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Comparative assessment of the fracture behaviour of micro-alloyed and API-5L X65 steels in simulated fuel grade ethanol environment

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In order to fully realize the benefit of pipeline and automotive materials in fuel ethanol applications, a comprehensive understanding of their fracture behaviour is essential. Very few studies have been undertaken on fracture of materials in stress corrosion environments. This paper presents a comparative assessment of the fracture toughness, tearing modulus and widths of stretch zones for API-5L X65 steel and micro-alloyed steel (MAS). The results show that MAS exhibits a better fracture resistance than API-5L X65 steel in air and in solution. API-5L X65 in solution shows a faster crack extension than MAS-in solution. It is found that J_{str} (fracture toughness derived from stretch zone geometry) obtained for the two steels exhibits a similar trend with J_i (initiation fracture toughness) which is obtained at the departure of the blunting line on their *J-R* curves and thus suitable for representing the initiation toughness of the two steels in solution. In general, fuel ethanol reduces fracture resistance in X65 and micro-alloyed steels.

1. Introduction

Due to the stress corrosion cracking failures often encountered in fuel ethanol end-user storage and blending facilities, fracture mechanics based analysis is crucial in order to predict the behaviour of applicable materials. Infrastructure plays a key role in ensuring safe, reliable and efficient distribution of fuels to end-users. Materials which normally are compatible with gasoline may be damaged by the presence of ethanol in the fuel. Consequently, a substantial number of notched slow-strain rate (N-SSR) tests have been conducted to study stress corrosion cracking initiation and propagation mechanisms of steels in fuel ethanol [1,2–8,9]. API-5L X52 carbon steel was reported to exhibit ductile fracture in the presence of 0.5–2 vol% water content in simulated E95 blend [9]. Crack growth rate increased with increasing ethanol concentration in N-SSR tests performed with X46 double submerged arc weld (DSAW) line pipe steel [10]. Crack growth rates of a seamless line pipe, cast steel and a low frequency electric resistance weld (LFERW) pipe are to a certain extent lower than for a DSAW pipe [10].

Additionally, the influences of simulated fuel-grade ethanol (SFGE) on fatigue crack propagation have been thoroughly evaluated for several pipeline and storage-tank steels. A36, X52 and X70 pipeline steels are susceptible to enhanced fatigue

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Nomenclature

σ_o, σ_{YS}, σ_{UTS}	flow stress, yield stress, ultimate tensile stress
%	percent
v	Poisson's ratio
ΔK	stress intensity factor range
a_i, a_{oq}, Δa_Q	instantaneous crack length, original crack length, crack extension
b_o, $b_{(i-1)}$	un-cracked ligament, at the start of test and at (i − 1)th step
e_u, e_T	uniform elongation, total elongation
n	strain hardening exponent as per Hollomon's equation
$A_{pl(i)}$	instantaneous area under the load-plastic load line displacement curve in fracture toughness test
B, B_N	specimen thickness, net specimen thickness
E	elastic modulus
H_v	Vickers hardness
$J_{0.2}, J_i, J_{IC}, J_{pl}, J_{str}$	an energy based fracture parameter, determined at 0.2 mm crack extension, initiation fracture toughness, qualified as plane strain fracture toughness, plastic part of fracture toughness, fracture toughness measured from stretch zone
K_i	instantaneous stress intensity factor
P_i	instantaneous load
S	specimen span
W	specimen width
T_R	tearing slope at critical crack extension

damage attributable to ethanol stress-corrosion cracking in fuel-grade ethanol environments [11]. It is worth noting that in spite of the investigations carried out so far, there are still growing concerns about the SCC behaviour of pipelines used to handle fuel ethanol. Similarly, not many studies using fracture mechanics techniques for steels in alcoholic stress corrosion environments have been made [12–17]. In addition, there is dearth of information on fracture toughness of steels in recently emerged fuel ethanol environments.

It is with a view to extending knowledge in this area of study that this research seeks to center its investigation on the fracture study of API-5L X65 and micro-alloyed steels in E20 simulated fuel ethanol environment with respect to a reference fracture behaviour in air. The effect of environment on fracture toughness, tearing resistance and stretch zone widths (SZW) of the two steels were investigated.

2. Experimental procedures

2.1. Materials

The API-5L X65 and micro-alloyed steels (MAS) used in this investigation were commercially produced rolled pipes and plates respectively. They have application in the automotive and pipeline industries. The X65 pipe was ~560 mm outer diameter with ~7 mm wall thickness. The micro-alloyed steel plate was 7 mm in thickness. The chemical composition of the as-received steels is shown in Table 1.

Specimens were fabricated for tensile and monotonic *J*-integral tests from the stock materials under as-received condition. Fabrication of tensile test specimens was in accordance with ASTM E8M-15a [18]. Round tensile specimens of 5 mm gauge diameter were fabricated from MAS whereas rectangular specimens were used for the API-5L X65 tensile test. Table 2 lists the mechanical properties of the two steels which were obtained from tensile tests at room temperature. The tensile flow curve of the steels exhibited prominent yield point effects. The microstructures of the two steels are shown in Fig. 1. Both steels consisted of predominantly ferritic structure with pearlite randomly oriented in the ferrite matrix. The MAS material contains larger-grained polygonal ferrite relative to the API-5L X65 material and thus accounts for its lower yield strength (301 MPa).

To evaluate fracture behaviour, three-point bend (TPB) specimens as shown in Fig. 2 were employed for carrying out monotonic *J-R* tests in air and fuel-ethanol solution (E20). The orientation of the specimens were LT (in case of MAS) and

Table 1
Chemical composition of MAS and API-5L X65 steels in as-received condition (wt.%).

Element	C	Mn	Si	Cr	Ni	Al	Ti	Mo	Cu	Fe
MAS	0.13	0.77	0.012	0.027	0.015	0.042	0.0025	0.0017	0.006	Balance
API-5L X65	0.08	1.22	0.245	0.022	0.023	0.026	0.0029	0.0062	0.008	Balance

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