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Thermographic Determination of Sucker Rod Fatigue Limit

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Abstract

Most failures in sucker rod strings in service are fatigue failures, the rods being subjected to maximum tensile stress on the upstroke and minimum tensile stress (sometimes compression) on downstroke. Since the fatigue limit of full size sucker rods is not known, the design of sucker rod string, at present day, is based on API Modified Goodman diagram, used to calculate the permissible variable stress.

An innovative technique for fatigue limit or endurance limit estimation is based on the measurement of the mean temperature variation of the sample, closely related to the plastic deformation and fatigue behavior during cyclic loading (thermoplastic effect).

This paper presents a method for sucker rod fatigue limit estimation using infrared thermography. The temperature evaluation of the sample during fatigue testing was performed by using high sensitive FLIR E50 thermographic infrared imaging system. The method has been validated by comparing the experimental data with the predicted fatigue limit, as presented within the final discussion of the results.

Key words: *fatigue limit, infrared thermography, sucker rod*

Introduction

Fatigue failures are the most common failures of the sucker rod strings in service. They cannot be avoided, but they can be minimized through improvements in the sucker rod quality and in the string design technology.

The design of sucker rod string is based on the API Modified Goodman diagram, used to calculate the permissible in service stress. This procedure is based on the fatigue tests conducted on simple specimens and does not take into consideration the factors that affect the fatigue limit of full size sucker rods like surface quality, residual stress and others, imposing very high safety factors. The fatigue analysis performed in the design phase of sucker rod string must be based on fatigue strength values of sucker rods obtained from fatigue tests conducted on full scale specimens. These tests are time consuming and costly experiments.

In recent years, progresses made possible the analysis of the fatigue behavior using thermographic infrared technique. This technique is used to measure the temperature variation of the cyclically loaded specimens resulting from the conversion of strain energy into heat during fatigue [1, 2, 4, 9]. The fatigue damage is directly related to an abrupt increase in surface temperature of the sample, used as a criterion for fatigue limit estimation. As presented in Figure 1, the fatigue limit is obtained as the point of intersection between the two regression lines representing the temperature variation vs. stress amplitude (the line without temperature increment and the line with abrupt temperature increment). The estimated fatigue limit determined by thermographic technique was found to be in good agreement with the experimental results.

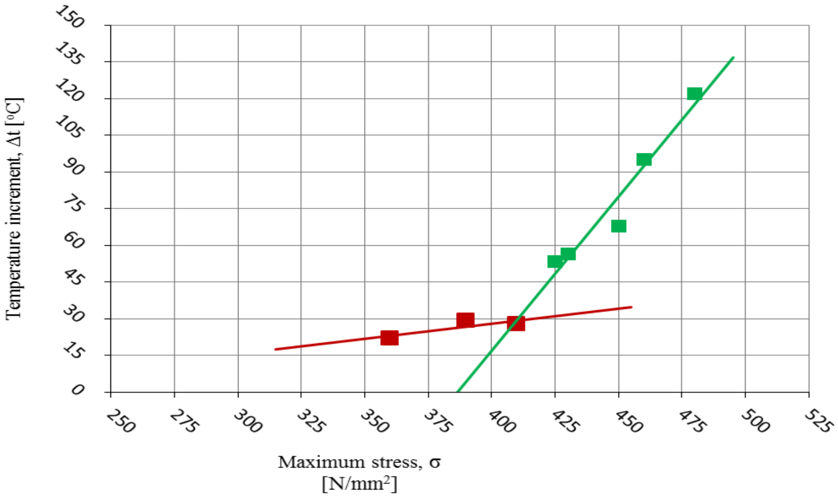

Fig. 1. Fatigue limit prediction based on linear interpolation of the temperature increment data [7]

This paper presents an experimental study conducted to estimate the fatigue limit (endurance limit) of full size sucker rods by monitoring the temperature increase during fatigue tests, using a thermographic infrared imaging system.

Experimental Procedure

The fatigue limit of full size sucker rods has been determined by means of mechanical fatigue testing and by means of thermographic techniques as is presented in Figure 2 [5,6].

Fig. 2. Experimental setup of the tests

The fatigue tests were carried out using a servo hydraulic Dynamic Multipurpose Testing System Type LFV Walter Bay – 300 kN. During the fatigue tests, thermal measurements of the specimen surface were carried out every 5 seconds by using Compact Infrared Thermal Imaging Camera with MSX 240 x 180 IR Resolution ***FLIR E50***, Measured Temperature up to 1202°F (650°C). In order to increase the thermal emissivity of the specimen surface for infrared temperature measurements, the surface of the specimen was black painted [3].

The fatigue tested samples, presented in Figure 3, are made by assembling two sucker rod ends screwed together with the coupling, so the rod and the connection are subjected to the same cyclic loading.

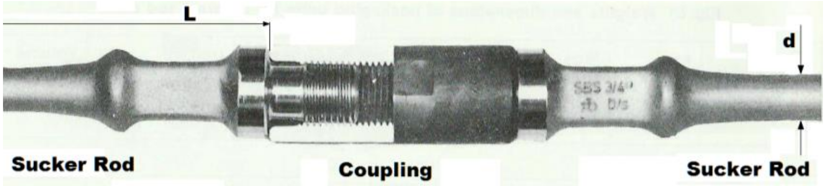

Fig. 3. The fatigue tested samples [13]

Two steel sucker rods samples has been fatigue tested as follows:

- 25.4 mm (1 in) size – diameter of rod body, Grade **D** – tensile strength 793…965 MPa [11, 12], according to API Specification 11 B, was subjected to axial fatigue tests ($R = \sigma_{min} / \sigma_{max} = 0.1$) by applying the load stepwise at different load levels, starting with 250 kN (σ = 494 MPa), increasing the load by 20 MPa, until the failure of the specimen at a maximum stress of 555 MPa; each load step was applied for 50000 cycles, at a frequency of 5 Hz;
- 22.2 mm (7/8 in) size, Grade **D** – tensile strength 793…965 MPa [11,12] according to API Specification 11B, was subjected to axial alternate symmetric fatigue test (stress ratio R = -1), applying the load stepwise at different load (stress) levels, starting with 280 MPa, increasing the load by 27 MPa, until the failure of the specimen at a maximum stress of 640 MPa; each load steps was applied for 1000 cycles, at a frequency of 5 Hz.

Results and Discussions

The correlation between the specimen temperature profile evolution vs. fatigue stress levels is shown in Figure 4, for 25.4 mm sucker rod. Figure 5 presents some temperature profiles measured during fatigue test of 25.4 mm (1 in) sucker rod. The highest temperature was reached in the rod body at the lower part of the specimen, where failure occurred.

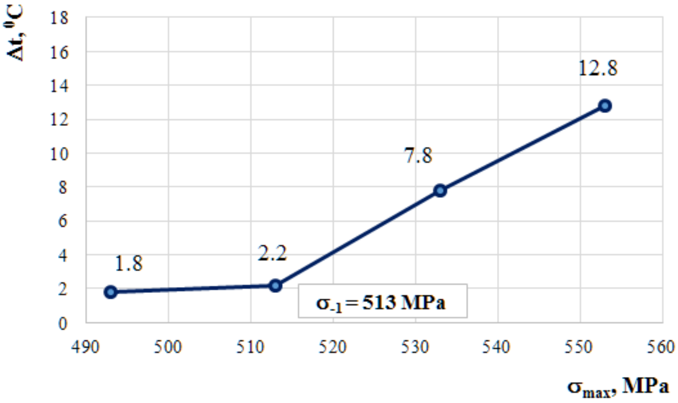

Fig. 4. Fatigue limit prediction for 25.4 mm sucker rod

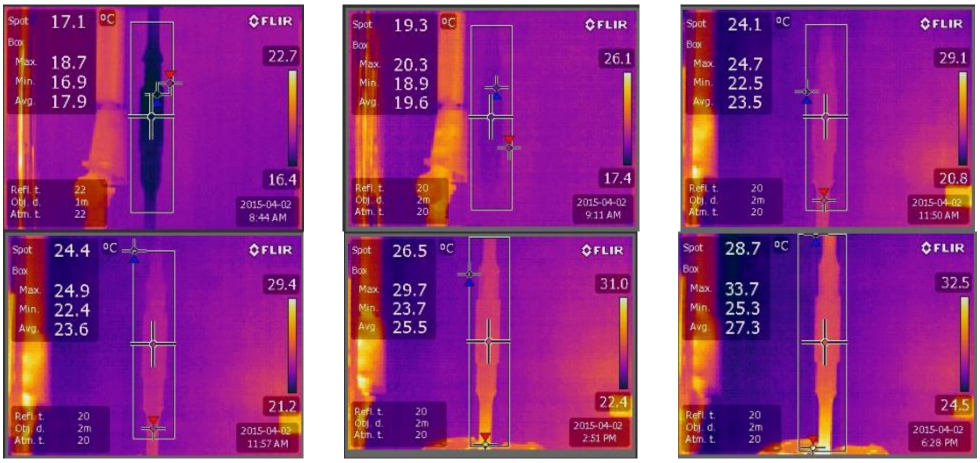

Fig. 5. Some temperature profiles measured during fatigue test of 25.4 mm (1 in) sucker rod

Temperature profile evolution vs. fatigue stress levels for 22.2 mm (7/8 in) sucker rod is shown in Figure 6. Some measured temperature profiles during fatigue test of 22.2 mm sucker rod are presented in Figure 7. The highest temperature was reached in the rod body at the upper part of the specimen, where failure occurred.

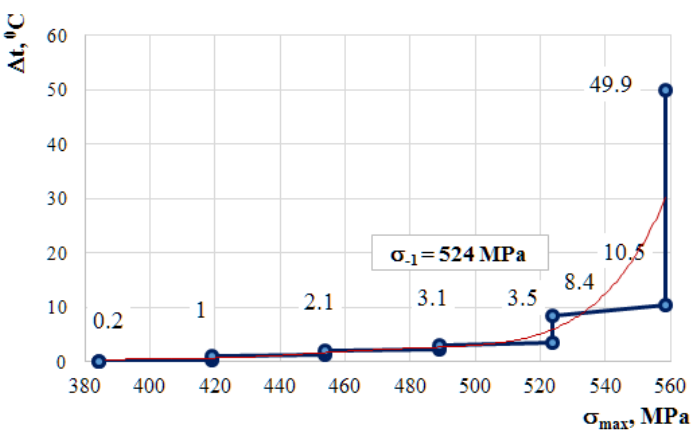

Fig. 6. Fatigue limit prediction for 22.2 mm sucker rod

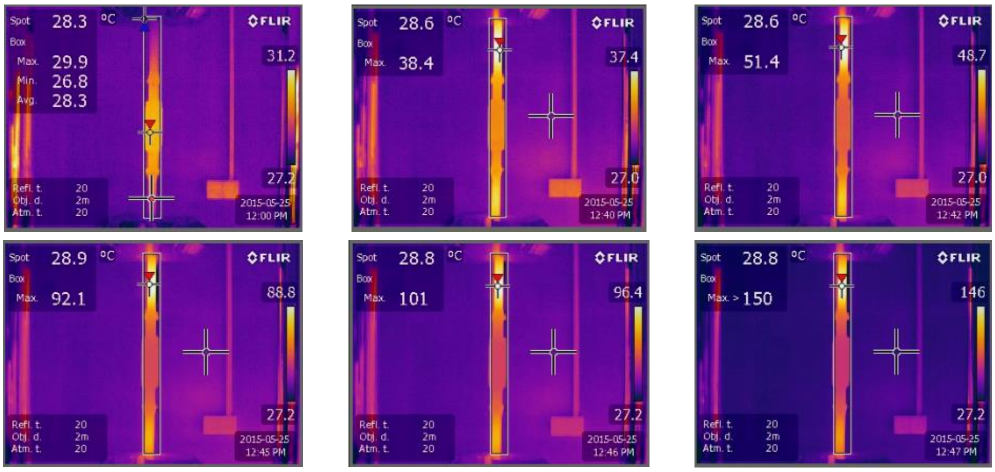

Fig. 7. Some temperature profiles measured during fatigue test of 22.2 mm (7/8 in) sucker rod

The fatigue limit estimation is based on the graphical representation of the temperature increase vs. fatigue stress levels, presented in Figures 4 and 6. The stress which corresponds to a sudden increase in the sample temperature, representing the damage evolution, is considered a good estimation of the fatigue limit. The estimated fatigue limit for 25.4 mm (1 in) sucker rod is 513 MPa and the estimated fatigue limit for 22.2 mm (7/8 in) sucker rod is 524 MPa.

In order to validate the results, a comparison have been performed between the estimated fatigue limit based on thermographic technique and the fatigue limit values determined by fatigue testing of full size sucker rods [8]. The fatigue limit of full size sucker rods (22.2 mm; 7/8 in diameter), grade D - $R_{p0.2}$ = 726 MPa, determined by using the Locati method, for tensile fatigue loading with stress ratio R = 0.23, was 595 MPa. To transfer the fatigue limit value determined for R = 0.23 to the condition of completely reversed axial loading mode (R = -1), the Soderberg relationship was used. Therefore the 524 MPa fatigue limit determined for completely reversed axial loading mode corresponds to 608 MPa fatigue limit for R = 0.23. This fatigue limit value is in very good agreement with the experimentally determined fatigue limit of 595 MPa [8].

Conclusions

The predictions of fatigue limit of sucker rods based on temperature evolution during fatigue test are found to be in good agreement with experimental results. This confirms the quantitative infrared thermography as an effective method to monitor temperature evolution used to evaluate the fatigue characteristics of materials and the mechanical structure components.

This study has provided a valid model for estimating the fatigue limit of full size sucker rods by means of infrared thermography.

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Determinarea termografică a limitei de oboseală pentru prăjinile de pompare

Rezumat

Deoarece limita de oboseală a prăjinilor de pompare nu este cunoscută, proiectarea la oboseală a garniturii de prăjini de pompare se bazează, în prezent, pe utilizarea diagramei API Modified Goodman pentru a calcula tensiunile variabile admisibile.

Lucrarea prezintă o metodă de estimare a limitei de oboseală a prăjinilor de pompare folosind termografia în infraroșu. Evaluarea temperaturii probei, în timpul testării la oboseală, a fost realizată prin utilizarea unui sistem termografic de înaltă sensibilitate in infraroşu FLIR E50. Metoda a fost validată printr-o comparație între datele experimentale obținute și limita de oboseală pentru prăjinile de pompare, comparaţie prezentată în partea finală a interpretării rezultatelor.