Experimental study and numerical simulation on the SSCC in FV520B stainless steel exposed to H₂S+Cl⁻ Environment

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ABSTRACT

Constant displacement loading tests using wedge opening loading specimens were carried out in aqueous hydrogen sulfide solution containing sodium chloride to investigate the susceptibility of stress corrosion cracking (SCC) of FV520B precipitation hardening martensitic stainless steel. Results of the SCC tests indicated that the stress corrosion critical stress intensity factor (K_{ISCC}) dramatically decreased in the corrosion medium investigated and decreased with the increasing of H₂S concentration. Microstructures of fracture surfaces were analyzed using a scanning electron microscope (SEM) with an energy dispersive X-ray spectroscopy (EDS). The fracture surface was typical of sulfide stress corrosion fracture. In addition, large amount of intermittent arc-crack on the side surfaces around the tip of main crack formed even no main crack propagated.

A sequentially coupling finite element analysis (FEA) program was utilized to simulate the stress field and calculate the diffused hydrogen concentration distribution of specimen exposed to the corrosion medium investigated. The FEA results indicated that corrosion pit affected the stress and diffusion hydrogen distribution around the corrosion pit where large stress gradients formed. Side surface cracks initiated from those corrosion pits and propagated under the synergy of stress and hydrogen. The effect of the corrosion pit on hydrostatic stress distribution was limited in superficial zone near the side surface, thus side surface cracks propagated along the hoop direction rather than along the direction of specimen thickness. Based on the morphology observation and FEA results, it can be concluded that the SCC mechanism of FV520B steel was hydrogen embrittlement mainly and combination of anodic dissolution. Simultaneously, corrosion pitting was the precondition of side surface crack formation while the stress induced hydrogen diffusion was the dominant factor.

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Introduction

Aqueous H₂S environments can easily form in the oil and chemical industries when equipment is in operation, overhaul or shutdown. Materials exposed to aqueous H₂S environments absorb atomic hydrogen which is produced via the H₂S reduction reaction on the surface. Atomic hydrogen can penetrate into material and accumulate in the matrix-inclusion interfaces, react with metal to form hydride, which will cause the embrittlement of materials, and therefore lead

to the premature damage of equipment, which significantly affects their long period safety operation. The sulfide stress corrosion cracking (SSCC) of steels have attracted great concern [1–6].

With the development of computer technology, the finite element method (FEM) has proved to be a powerful tool to calculate the distribution of diffusion hydrogen concentration and analysis influence of hydrogen on the material properties [7–14]. Vigdis et al. [7] used the FEM to simulate the onset of hydrogen-induced fracture of API X70 pipeline steel through a finite element cohesive element approach. The results shown that the base metal of X70 steel revealed a low susceptibility to hydrogen embrittlement while the weld metal of X70 steel showed marginal susceptibility to hydrogen. Jiang et al. [10] developed a 3D sequential coupling calculating method to calculate the residual stresses and distribution of diffused hydrogen. The effects of welding residual stress and microstructure on the hydrogen diffusion were taken into account [11]. Vergani et al. [13] used a numerical model to simulate crack propagation of compact tensile specimens for evaluating the effect of hydrogen embrittlement on low-alloy steels. Abderrazak et al. [14] provided a comprehensive finite element model for the numerical simulation of hydrogen induced cracking in steel pipelines exposed to sulfurous compounds, such as hydrogen sulphide (H_2S). The model is able to mimic the pressure build-up mechanism related to the recombination of atomic hydrogen into hydrogen gas within the crack cavity.

FV520B is one of the most widely-used materials for rotating equipment in the oil and chemical industries due to its high strength, excellent plasticity and corrosion resistance. Many investigations on the FV520B steel have been done so far [15–22]. There were failure cases that FV520B steel used in compressor impeller premature damaged because of SSCC, which was accelerated by hydrogen induced cracking [20–22]. Based on the actual service condition of FV520B steel used as compressor impeller, K_{ISCC} of FV520B steel exposed to aqueous hydrogen sulfide solution with the presence of sodium chloride were measured through constant displacement loading tests using wedge opening loading specimens. Scanning electron microscopy with energy dispersive X-ray spectroscopy was also utilized to analyze the morphology of fracture surface. In addition, a sequential coupling stress-hydrogen diffusion analysis program was established by FE software ABAQUS according to the intermittent arc-crack generated on the side surface. Stress field and diffused hydrogen distribution around the tip of main crack were calculated to investigate the mechanism of side surface cracking.

SCC experiment for FV520B steel

The testing material used in this study was a hot-rolled plate of FV520B martensitic precipitated hardening stainless steel.

The material tested in this study was treated by the following steps:

(1) Solution treatment: temperature was risen to 1050 °C and maintained for 2 h, then quenched in oil until the temperature dropped to 200 °C and then cooled in air.
(2) Intermediate treatment: temperature was risen to 780 °C and maintained for 2 h, then quenched in oil.
(3) Aging: temperature was risen to 620 °C and maintained 3 h, then cooled in air.

The chemical composition (wt.%) of the testing material was determined using a SPECTRO MAXx analyzer and was listed in Table 1. It met the requirements of EN10088-1. In order to observe the surface microstructure of FV520B steel, the metallographic sample was first mechanically wet ground to 2000 grit silicon carbide paper, then polished with 1 μm diamond paste, at last it was etched in a solution consisted of 5 ml hydrochloric acid, 1 g picric acid and 100 ml ethanol. Subsequently, the metallographic sample was observed with a ZEISS SUPRA40 field emission scanning electron microscope. Fig. 1 displayed the typical SEM image of FV520B steel, it can be seen that the microstructure of the steel mainly consists of martensite. The mechanical properties of FV520B steel was measured by tensile test under the loading rate of 1 min/min. The sample was a standard round bar with a diameter of 8 mm. The stress-strain curve of this material was shown in Fig. 2. The Vickers hardness (HV) of FV520B was measured with a load of 10 kgf for 15 s on a DVK-1s hardness tester. The mechanical properties of FV520B steel used in this study were listed in Table 2.

The test was conducted in 5% sodium chloride solution with different concentration of aqueous hydrogen sulfide in ambient temperature. The wedge opening loading (WOL) sample was machined according to the national standard GB/T 15970.6–2007 [23]. In order to reveal the state of crack
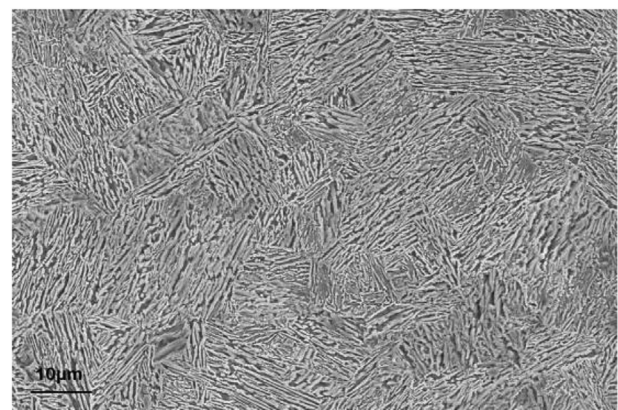

Fig. 1 – Metallographic microstructure of the FV520B steel.

Table 1 – Chemical composition of FV520B steel (wt%).											
	C	Mn	P	S	Si	Ni	Cr	Cu	Mo	Nb	Fe
FV520B	0.057	0.456	0.025	0.0032	0.314	5.43	13.49	1.30	1.45	0.319	Bal.
EN10088-1	≤0.07	≤1.00	≤0.040	≤0.015	≤0.70	5.0–6.0	13.0–15.0	1.2–2.0	1.2–2.0	0.15–0.60	Bal.