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Role of microtexture in the interaction and coalescence of hydrogen-induced cracks

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The role of microtexture in hydrogen-induced crack interaction and coalescence is investigated in line pipe steels using electron backscatter diffraction. Experimental evidence shows that, depending on the local grain orientation, crack interaction and coalescence can depart from the conditions predicted by the mixed-mode fracture mechanics of isotropic linear elastic materials. Stress simulation and microtexture analysis are used to explain the experimental observations.

1. Introduction

Hydrogen-induced cracking (HIC) affects low-strength carbon steels used in pipelines and pressure vessels carrying wet sour gas [1]. The interaction and coalescence of HIC cracks can lead to the stepwise growth of this damage and eventually, the unexpected failure of in-service components. To date, the strategies used to improve the resistance of line pipe steels to HIC have not been entirely successful [1–3]. The engineering of crystallographic texture and grain boundary has recently been proposed as a means to further reduce the susceptibility of these steels to HIC [3,4].

Little information is available in the literature on the role of grain orientation in the interaction and coalescence of non-coplanar (offset) HIC cracks. The interaction of offset cracks has been mostly modelled based on the mixed-mode fracture mechanics of isotropic linear elastic materials [5,6]. However, because the crystallographic orientation at the crack tip determines the feasibility of crack propagation along low-resistance paths such as cleavage planes, the conditions for crack coalescence in real materials might differ greatly from those predicted using the isotropic model. The unanticipated coalescence of offset cracks may produce a sudden increase in the crack growth rate, thereby reducing the expected life of structural components affected by HIC.

This paper presents experimental evidence that microtexture can play a significant role in the interaction and coalescence of HIC cracks. HIC samples of line pipe steels have been studied using automated electron backscatter diffraction (EBSD) and Orientation Imaging Microscopy (OIM). The analysis of the microtexture and stress fields in the interaction region of closely-spaced offset cracks explains why the experiential coalescence conditions differ from those predicted by the fracture mechanics of isotropic linear elastic materials. The results of this paper can also be extended to the coalescence of cracks in materials affected by stress corrosion cracking and corrosion-fatigue [7,8].

2. Experimental

The interaction and coalescence of non-coplanar cracks were investigated in samples taken from an HIC-stricken section of a 610 mm diameter, 12 mm thickness, API-5L-X46 pipeline used for about 25 years for transporting wet sour gas (Steel I) and from a new 610 mm diameter, 12 mm thickness, ASME-A106 grade B line pipe (Steel II). The procedures described in the NACE TM0284-96 (TM 0177 solution) were used to produce HIC in this latter steel by hydrogen absorption from aqueous sulfide corrosion [9]. The chemical composition of the investigated steels is shown in Table 1.

Optical and scanning electron microscopy and automated FEG-EBSD were used, respectively, to carry out metallography inspections and to collect microtexture data on transversal sample cross-sections of the HIC samples under investigation. OIM was used to analyze the EBSD measurements performed on a hexagonal mesh with a measurement step in the range from 0.1 to 3 μm. The distribution of individual grain orientations was mapped in sample regions containing cracks that had interacted and coalesced. In these regions grain boundaries were located in the orientation maps by the presence of point-to-point misorientation greater than 3°. The orientation of cleavage planes and slip systems in

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Table 1
Chemical composition of the investigated steels.[a]

Steel	C	Mn	S	P	Si	Cu	Cr
I	0.212	1.334	0.032	0.028	0.037	–	0.009
II	0.085	0.916	0.009	0.017	0.252	0.272	0.011

[a] The composition values are given in weight%.

grains suffering transgranular cracking in these regions was determined and compared with the observed trace of the coalescence path.

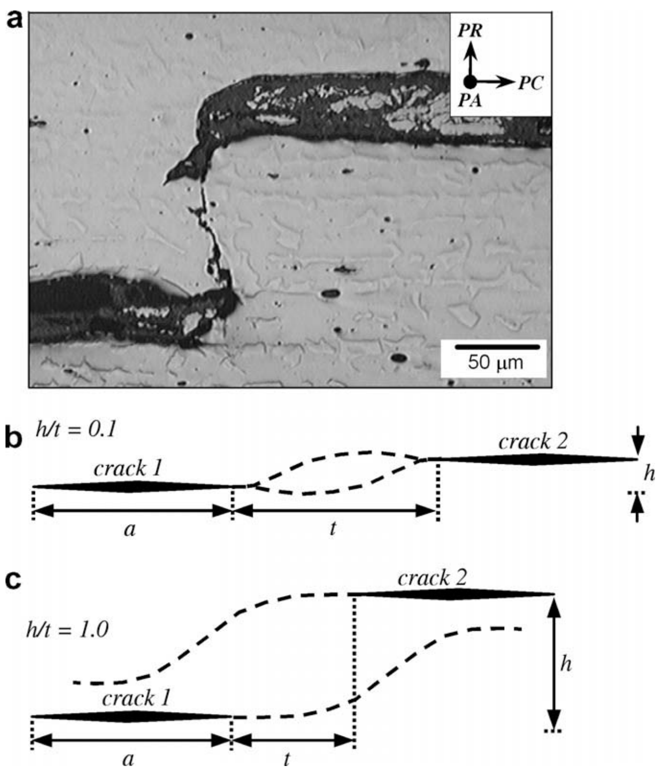

Fig. 1. (a) Optical micrograph of a HIC region in Steel I. (b) Merging and (c) non-merging crack interaction paths consistent with the fracture mechanics of isotropic linear elastic materials [4,6]. *PR, PC and PA* refers to the pipe radial, circumferential and axial directions, respectively.

The numerical simulation of the stress fields in the crack interaction regions was conducted assuming a linear elastic material and a plane stress condition [5,7,10]. The mixed-mode stress intensity factors (K_I and K_{II}) [7] at the interacting crack tips and the resulting maximum shear and principal stresses were computed using methods described elsewhere [5,10,11]. The Appendix to this paper contains a brief outline of the method used to simulate the stress fields.

3. Results and discussion

The investigated steel samples exhibited the characteristic pearlite/ferrite microstructure of low-strength carbon steels [10]. Steel I shows a ferrite grain size close to 20 μm and a proportion of pearlite of about 30%. In this steel, elongated (type II) MnS inclusions were found to be the preferred sites for crack nucleation. Steel II shows a more banded pearlite/ferrite microstructure with a pearlite proportion of about 8% and a ferrite grain size close to 15 μm. In this material, the MnS inclusions were spherical and much less numerous. Consequently, HIC nucleation sites were found located primarily at ferrite/pearlite interfaces.

In both steels the investigated HIC regions were located at mid-pipe wall thickness. The development of HIC occurred parallel to the pipe wall and also in a stepwise manner due to crack coalescence (Fig. 1a). Crack growth occurred mostly in an intergranular mode while transgranular propagation, though less frequent, contributed to both the planar and stepwise propagation.

The merging of the non-coplanar cracks shown in Fig. 1a takes place through the shortest path between the nearest crack tips, following a trajectory that is close to the pipe radial direction (*PR*). This behaviour is unexpected according to the coalescence model based on the mixed-mode fracture mechanics of isotropic linear elastic materials [5,7]. In this model, the mixed-mode loading (mode I and II stresses) resulting from interaction of closely-spaced cracks produces an initial slight repulsion of the nearest interacting cracks tips before they overlap ($t/a > 0$, $K_{II}/K_I > 0$, see Figs. 1b and 2b). After overlapping ($t/a \leqslant 0$, $K_{II}/K_I < 0$), the crack tips are attracted to each other [5,7]. The offset distance (h), relative to the nearest tip separation (t), determines whether each tip merges with the other crack ($h/t \leqslant 0.85$, Fig. 1b) or not ($h/t > 0.85$, Fig. 1c).

The criterion for crack coalescence is based on the maximum tangential stress theory [5,12]. According to this theory, the direction of the crack path under a mixed-mode loading condition is determined by the direction (θ_{mt}) of the maximum tangential

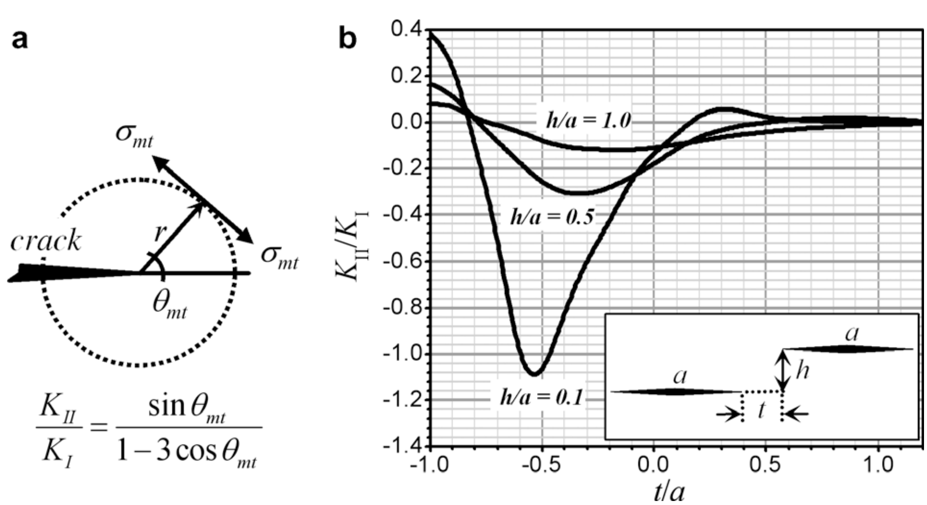

Fig. 2. (a) Direction (θ_{mt}) of the maximum tangential stress. (b) Ratio of the stress intensity factors (K_{II}/K_I) for the nearest tips of two non-coplanar cracks as a function of their horizontal distance.