch. The two end of the pipe sample was sealed and the 25 Mpa internal pressure was pumped into the pipe. One side was limited by clamp and the other side of the pipe was loaded by the head. Because of the limit of the testing, the sample was taken off. The fatigue machine was tested every 100 cycles. The sizes at every key point was measured and calculated. Based on the experiment analysis the maximum diameter occurred in the direction of AC and the minimum one occurred in the direction of BD. By measuring diameters of the each point in the different directions, the ellipse degree was calculated.

The surface of the pipe was divided into 4 equal sections. The 4 generatrices that paralleled the axis were gained A, B, C, D. 14 key points to be measured on the different axis and the distance between the adjacent two points was 20 mm. 4 points on every key point's section are on the 4 generatrices, such as from I-I, point 1 has 4 directional points 1A, 1B, 1C, 1D. So, the diameters were measured on the two different directions AC and BD at every key point. The ellipse degree was calculated based on the different directional diameters at each key point. The circumference was tested at different key points.

RESULTS

Diameter variation at every point: The expansion ratio of diameter was the change ratio of the diameter which could describe the change degree, namely the deformation degree. The equation was $(Dimax-D_0)/D_0$. Dimax was the maximum of the diameter of every 100 cycles. D_0 was the initial diameter. The relationship between expansion ratio of diameter and the cycle (T), namely, remaining life (N), was shown as Fig. 3a.

As the cycle increased, the diameters at every point were all increasing. The area from point 1 to point 10 was the place which the diameter changed greatly. And the area which was consisted of from point 3 to point 6 was the most dangerous area, on which the deformation was the most severely and the fracture occurred in this area. The expansion ratio of maximum diameter was studied as Fig. 3b and c.

The relationship between maximum diameter variation and the remaining life was shown as Fig. 3b. As the cycle increased, the maximum diameter was nonlinear growth. After 600 cycles, the diameter approximately increased linearly until fracture [8-10]. The fitting curve was shown as Fig. 3c. Under 25 MPa the relationship between diameter growth and the remaining life was followed as Eq. 1:

$$Y = 2\times10^{-8}x^2+3\times10^{-5}x+0.008 \qquad (1)$$

According to the equation fitted by the curve the diameter could be predicted accurately and timely.

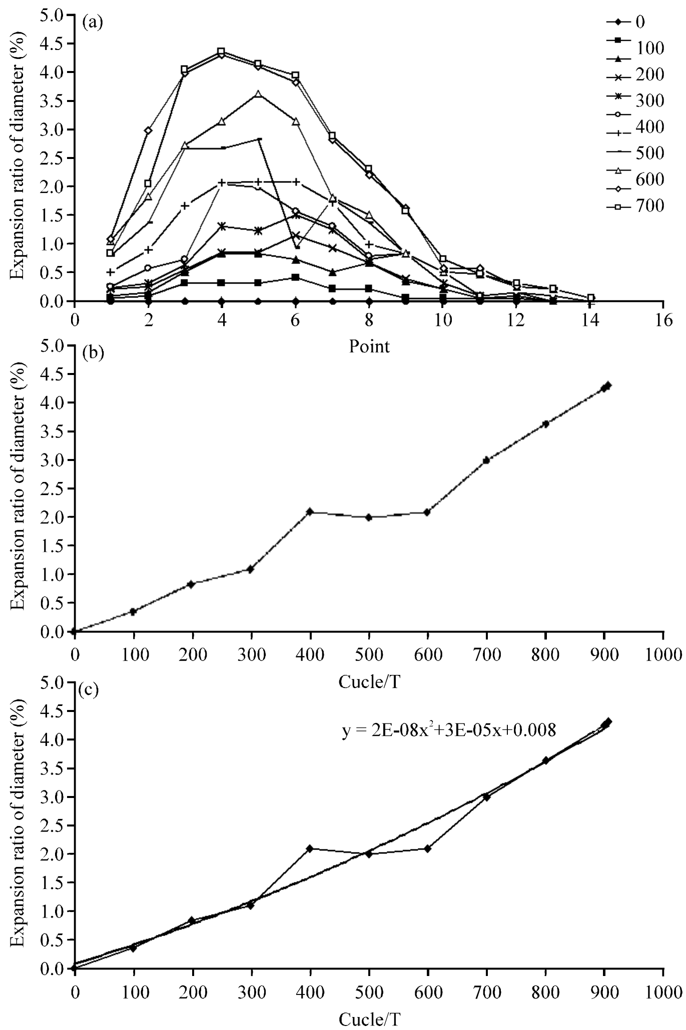

Fig. 3(a-c): (a) Relationship between expansion ratio of diameter and the remaining life at different points, (b) Relationship between remaining life and the expansion ratio of the maximum diameter and (c) Fitted curve relationship between remaining life and the expansion ratio of the maximum diameter

Variation of circumference: The normalized circumference which was shortened as C was shown as Eq. 2:

$$C = (C_{imax}-C_0)/C_0) \quad (2)$$

where, C_{imax} was the maximum circumference of every 100 cycles. C_0 was the initial circumference. The change law of the circumference of the sample at every point was shown as Fig. 4a.

The relationship between circumference variation ratio and the remaining life was shown as Fig. 4a. The variation tendency was the same as the diameter. The area from point 1-10 changed distinctly. And the area which was made up of the range from point 3-6 was the dangerous place. So, by controlling and monitoring the circumference in dangerous place, CT could work safely. Therefore, the study on the variation of maximum circumference as the cycle increasing was very important. Fig. 4b was the relationship between the maximum circumference and the cycles.

As the cycle increased, the normalized circumference changed with a nonlinear growth. The maximum of the normalized circumference reached 2.1%. The equation from fitted curve about relationship between normalized circumference and remaining life was Eq. 3:

$$y = 9\times10^{-9}x2+3\times10^{-5}x+0.009 \quad (3)$$

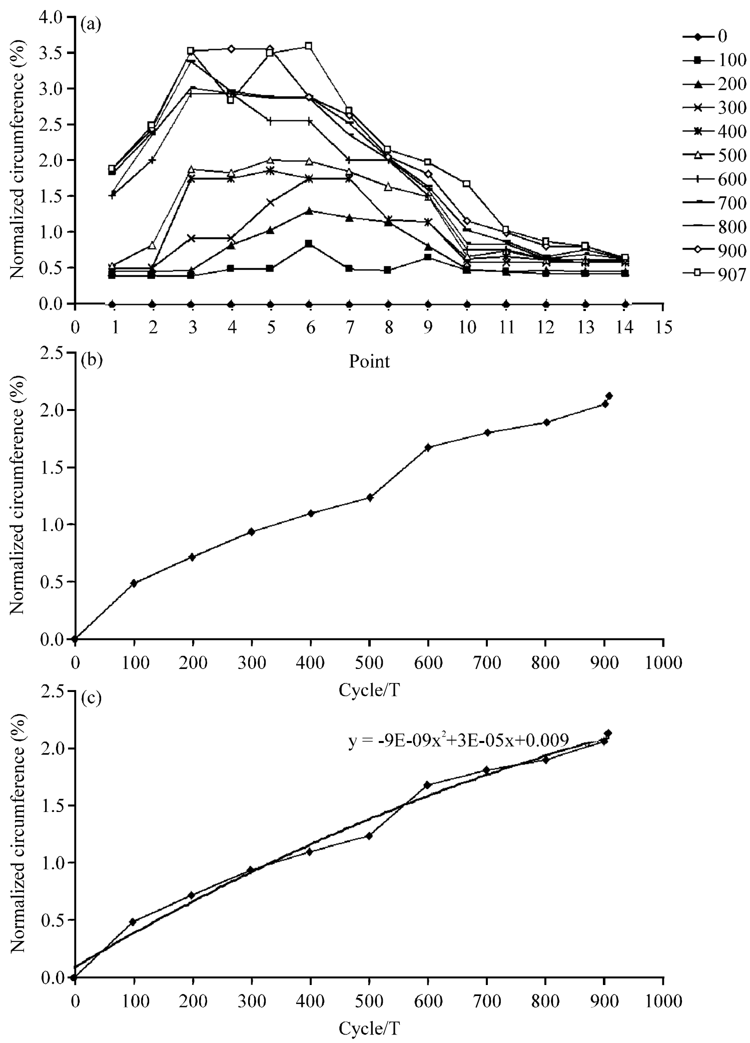

Fig. 4(a-c): (a) Relationship between normalized circumference and the remaining life at different points, (b) Relationship between remaining life and the maximum normalized circumference and (c) Fitted curve relationship between remaining life and the maximum normalized circumference

So, according to the variation law of the circumference and the relationship between remaining life and the maximum circumference, the damage degree of the pipe would be grasped during CT was serving.

Variation of ellipse degree: The definition of ellipse degree was described as Eq. 4:

$$\text{Ellip} = \frac{|D_{max} - D_{min}|}{D_{ave}} \quad (4)$$

Dmax was the maximum diameter. Dmin was the minimum diameter. Dave was the average diameter.

And sometime it was instead of nominal diameter. The equation of average diameter was Eq. 5:

$$D_{ave} = (D_{max}+D_{min})/2 \quad (5)$$

The relationship between ellipse degree and the remaining life at different points was shown as Fig. 5a. It was shown that with the cycle increased, the ellipse degree at different point grew. But the area from point 1-10 changed greatly. The tendency was the same as diameter and circumference and the place range from point 3-6 was dangerous deformation area. So, the biggest ellipse degree was studied. The relationship between maximum ellipse degree and the remaining life was shown as Fig. 5b. As the cycle increased the ellipse degree increased nonlinearly. Then from cycle 600 the ellipse degree was an approximately linear increasing until fracture. The biggest ellipse degree after fracture reached 2.3%. The

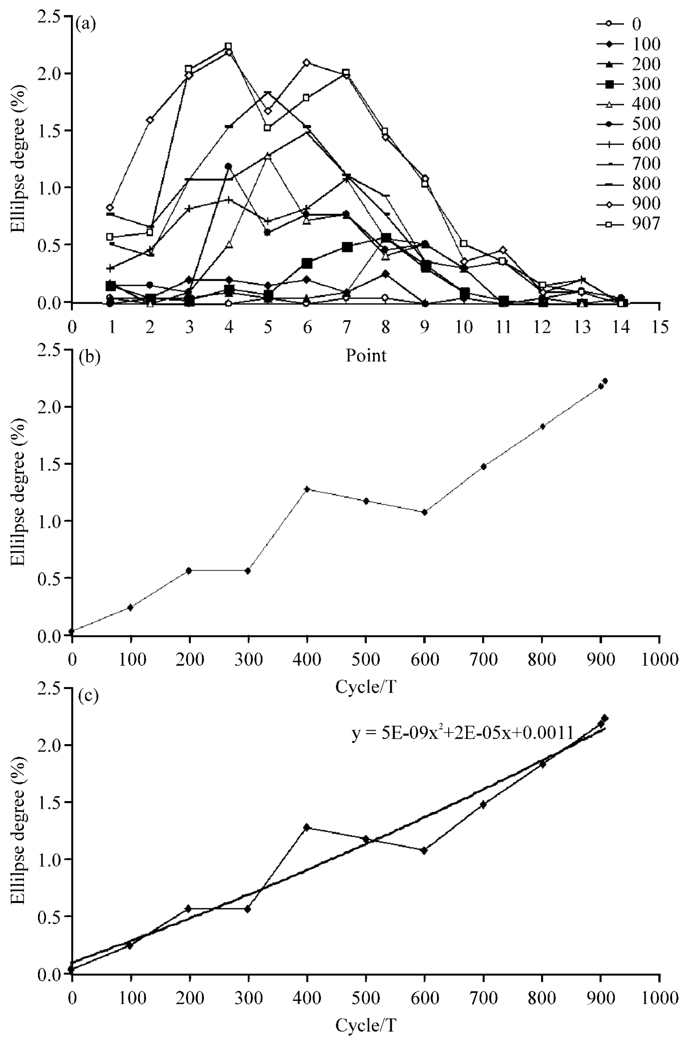

Fig. 5(a-c): (a)Relationship between ellipse degree and the remaining life at different points, (b) Relationship between remaining life and the maximum ellipse degree and (c) Fitted curve relationship between remaining life and the maximum ellipse degree

relationship between the maximum ellipse degree and the remaining life was shown as Eq. 6 according to the fitted curve Fig. 5c:

$$y = 5\times10^{-9}x^2+2\times10^{-5}x+0.0011 \qquad (6)$$

So, based on the relationship between the ellipse degree and the remaining life, the deformation degree could be predicted timely.

DISCUSSION

Tipson believed that the change of stress and strain, namely axial, hoop, radial stress and strain , triggered the deformation mechanisms which leaded to plastic diametral growth and elongation. The most important factors affecting the deformation behavior was the bending-straightening cycles correlating of the reel and the gooseneck. And in our experiment we found this. And based on the fatigue experiment of Tipson, the fatigue damage related to gooseneck arch was considered in this paper. And the position of maximum stress concentration and the most dangerous area of the deformation were predicted among the changes of sizes of CT. The first 1/4 position along the bending board was the most dangerous. Because the hoop stress and the bending strain changed, the diameter varied. But the strain of 4-8% was found on the fatigue experiment which was according to the 6-8% strain on the oil field, not the strain of 20%. The change of the hoop stress and the strain caused the change of the circumference. The change of diameter caused the ellipse degree change. With the cycle increasing, the deformation increased, the dangerous area and the stress concentration increased too. The microscopic stress and the strain change leaded to the macroscopic dimensional changes. So, the dimensional changes, namely diameter, circumference and the ellipse degree could reflect the deformation degree. And based on the fatigue experiment, the relationship between maximum of diameter and the cycle, the maximum of circumference and cycle, as well as the ellipse degree and the cycle were discussed compared with the experimental analysis of Tipson and Y. S. Yang. The change laws of sizes of CT could reflect the microscopic mechanism and the plastic deformation degree.

CONCLUSION

The distribution and the variation law of the sizes at the different points can describe the deformation dangerous area. Measurement can be taken at the dangerous area to monitor the deformation. The diameter, circumference and the ellipse degree can reflect the damage degree in the whole fatigue plastic procession. So, the relationship between the remaining life and the sizes of pipe, namely, the maximum diameter, circumference and ellipse degree can be evaluated the damage degree while CT is serving. According to the fitted curve and the relationship the sizes of the pipe can be grasped in real-time. The variation of diameter can cause the change of circumference and ellipse degree. So, the diameter, circumference and the ellipse degree can be taken as one of the standard of the damage degree. However, the effect of different types of stress and internal pressure to the damage degree and the sizes of CT is very complicated. So much work still will be studied on the relationship between remaining life and the sizes of the pipe under different internal pressure.

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