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X-ray diffraction study of microstructural changes during fatigue damage initiation in steel pipes

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ABSTRACT

Steel pipes used in the oil and gas industry undergo the action of cyclic loads that can cause their failure by fatigue. A consistent evaluation of the fatigue damage during the initiation phase should fundamentally be based on a nanoscale approach, i.e., at the scale of the dislocation network, in order to take into account the micromechanisms of fatigue damage that precede macrocrack initiation and propagation until the final fracture. In this work, microstructural changes related to fatigue damage initiation are investigated in the API 5L X60 grade steel, used in pipe manufacturing. Microdeformations and macro residual stress are evaluated using X-ray diffraction in real time during alternating bending fatigue tests performed on samples cut off from an X60 steel pipe. The aim of this ongoing work is to provide ground for further development of an indicator of fatigue damage initiation in X60 steel. This damage indicator could allow a good residual life prediction of steel pipes previously submitted to fatigue loading, before macroscopic cracking, and help to increase the reliability of these structures.

1. Introduction

Steel pipes used in the oil and gas industry undergo the action of cyclic loads that can lead to fatigue failure. As a matter of fact, fatigue is one of the major causes of failure detected in oil and gas steel pipes [1–4], which can be followed by catastrophic environmental damage and also significant financial loss. Oil and gas subsea pipes are usually made of high strength API 5L steels of different grades, as X60, X65, X70 and X80, for instance [5]. To assure their structural integrity and forewarn a fatigue failure it is important to be able to detect and follow the fatigue damage during operation.

Fatigue damage may be split in two phases: an incubation phase, during which only microstructural changes, microcracking and microcrack nucleation can be observed, and a propagation phase, characterized by macroscopic cracking and macrocrack propagation which lead to fatigue failure. During the second phase, fatigue damage (macrocrack propagation) is easier to be detected and followed. In addition, macrocrack propagation can be modeled by the classical Paris's law [6] and modified versions within the linear elastic fracture mechanics (LEFM) approach. Moreover, risk-based inspections are usually based on the probability of macrocrack detection, as in the case of steel pipelines [7]. Regarding the first phase, even if the mechanisms developed in the early stages of fatigue are well known – multiplication of dislocations, formation of slip bands, extrusions, intrusions, and microcracks [8–10] – it is not always clear which microstructural changes, and to what extent, can be associated with fatigue damage. Another difficulty concerning this phase is related to the evaluation techniques employed. Since damage evolution, at least at the onset of fatigue, is associated with the movement, density and arrangement of dislocations, changes have to be observed at the nanoscale. The destructive character of the observation techniques available for this purpose represents a real problem, since in this case it is not possible to perform a series of observations on a same sample during fatigue test. In addition, they require the extraction of very small samples or even thin lamellae from the test piece, which is technically complicated and very time-consuming.

Therefore, the use of nondestructive evaluation (NDE) techniques to investigate physical and microstructural changes associated with fatigue has greatly increased in the recent past. Among these techniques, thermography [11], ultrasonic testing [12,13], magnetic inspection [14,15], and X-ray diffraction [16–19] have indicated notable perspectives. Although most of the currently used NDE techniques may help to detect microstructural changes during the damage process, it is still not possible to correlate fatigue

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Nomenclature

d_0	lattice spacing in nonstressed material
N	number of stress cycles at failure
R	stress ratio, $\sigma_{min}/\sigma_{max}$
S_e	endurance limit of the samples
S_n	alternating stress that causes failure at N cycles
S_u	ultimate tensile strength
Y/T	yield strength to ultimate tensile strength ratio
σ_a	alternating stress amplitude
σ_{max}	maximum stress
σ_{min}	minimum stress
σ_o	yield strength

damage to these changes for damage quantification and prediction of the residual life of a component submitted to cyclic loading. Among available NDE techniques, though, X-ray diffraction (XRD) offers the more interesting perspectives, since it can deliver some important information about the dislocation network, microdeformation changes and residual stress state of a fatigued material. Moreover, this technique allows the use of portable systems to directly evaluate the surface of test pieces positioned in the testing equipment.

The long-term objectives of this ongoing work are (1) to evaluate and quantify changes in microdeformations and macro residual stresses in real time during fatigue initiation and (2) to develop an indicator of fatigue damage initiation in order to allow the residual life prediction of a component submitted to cyclic loading. The present study deals with the first objective of the work. The material concerned in the study is the API 5L X60 grade steel, used in pipe manufacturing for the offshore petroleum industry. The XRD technique is used to detect and evaluate microdeformations, characterized by the full width at half maximum (FWHM) of the XRD peak, and macro residual stresses in real time during high cycle fatigue (HCF) tests performed on API 5L X60 grade steel samples under alternating bending loadings. Thus, microstructural changes in terms of variations in FWHM and residual stresses are evaluated during fatigue cycling as a function of the loading level (stress amplitude). The experimental results obtained are analyzed in view of the second objective of the work, regarding the development of an indicator of fatigue damage initiation for the X60 grade steel that could allow evaluation of the residual life before macroscopic cracking and help to increase the reliability of pipelines submitted to cyclic loadings.

2. X-ray diffraction technique for fatigue characterization

The X-ray diffraction (XRD) technique presents two main interests for the study of microstructural changes during fatigue. Considering that X-ray penetration depth reaches about 5–10 μm, measurements are restricted to the near-surface zone of the material and the technique is particularly suitable, since during fatigue process the major microstructural evolutions take place in this zone. Additionally, this technique is nondestructive and can be employed several times during fatigue test. The use of modern portable systems extends the feasibility of the technique.

The shape and position of an X-ray diffraction peak depend on microstructural parameters such as crystallite size, residual stresses, microstrains, stacking faults etc. [20]. It is well known that the analysis of broadened XRD peaks can be used to study microstructural changes of plastically deformed crystalline materials [21]. Schematically, a material may be considered as a multitude of regular pilling of atomic planes bounded by a dislocation network, called coherently diffracting domain (CDD) and characterized by its lattice spacing d_0 (nonstressed material). Changes in lattice spacing arise from deformation of the crystal lattice space, which can be detected by XRD, as illustrated in Fig. 1.

Deformation of the crystal lattice space produces different effects on the XRD peak whether it is classified as uniform or nonuniform. In the case of a uniform deformation $\varepsilon = \Delta d/d_0$ ($\varepsilon < 0.2\%$), first order stresses (macrostresses) are concerned, being homogeneous over large scale involving many grains, i.e., a few hundreds of microns. In this case, the XRD peak corresponding to a family of crystalline planes is shifted toward a higher or lower angular position according to the Bragg's law [22]. This is schematically shown in Fig. 1a. A nonuniform deformation is related to second and third order stresses (microstresses). Microstresses (microdeformations) are homogeneous over small domains such as a part of a grain, with dimensions of about tens of microns. The mechanism of microstress development is clearly important to fatigue, since fatigue itself is characterized by gradual development of inhomogeneous mechanical behavior that leads to strain localization and eventual crack initiation [23]. When microdeformations are concerned, broadening of the XRD peak is observed (Fig. 1b), related to changes in the dislocation density [8]. A very common parameter used to characterize peak broadening is the full width at half maximum (FWHM) [17–21,23–25]. The evaluation of peak broadening by the FWHM can give at least qualitative information upon the dislocation network state. XRD peak broadening can be also studied by mathematical theories (peak profile analysis) that allow an estimative of microdeformations and CDD sizes [21,26–28].

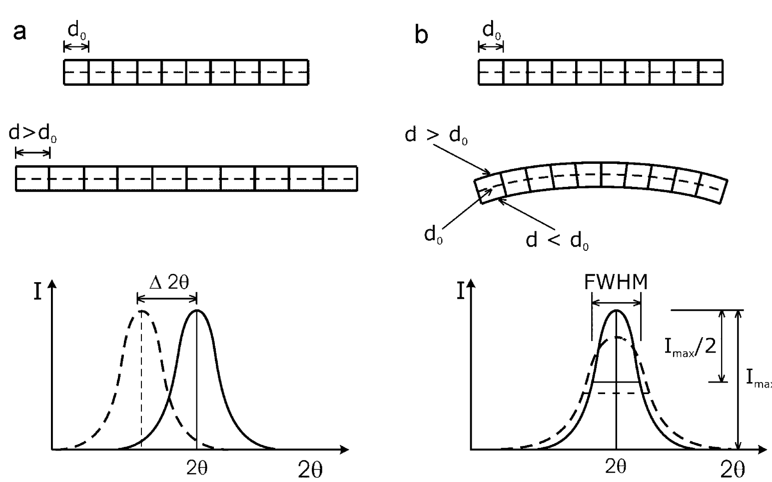

Fig. 1. Influence of (a) macrostresses (uniform deformation) and (b) microdeformations (nonuniform deformation) on X-ray diffraction peak.