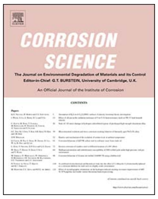
ARTICLE IN PRESS

Corrosion Science xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Corrosion Science

journal homepage: www.elsevier.com/locate/corsci



Evaluation of multiple stress corrosion crack interactions by in-situ Digital Image Correlation

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ARTICLE INFO

Keywords:
Stress corrosion cracking
Multiple cracking
Crack interactions
Digital image correlation
Electrochemical noise
Acoustic emission

ABSTRACT

Digital Image Correlation (DIC), Acoustic Emission and Electrochemical Noise measurements were applied to study the growth of multiple intergranular cracks as a colony on an Alloy 600 in a tetrathionate solution. Cracks exceeding 55 μm in length and 0.45 μm in opening were successfully detected by DIC. Moreover, crack population was classified into initiating, active and dormant cracks, active population being the larger one. The emergence and intensification of interactions produced a modification on the colony growth behavior. They range from a mostly surface crack propagation (in the absence of interactions), to in depth propagation predominantly governed by crack shielding.

1. Introduction

Stress Corrosion Cracking (SCC) is a premature degradation process of metals and alloys generated by the synergistic effect of static mechanical loading and environmental factors [1]. As such, SCC represents a common localized corrosion issue in industries operating under extreme conditions, especially in nuclear power plants (e.g. the primary cooling circuit) [2–4]. Most nuclear reactors around the world were designed to operate for 30–40 years and are actually reaching the average age of 30 years [5,6]. In this context, much of the safety assessments concerning SCC risk have over-simplified some stages in the aging process, such as initiation and the periods of interactions between several cracks (e.g. shielding effects, coalescence and irregular propagation) [7–11]. Therefore, the predicted lifetime is often over-conservative, as the initiation stages and the interaction periods play a considerable role in the cracking process [12]. Subsequently, current trends indicate that the lifetime of certain structures is extended by as much as possible, until the next reactors are constructed (i.e. IV generation) [3-4,13]. The latter implies a better understanding of the growth behavior of multiple cracking, which is modified by both initiation kinetics and crack interactions, in order to adapt the prevailing models.

A crack colony is defined by an assembly of cracks sharing a well-confined surface. Individual cracks in the colony exhibit irregular growth behavior controlled by crack interactions. Such mechanical interactions between cracks result from the reorganization of the stress field ahead of the different cracks tips (stress concentration) and crack flanks (stress shielding) [14]. Interactions considerably affect the individual crack growth rate and turn the study of multiple cracking into a challenging problem. However, the multiple cracking phenomenon is not only related to SCC issues [15]. It is also observed in the fatigue field (fatigue, corrosion fatigue and thermal fatigue) also due to the existence of multiple initiation sites [16–20].

Analytical and experimental analyses have been recently carried out in both domains. In numerical analysis, interactions are usually studied under Linear Elastic Fracture Mechanics (LEFM) for which the local stress conditions near the crack tip are defined by the Stress Intensity Factor (SIF). Interaction effects have been studied by calculating the evolution of the SIF for a couple of neighboring cracks by using the Body Force Method (BFM) and Finite Element Modelling (FEM) [21–26]. A consensus in the results shows that the SIFs values in the vicinity of the approaching crack tips are magnified and cause acceleration in the crack growth [15]. Despite this, in the cases of overlapping crack tips, the interaction level decreases due to the shielding effect [22]. After several numerical simulations, Kamaya et al. attributed the different behaviors to the high dependency of the SIF magnitude against the relative position, the relative sizes and crack shape [27]. Furthermore, they proved that the intensity of the interactions varies across the position in the crack front of a 3D semi-elliptical crack. The SIF values are therefore higher at the surface approaching crack

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http://dx.doi.org/10.1016/j.corsci.2017.09.001
Received 4 November 2016; Received in revised form 29 August 2017; Accepted 1 September 2017

Please cite this article as: Bolivar, J., Corrosion Science (2017), http://dx.doi.org/10.1016/j.corsci.2017.09.001

tips than in the middle point of each crack in the depth direction [28].

Nevertheless, the high crack densities observed in a crack colony limit such numerical analysis in the case of 3D simulations. In contrast, experimental approaches based on the indirect evaluation of SIF-values remain attractive and manageable in the case of multiple cracking [9,22,27]. Such observations deal principally with the study of crack interactions as a function of crack parameters as length, crack opening, offset distance, crack growth rate and coalescence events. Wang et al. used an ex-situ approach based on interrupted tests in order to study multiple cracking [9]. They evaluate the influence of interactions on crack growth by measuring the evolution of the crack parameters. They highlighted the importance of the mixed loading conditions (modes I and II) in the vicinity of the approaching crack tips. In addition, they collected multiple data concerning initiation kinetics and the localization of cracks with regard to modeling the multiple SCC process [12,29]. Notwithstanding, although ex-situ observations provide crucial information, in-situ observations display more suitable characteristics for SCC studies. Yet direct access to the sample must avoid the variations in testing conditions which may deeply interfere with the SCC process [30].

In this context, several studies have shown some advantages of Digital Image Correlation (DIC) for studies devoted to cracking [31–34]. DIC has been widely used in the fracture mechanics field due to its simplicity and high resolution capabilities. This technique allows the measurements of full/local field strain by comparing an image, corresponding to a deformed state, to one that corresponds to a reference state. The appearance of discontinuities in the surface (e.g. cracks) is easily identified by a jump in the displacement field facilitating the early identification of crack initiation. Some studies have already applied DIC to SCC experiments [35–39]. Cook et al. were the first to implement DIC to SCC studies [40]. They detected and quantified the growth of a few cracks at room temperature, in a 304 L stainless steel with a detection resolution of 250 μm in length and an opening of 5 μm. Today, improvements in the technique make it possible to identify cracks larger than 30 μm in length and opened more than 1 μm without decreasing the size of the Region Of Interest (ROI). These detection limits are advantageous in contrast to classic image analysis where very narrow cracks (initiation stages) could be difficult to detect.

In addition, some authors coupled DIC with complementary techniques such as Acoustic Emission (AE) and Electrochemical Noise (EN) in order to increase the monitoring capabilities of the SCC process, especially the sequence of electrochemical and mechanical events [41–44]. The EN technique is based on the measurement of current and potential fluctuations, generated by electrochemical processes such as corrosion reactions. One variant of the technique allows us to measure both the current and potential at the open circuit potential, classifying the method as non-intrusive. Between the several applications of EN, the possibility and sensitivity to detect the initiation process of cracking must be cited. Several investigators have already reported the relation between crack initiation and EN measurements in different systems [45,46]. Their results were discussed on the base of the slip dissolution model and the film-rupture model. The dissolution of the bare surface generated during the initiation process or the propagation of the crack tip, generates positive current transients and negative potential fluctuations. The shape of these transients was of particular interest [47,48] during the propagation of one or multiple cracks. Breimesser et al. [48] registered three different transients during an SCC test in a notched specimen. They attributed the three different fluctuations to metastable pitting, propagation of single cracks and coalescence events. The superposition of transients, coming from different propagation steps simultaneously, produces the apparition of a DC level. Kovac et al. [44] showed that the DC part of the Electrochemical Current Noise (ECN) increases with the intensification of the dissolution process. In addition, the DC part showed high correlation with the anodic area generated by the active cracks. In contrast, Breimesser et al. [46] related the charge associated with current transients to the individual crack propagation step, with the volume of metal dissolution due to the crack tip advance through the Faraday relation.

On the other hand, Acoustic Emission is known for its great ability to detect the evolution damage in different materials [49,50]. This technique is based on the detection of elastic acoustic waves, released by the fast energy relaxation of an irreversible localized damage phenomenon. AE have been widely used in SCC studies due to the energetic character of SCC and the numerous sources of AE activity that participate in the process [51]. Several authors have already used the evolution of AE activity in order to detect crack initiation and/or monitoring crack propagation. Indeed, the acoustic emission activity increases as cracks initiate and propagate. Moreover, other studies have centered the attention on the characteristics of acoustic events. Different sources of AE produce waves exhibiting distinctive AE parameters. Among the sources, the rupture of the oxide film, the dissolution of metal, H_2 gas evolution (related to pitting), plastic deformation of the crack tip, the fracture of ligaments and crack propagation can be cited. The classification of such events into their different nature, has given us lots of information on the cracking mechanism. For example, the distinction between continuous or discontinuous cracking, intergranular or transgranular cracking and the initiation or propagation of cracks can be obtained. [43,52–55].

The present study aims to develop a methodology based on DIC, AE and EN techniques for characterizing the behavior of an SCC colony considering the individual evolution of each crack. The synergic use of these three techniques is expected to allow the reliable detection, monitoring and study of Intergranular Stress Corrosion Cracking (IGSCC). Attention will be focused on identifying the different stages of the crack colony evolution and the mechanisms involved in each stage. Specific parameters will be defined for this purpose.

2. Experimental procedure

2.1. Material and sample preparation

The tested material consisted of a 2 mm thick plate of Alloy 600, whose chemical composition is given in Table 1. The specimens were machined out by Electrical Discharge Machining with a gauge length of 117 mm and a width of 8 mm (Fig. 1a). The samples underwent a full sensitization heat treatment (30 h at 600 °C and air-cooled) to obtain the precipitation of carbides at the grain boundaries in order to increase susceptibility of IG-SCC of the alloy (in a tetrathionate solution at room temperature). The resulting microstructure exhibits an austenitic matrix with a grain size of 70–100 μm. Prior to testing, the sample surfaces were prepared by grinding up to 1200 grit SiC paper, and then electroetched in a solution of 8 vol% perchloric acid and 92 vol% glacial acetic acid in two stages: at 5 V for 30 s, and then 10 V for 1 min. This surface treatment produces a very shallow and random heterogeneous pattern, suitable for further DIC analysis.

In order to reduce the exposed surface, the specimens were partially covered with silicon rubber. Both sides of the middle section of the samples were exposed to the electrolyte, each with an exposed area of $120\ mm^2$ (15×8 mm). The experiments were performed in a three electrode cell test with optical access for DIC measurements (Fig. 1b). For all the experiments, the test solution consisted of 0.01 M potassium tetrathionate acidified at pH 3 by H_2SO_4 addition.

Table 1
Composition of by tested Alloy 600.

Element	Ni	Fe	Cr	Mn	Cu	Co	Ti + Al	C	S
Wt.%	bal.	9,25	15,52	0,12	0,1	0,1	0,25	0,03	0,002