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Microstructural aspects of intergranular and transgranular crack propagation in an API X65 steel pipeline related to fatigue failure

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ABSTRACT

In this research, we investigated microstructural aspects of intergranular and transgranular fatigue crack propagation in an API X65 steel pipelines. For this purpose, the fatigue testing, based on ASTM E647 Standard, was carried out on CT specimens. The micro-texture measurement results showed that fatigue micro-cracks propagates dominantly in transgranular manner through differently oriented grains. It was also observed that most of the grains involved in crack propagation are broken during the crack growth. Coincidence site lattice (CSL) boundaries are considered as crack resistant paths; however, there was an accumulation of Σ3 boundaries around the fatigue micro-cracks showing that such boundaries acts as high energy boundaries during crack propagation. Elongated manganese sulphide inclusion was determined as the most detrimental inclusion for crack propagation due to the highly disordered boundaries between metal matrix and this inclusion. In other words, this type of inclusion may initiate the fatigue crack due to a high stress concentration factor that can provide in some sharp edges. Moreover, it can facilitate fatigue crack growth by reducing the local fracture toughness. Many manganese sulphide inclusions were found on fatigue fracture surfaces.

1. Introduction

Since steel pipelines carry oil and natural gas in a safe and economical way, they are very important to the nation's economy. In the United States, pipelines carried more than four trillion barrel-miles in 2001. Mostly, steel pipelines are used to carry sour hydrocarbons in severe environments. Therefore, they are exposed to different types of failure modes. For instance, hydrogen induced cracking (HIC) and stress corrosion cracking (SCC) have been recognized as the most important failure modes in sour environments [1–3]. Moreover, due to the some external factors such as wind, ground movements, pressure fluctuations inside the pipe body, such steels are exposed to the fatigue failure as well. Since long cracks initiate from structural defects, crack initiation is very important to scientists and industry as well. It is well accepted among researchers that structural defects, such as non-coherent inclusions, precipitates and hard phases, play a crucial role during crack nucleation in all types of failures [4–8]. Aside from the crack nucleation sites, crack propagation is also important in fatigue failure. There are several works in the literature which have been focused on crack propagation sites in steel pipelines [9–12]. However, most of such works concentrated on HIC and SCC related failure and there are not sufficient studies on fatigue crack propagation in steel pipelines. It is worth-mentioning that the mentioned cyclic loads

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weaken the pipe body by crack nucleation and propagation.

There are some parameters involving crack propagation in steel pipelines. First, the microstructure of pipe has a key role in crack propagation. Crack growth can easily occur through hard phases, such as martensite and bainite. Fatigue failures are divided to three steps. In the first step, cracks nucleate from structural defects, such as inclusion and precipitates. Some inclusions such as manganese sulphide are hard and brittle and have an elongated shape as well. This type of inclusions may provide regions with high stress concentration factor and can be considered as crack initiation site [13]. The second step in fatigue failures is the crack propagation step in which crack growth occurs through the thickness where crack propagates easily. Basically, crack chooses easily paths for propagation which are grain boundaries, hard phases and special grain orientations. Several researchers studied fatigue crack propagation in steel pipeline. However, most of them discussed the role of microstructural parameters on fatigue failure. The effect of crystallographic texture and grain boundary character on fatigue crack propagation has been less considered in the literature. The third step in fatigue failure is the final fracture. Even though most researchers believe that the crack initiation and fracture life times are negligible compared with the crack propagation time in steels [14], most pipeline designers do not consider crack initation to be negligible. Some researches focused on fatigue failure in steel pipelines. For instance, the finding of Sowards et al. illustrated that the thermal residual stresses retards the fatigue crack propagation rate in friction stir weld region in steel pipeline. The role of inclusions and precipitates on HIC and SCC in steel pipelines have been investigated by several researchers. Yu et al. investigated the role of different microstructural parameters on fatigue failure in steel pipelines and concluded that some types of inclusions, such as manganese sulphide, have a key role in fatigue crack propagation [13]. More likely, fatigue cracks initiate from inclusions due to the highly disordered boundaries between metal matrix and inclusions. Moreover, some types of inclusions with an elongated shape may provide regions with high stress concentration factor and consequently are prone for crack nucleation. In another study, the findings of Hayne et al. [14] documented that the orientation of manganese sulphide is very important on fatigue failure of induction hardened 4140 steel. The same authors concluded that the effect of manganese sulphide orientation on fatigue behavior outweigh the effect of different orientations of the banded microstructure. The effect of sulphide inclusion, its level and orientation on fatigue properties of SAE 4140 steel was investigated by Cyril et al. [15] and they concluded that this type of inclusion can be considered as the fatigue crack initiation site. It is notable that aside from the role of inclusions, hard phases, such as martensite-austenite constituents, play a critical role in crack initiation in steel pipeline [16].

In this study, we investigated the microstructure of an API X65 steel pipeline with an FEI Quanta 200 FEG environmental scanning electron microscope (SEM) under high vacuum. We also performed the fatigue tests on compact-tension (CT) specimens. As mentioned earlier, the role of texture and micro-texture on fatigue crack propagation has been less considered in the literature. Therefore, we also carried out EBSD measurements on the fatigue cracked regions to deeply understand the role of texture and grain boundary character on fatigue crack propagation in steel pipeline. Moreover, the effect of manganese sulphide inclusion on fatigue crack propagation was investigated. Finally, we discussed the microstructural aspects of intergranular and transgranular of fatigue cracks in X65 steel pipelines.

2. Experimental procedure

2.1. Tested material

We investigate an as-received API X65 steel pipeline with the thickness $t = 8.5$ mm, modulus elasticity E = 200 GPa, yield strength $\sigma_y = 568$ MPa and ultimate tensile strength $\sigma_{UTS} = 650$ MPa in this work. Table 1 shows the chemical composition of the X65 specimen. We simply abbreviated the rolling, transverse and normal directions of X65 steel as RD, TD and ND, respectively. We grinded the surface and the cross section of steel with MD-Piano 120, 220, 500, 1200, 2000 and 4000 discs and then polished with the MD-Dac 3 μm and MD-Nap1μm polishing discs to observe the microstructure of steel. Then, we etched the surface and cross section of polished areas with 2% nital solution. We performed the SEM observations using with a FEI Quanta 200 FEG environmental SEM equipped with electron backscatter diffraction (EBSD) detector. We used EBSD measurements to investigate the role of texture and grain boundary character in fatigue crack propagation.

2.2. Fatigue experiments

We carried out fatigue experiments on six typical CT specimens using an Instron Fatigue Testing Machine. Fig. 1 shows the dimension of X65 specimen that was used in fatigue testing. Based on the ASTM E647 (2008) standard, CT specimens were provided from X65 steel pipeline with an outer diameter of 762 mm and thickness of 8.5 mm using a wire electrical discharge machining (EDM). As shown in Fig. 1, a notch was created in the circumferential (rolling) direction in order to achieve a fatigue crack. In this test, the applied load was from sinusoidal type and varied from 5 kN to 10 kN (stress ratio = 0.50) and the frequency of the test was 50 Hz. We used an electrical discharge machine (EDM) to create a notch on the outer surface of each specimen. The notch was

Table 1
Chemical composition of the X65 specimen.

Pipeline Steels	C	Mn	Si	Nb	Ti	Cu	V	S	P	N
X65	0.081	1.54	0.33	0.04	0.002	0.18	0.001	0.003	0.01	0.009