24th ABCM International Congress of Mechanical Engineering
December 3-8, 2017, Curitiba, PR, Brazil

COBEM-2017-0680
CRACK INITIATION TEST IN BENDING FATIGUE: DETECTING BY THE LOSS OF GAS-TIGHTNESS

José Felipe Dias
Tomás Pessoa Londe Camargos
Ewerton Augusto de Sousa Nogueira
Denilson José do Carmo
Universidade de Itaúna. Rod. MG 431 - Trevo Itaúna/Pará de Minas, CEP: 35680-142 – Itaúna – Minas Gerais, Brasil.
jfelipe@uit.br; tomascamargos@yahoo.com.br; ewertonasnogueira@gmail.com; denilsonjcarmo@uit.br.

Gabriel de Oliveira Ribeiro
Ana Maria Gontijo Figueiredo
Departamento de Engenharia de Estruturas, Universidade Federal de Minas Gerais - UFMG. Av. Antônio Carlos 6627, Bloco 1, 4º andar, CEP: 31270-901 – Belo Horizonte – Minas Gerais, Brasil
gabriel@dees.ufmg.br; anamaria@dees.ufmg.br.

Abstract. *The fatigue crack initiation method is investigated in a specimen with a cavity under positive or negative pressure. The test is stopped automatically when a fatigue crack causes the loss of tightness of the cavity. A bending fatigue testing machine has been developed and adapted to test specimen with a pressurized cavity or under vacuum. Fatigue tests were performed under constant strain amplitude on test specimens made of SAE 1045 steel with a pressurized cavity of inert gas and a wall thickness of 1 mm. In order to verify if the investigated method would be able to detect the influence of surface finishing on the initiation of fatigue crack, machined and drawn specimens were used. In the analysis of the experimental results the Coffin-Manson curve and the SWT models were used. The curve parameters ε-N according to Baumel-Seeger, Roessle-Fatemi and Castro-Meggiolaro were applied. The test results showed consistent with the predictions of the models used, indicating that the method of crack detection by the loss of tightness is effective and technically viable and capable of detecting the influence of the surface finish in the fatigue crack initiation resistance. The tests demonstrated that the sensitivity of the method is related to the used type of pressure sensor and differential pressure specified for the shutdown of the machine after the loss of gas-tightness.*

Keywords: *fatigue, fatigue crack initiation, crack detection method, bending test apparatus, strain control.*

1. INTRODUCTION

The American Society for Testing and Materials (ASTM) E 1150 standard defines fatigue as the gradual process of permanent structural change in a material subjected to conditions that produce fluctuating stresses and strains at some point (or points) and that can culminate in cracks or in fracture after a sufficient number of fluctuations. Fatigue is responsible for at least 90% of the service failures of mechanical and structural components, causing significant economic, environmental, and social losses. Structural components often operate under varying loads, which are sufficiently severe to make fatigue resistance an important project criterion. Our present knowledge of fatigue processes has already been translated into project criteria that are efficient to prevent fatigue failure. However, this knowledge has not yet achieved the same conceptual level of other types of common mechanical failures, such as those by overload. Thus, fatigue failure has become a major concern in engineering projects, and based on more sophisticated models, project criteria that consider this effect are now being incorporated into the main technical standards. The study of the fatigue phenomenon in materials, which is inherently interdisciplinary in nature, exists in two strongly interrelated main areas, including the development of materials with high fatigue resistance in the field of materials science as well as the development of reliable methods for predicting the behavior of elements subjected to fatigue in the field of applied mechanics.

The detection of cracks in their initial phases (crack initiation) allows a better understanding of the mechanisms involved in the fracture process, which is important to improve the analysis and design of material service life in order to reduce the occurrence of failure by fatigue. In this way, the sensitivity of the crack detection method plays an important role. Usually in the conventional methods, the sensitivity ranges from 10^{-4} mm to 0.5 mm in length

(Shanmugham and Liaw, 1996). However, most of these methods require sophisticated and costly equipment, and some of them cannot be applied in service conditions or in routine tests. Additionally, the need to interrupt the fatigue test to assess the existence and extension of any crack that may occur is one of the significant problems presented by most of the typical methods. This aspect implies in undesirable loading and unloading cycles, which can affect the phenomenon of crack initiation.

Among the various types of existing fatigue tests, the bending fatigue test has some advantages over the other commonly used tests, such as bending-rotation, due to the greater simplicity of the operating stress state, which produces less interference in the results, and thus, facilitates the analysis (Figueiredo *et al*., 2015).

This study shows the initial results of the assessment and use of the known crack detection system for loss of tightness as a possible method for detecting fatigue crack initiation. A bending fatigue test apparatus was developed and adapted to test specimen with a pressurized cavity or under vacuum (Borges, 2011).

2. EXPERIMENTAL PROCEDURE

The experimental procedure was carried out in three steps: (i) preliminary tests were performed to evaluate the machine's operation, the sensitivity of the test and the comparison of two types of test specimens proposed; (ii) corrections and changes were made to improve the sensitivity of the crack initiation detection method and the definition of the specimen more appropriate to the proposed method; (iii) finally, it was carried out the tests to build prediction curves for initiation of cracks by fatigue using the method of the loss of the gas-tightness.

The design and details for the construction of the test machine used in the tests, Fig. 1, were presented by Borges (2011). The machine performs fatigue tests by alternating bending, and the crack detection is done by the loss of gas-tightness. The method used is to pressurize argon gas through a hole in the specimen. The gas is pressure tightened until the occurrence of crack initiation and its propagation throughout the controlled thickness of the hole, causing loss of gas-tightness. The gas pressure is read by a differential pressure transducer. The test can be interrupted by the pressure drop due to the initiation of the crack; by total rupture of the specimen, detected by fiber optic sensor or when the programmed number of cycles has been reached.

Three SAE 1045 steel bars were used and 45 specimens were tested. Figure 1 shows the geometry developed for the specimen and the two positions of the holes pressurized with argon gas. The nominal wall thickness, where the crack started, was 1 mm because this is the smallest dimension detectable by traditional non-destructive inspection (Castro and Meggiolaro, 2009). The fatigue tests were performed with R = 0.1 after adjusting the equipment. Table 1 shows the mechanical properties of the bars.

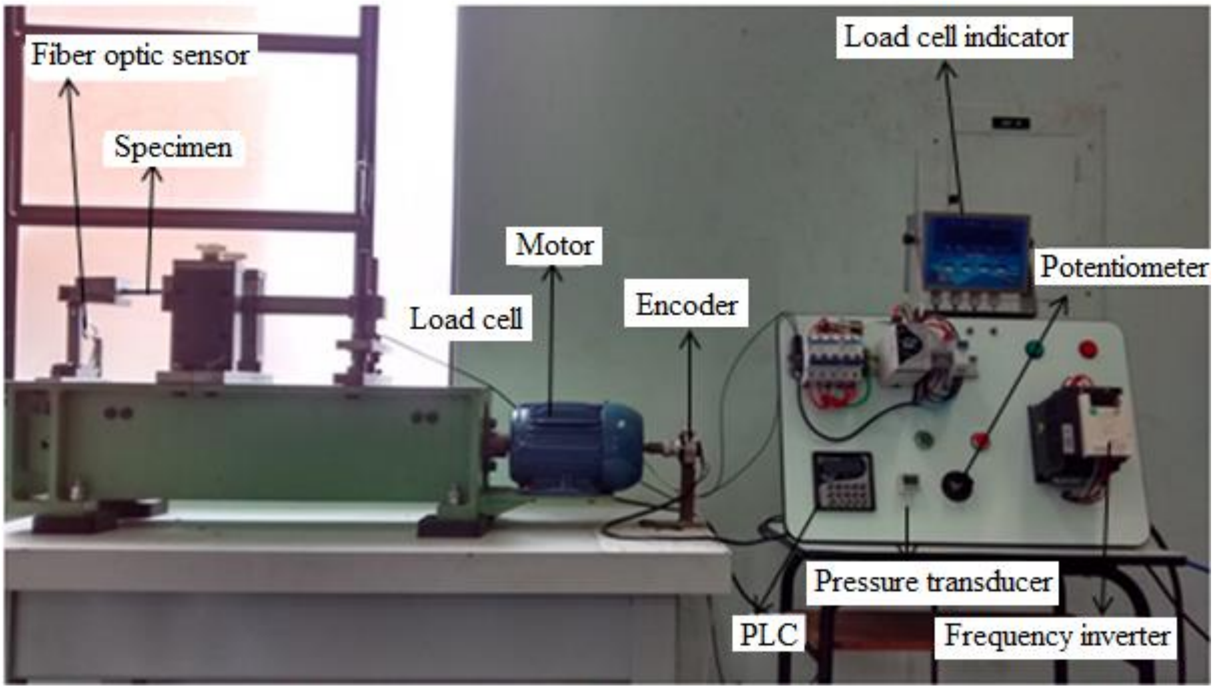

Figure 1. Bending fatigue testing machine used in the tests.

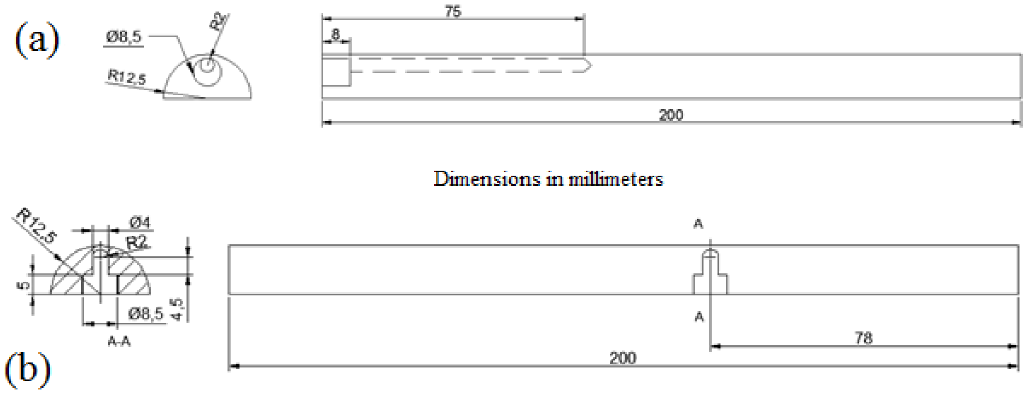

Figure 2. The test specimen geometry showing the pressurized cavity. (a) Type 1; (b) Type2.

Table 1 – Mechanical properties of SAE 1045 steel bars used in the manufacture of specimens.

Bar	Specimen type	σ_u (MPa)	σ_y (MPa)	Hardness (HB)	E (GPa)
1 (drawn)	1	864,3	802,5	241	206,5
2 (drawn)	1 and 2	724,0	634,0	229	200,2
3 (machined)	2	786,0	718,0	229	205,0

3. RESULTS AND DISCUSSION

For comparison of the experimental results with estimates of fatigue resistance of the specimens, was used the model of Smith-Watson-Topper (SWT) that quantifies the maximum stress effect (Suresh, 2001; Castro and Meggiolaro, 2009):

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_c^2}{E\sigma_{máx}}(2N)^{2b} + \frac{\sigma_c\,\varepsilon_c}{\sigma_{máx}}(2N)^{b+c} \tag{1}$$

Where *Δε, N, E e* $\sigma_{máx}$ respectively represent strain amplitude, number of cycles, modulus of elasticity and maximum stress. The coefficients and exponents of Coffin-Manson's elastic and plastic parts (σ_c, ε_c, b and c) were estimated according to Tab. 2, as proposed by Castro and Meggiolaro (2009).

Table 2. Estimated values of the coefficients and exponents of Coffin-Manson's elastic and plastic parts for steel SAE 1045.

Estimates	σ_c	ε_c	b	c
Baumel and Seeger (1990)	$1.5.\sigma_u$	0.59 if $\sigma_u/E \leq 0.003$, or 0.812-74. σ_u/E	-0.087	-0.58
Roessle and Fatemi (2000)	4.25.HB+225MPa	$[0.32HB^2$-487HB+191000MPa]/E	-0.09	-0.56
Medians of Castro and Meggiolaro (2001)	1.5. σ_u	0.45	-0.09	-0.59

With the data of Tab. 2 the coefficients and exponents of the elastic and plastic parts of Coffin-Manson curve could be calculated, and their values are presented in Tab. 3.

Figure 3 shows the results of the crack initiation tests on specimens extracted from bars 1,2 and 3 compared to the fatigue life prediction of SWT model, calculated by Eq. (1), using the parameters according to Tab. 3 for SAE 1045 steel. In the same figure it was possible to note that the number of cycles to start and propagate cracks up to 1 mm were below of the number of cycles required for total fatigue rupture predicted by the SWT model. Thus, it has been pointed out that the fatigue crack detection method by the loss of the gas-tightness was effective in determining the crack initiation stage.

The results of bar 1 showed greater dispersion because the fatigue machine was being adjusted and the coefficient R was not homogeneous.

Table 3. Estimation of the parameters of the Coffin-Manson curve.

Estimates	Bar	σ_c	ε_c	b	c
Baumel and Seeger (1990)	1 (drawn)	1296.45	0.502	-0.087	-0.58
	2 (drawn)	1086.00	0.544	-0.087	-0.58
	3 (machined)	1179.00	0.528	-0.087	-0.58
Roessle and Fatemi (2000)	1 (drawn)	1249.25	0.446	-0.09	-0.56
	2 (drawn)	1198.25	0.480	-0.09	-0.56
	3 (machined)	1198.25	0.469	-0.09	-0.56
Medians of Castro and Meggiolaro (2001)	1 (drawn)	1296.45	0.45	-0.09	-0.59
	2 (drawn)	1086.00	0.45	-0.09	-0.59
	3 (machined)	1179.00	0.45	-0.09	-0.59

The experimental results of the tested specimens of the bar 2 were concentrated in a small range of the Coffin-Manson curve. However it is possible to notice coherence between the experimental numbers of cycles and the numbers of cycles predicted by the SWT model, independently of the parameters used. For bar 3, tests were done on a larger extent of the Coffin-Manson curve and the same coherence could be noticed.

The samples with machined surface presented smaller number of cycles than those drawn surface, with equivalent loads. This is consistent if the beneficial effects of the cold drawing process are considered on crack initiation life.

The fracture surface of both types of test specimens is shown in Fig. 4, showing regions of a fatigue crack, saw cut and intentionally caused sharp fracture.

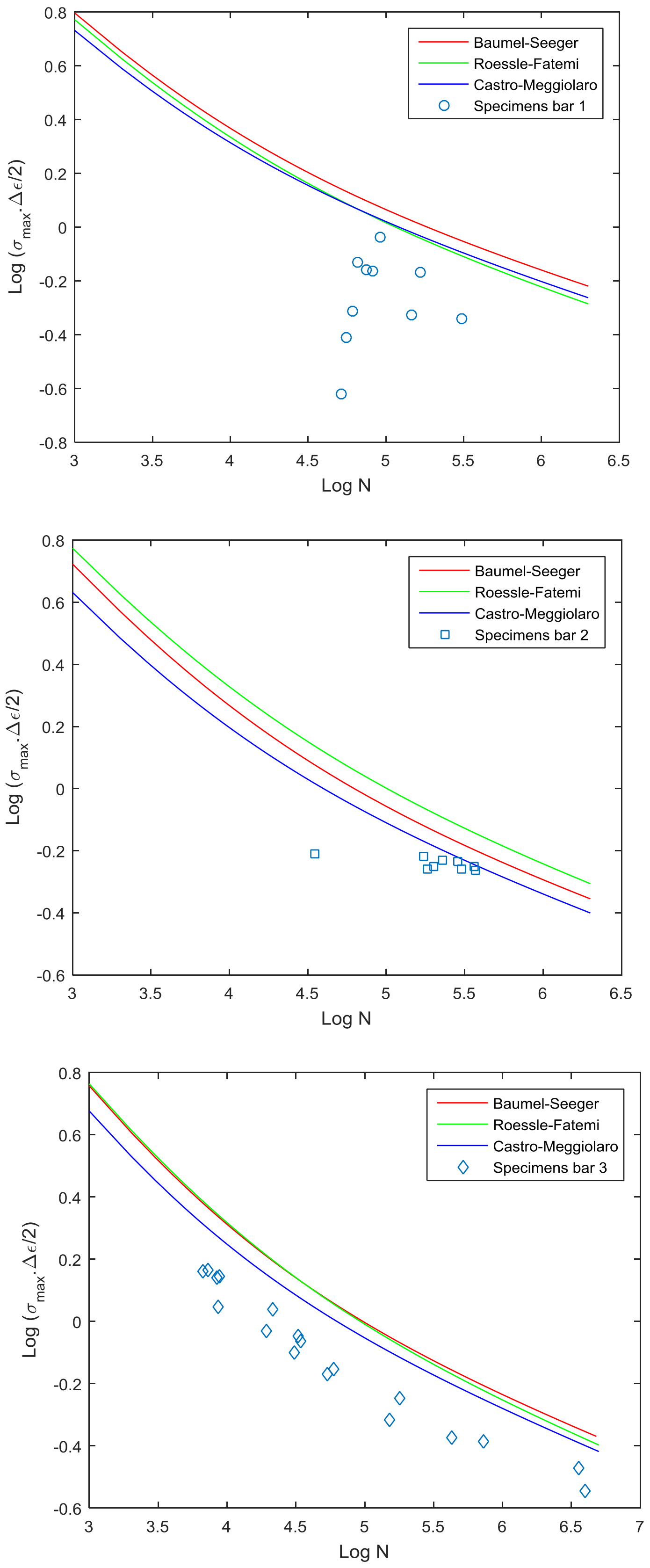

Figure 2. Comparison of the experimental results of each bar by the SWT model with the Baumel - Seeger, Roessle - Fatemi and Castro and Meggiolaro's estimates.

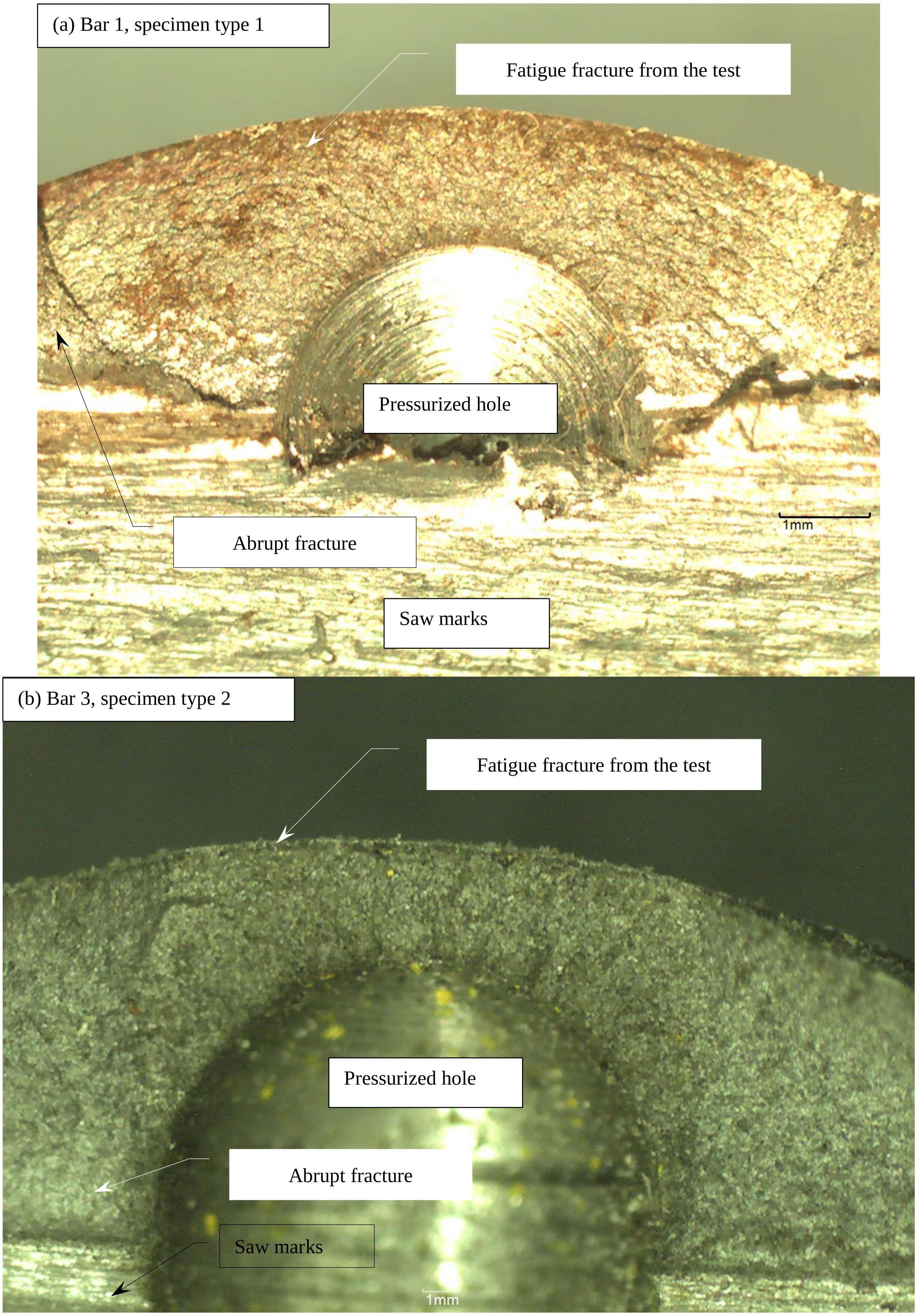

Figure 3. The fracture surfaces of the test specimen. (a) Type 1; (b) Type 2.

4. CONCLUSIONS

Considering that all the test specimens had a number of cycles below the fatigue life prediction curve for the SAE 1045 steel, it can be concluded that the results were consistent with the models and data used, indicating that the method of crack detection for the loss of tightness is effective and technically feasible.

The samples of the machined bar presented smaller number of cycles to start the crack when compared with tests of equivalent loads of drawn bars. This indicates that the method showed sufficient sensitivity to detect the influence of the surface finish on fatigue crack initiation life.

The results of the tests made it possible to infer that the sensitivity of the test is related to the wall thickness of the pressurized cavity, the type of pressure transducer and the specified differential pressure value.

5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge Saulo P. Cabral and Mateus Ribeiro who participated in the tests of the bars and the financial support received from the Minas Gerais State Research Foundation (FAPEMIG) and the University of Itaúna.

6. REFERENCES

Baumel Jr, A. and Seeger T., 1990. *Materials Data for Cyclic Loading* – Supplement I, Elsevier, New York.

Borges, V.F., 2011. *Máquina para ensaio de iniciação de trinca por flexão alternada: detecção pela perda de estanqueidade*. Universidade de Itaúna, Itaúna.

Castro, J.T.P. and Meggiolaro, M.A., 2009. *Fadiga - Técnicas e Práticas de Dimensionamento Estrutural sob Cargas Reais de Serviço Volume I.* CreateSpace, Rio de janeiro.

Castro, J.T.P. and Meggiolaro, M.A., 2001. On the errors induced by the hookean of nominal stresses in the ε-N method. *Fatigue*, p. 257-266, (SAE P2001-01-4067).

Figueiredo, A.M.G et al., 2015. An investigation of bending fatigue crack propagation in structural steel by the measurement of indirect parameters. *J Braz. Soc. Mech. Sci. Eng*. Vol.37, p. 305-312.

Roessle, M.L. and Fatemi A., 2000. Strain-controlled fatigue properties of steel and some simple approximations. *International Journal of Fatigue*, Vol.22, p.495-511.

Shanmughan, S and Liaw, P.K., 1996. Detection and Monitoring of Fatigue Cracks. In *ASM Handbook – Fatigue and Fracture, v. 19, p. 517-552.*

Suresh, S., 2001. *Fatigue of materials*. Cambridge University Press, Cambridge, 2nd edition.

7. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.