MICROSTRUCTURAL EFFECTS ON SULFIDE STRESS CORROSION CRACKING IN LOW-ALLOY TUBULAR STEELS

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The resistance of the low-alloy tubular steel 30G2 to the SSCC process was evaluated. The influence of microstructure and heat treatment on the SSCC susceptibility was investigated. Four differently heat-treated casings with various microstructures and shapes of nonmetallic inclusions were used. Threshold values σ_{th} and K_{1SSC} were determined. Fractographic and metallographic methods were used to analyze specific microstructural mechanisms of damage accumulation in the SSCC process.

INTRODUCTION

Sulphide stress corrosion cracking (SSCC) of oil country tubular goods is one of the most important problems in sour oil and gas wells. SSCC of low-alloy steels is a complex process of interaction of a corrosive sour environment with metal. SSCC is believed to be caused by hydrogen embrittlement of metal during corrosion reaction in environments containing hydrogen sulphide. Such factors as metal microstructure, type of heat treatment, grain size, shape of nonmetallic inclusions exert great effect on the SSCC process.

The objective of this study is to evaluate the susceptibility of some casings to the SSCC process and to analyze the influence of microstructure and heat treatment on the SSCC resistance. Normalized as well as quenched and tempered casings manufactured from the low-alloy tubular steel 30G2 to different microstructures and shapes of nonmetallic inclusions were investigated. NACE Standard TM-01-77-90 tests were used to determine the threshold values of the tensile stress σ_{th} and the stress intensity factor K_{1SSC}.

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EXPERIMENTAL PROCEDURE AND RESULTS

Materials

Four as-received casings with different strength levels obtained by different heat treatment and manufactured from the low-alloy steel grade 30G2 (0.31% C, 1.40% Mn, 0.24% Si, 0.019% P, 0.017% S, Cu, Ni, Mo and Cr < 0.1%) were investigated.

TABLE 1- Mechanical Properties of Casings Tested

Pipe Number	Heat Treat-ment	Yield Strength (MPa)	Tensile Strength (MPa)	Elon-gation (%)	Reduction of area (%)	Grain size (μm)
1	N	463	712	20.4	43.8	10
2	QT	622	863	22.4	41.7	100
3	QT	715	846	18.0	48.5	100
4	QT*	676	780	21.1	56.6	15

Heat treatment and microstructure

In the process of casing manufacture the pipe metal was subjected to different types of heat treatment. The pipe 1 after normalization (N) had a ferrite-pearlite microstructure and wide (600*30 μm) sulphides. The pipes 2 and 3 after quenching and tempering in a standard manner (QT) had tempered martensite microstructures and narrow (100*2 μm) sulphides. The initial microstructure in pipe 4 was subjected to recrystallization by special heat treatment (QT*).

SSCC testing

All corrosion tests were carried out at room temperature 25°C in the NACE solution (5 % sodium chloride and 0.5 % acetic acid saturated with hydrogen sulphide to pH =3.3-3.5).

The simplest estimation of the SSCC resistance of a casing can be made on the basis of the threshold stress value σ_{th}. Accordingly the NACE Standard TM-01-77-90 (1) tensile tests were conducted in NACE solution on 6-mm dia cylindrical specimens under a constant stress until the specimens were broken. The maximum stress σ at which no failure occurs during 720 h is referred to the threshold stress value σ_{th} and is used as the measure of the SSCC resistance. The results of the tensile tests for the casings investigated are given in Table 2.

Another test method proposed in the NACE Standard TM 01-77-90 (1) estimates the SSCC resistance from a linear fracture mechanics point of view. This kind of tests is carried out on double cantilever beam (DCB) specimens and determines the threshold fracture toughness K_{1ssc}. The test procedure was firstly described by Heady (2). In brief, DCB specimens are wedge loaded and placed in the NACE solution for 360 h. After removal from the solution the equilibrium wedge load P and the crack length l are determined and the K_{1ssc} value is calculated as follows (1,2)

$$K_{1ssc} = \frac{2\sqrt{3}Pl(1+ch/l)}{Bh^{3/2}}(B/B_n)^{1/\sqrt{3}} \tag{1}$$

where 2h, B, B_n are the height, thickness and side-grooved cross-section thickness of the specimen, c=0.687.

As shown by Astafjev at al (3,4) the direct measurement of the equilibrium wedge load P can lead to certain errors. The more convenient method for the calculation of K_{1ssc} proposed in (3,4) can be rewritten as

$$\frac{K_{1ssc}}{K_{1o}} = \frac{l+ch}{l_o+ch}\;\frac{(l_o+ch)^3-(ch)^3}{(l+ch)^3-(ch)^3} \tag{2}$$

where l_o is the initial crack length, K_{1o} is the initial stress intensity factor calculated for the initial wedge load P_o in accordance with equation (1). In our investigation the dimensions of the DCB specimens were 100x25x5.5 mm with B_n=3.5 mm, l_o=30 mm, and P_o given in Table 2. The results of the DCB tests are also given in Table 2.

TABLE 2- SSCC Resistance of Casings Tested

Pipe Grade	Heat Treat-ment	Stress Ratio σ/σ_y	Time to Failure (h)	Initial load P_o (kN)	K_{1o} (MPa$\sqrt{m}$)	$l-l_o$ (mm)	K_{1ssc} (MPa$\sqrt{m}$)
1	N	0.8	>720	3.25	74.5	5	58.2
		0.9	528				
2	QT	0.6	>720	3.30	75.7	19	33.7
		0.7	456				
3	QT	0.4	>720	4.15	95.2	50	17.9
		0.5	672				
4	QT*	0.8	>720	3.75	86.0	24	32.4
		0.9	600				

DISCUSSION AND CONCLUSIONS

The results obtained show that the pipe 1 after normalization with ferrite-pearlite microstructure and low yield strength can be regarded as the SSCC resistant one. In this pipe the multiple-step process of damage accumulation occurs (5). At the first stage microcracks appear on the wide sulphides owing to hydrogen delamination. At the second stage the microcrack tips undergo hydrogen embrittlement (Figure 1a,b). The embrittled zones grow, coalescence and initiate the main macrocrack (Figure 1c,d).

The distribution of the Knoop's microhardness HK near a sulphide or microcrack tip compared with its value HK_0 in the base metal ($DH=HK-HK_0$) is plotted on Figure 2. At first, this value increases, which corresponds to the appearance of a hardened zone near a sulphide tip (Figures 1a and 2a). Then the microcracks on sulphides occur and there appears a weakened zone bounded by a hardened zone (Figures 1b and 2b-2d).

Among the pipes after quenching and tempering with martensite microstructure and high yield strength only the pipe 4 can be regarded as the SSCC resistant one. The pipe 2 differs by low σ_{th} value and the pipe 3 has both low K_{1ssc} and σ_{th} values. It was found that in this case the hydrogen delamination and hydrogen embrittlement near sulphides do not occur and the intergranular brittle fracture is observed (Figure 3). Hence, the decrease of the grain size by special heat treatment in the pipe 4 increases the σ_{th} value and the resistance of this pipe to the SSCC process.

ACKNOWLEDGEMENTS

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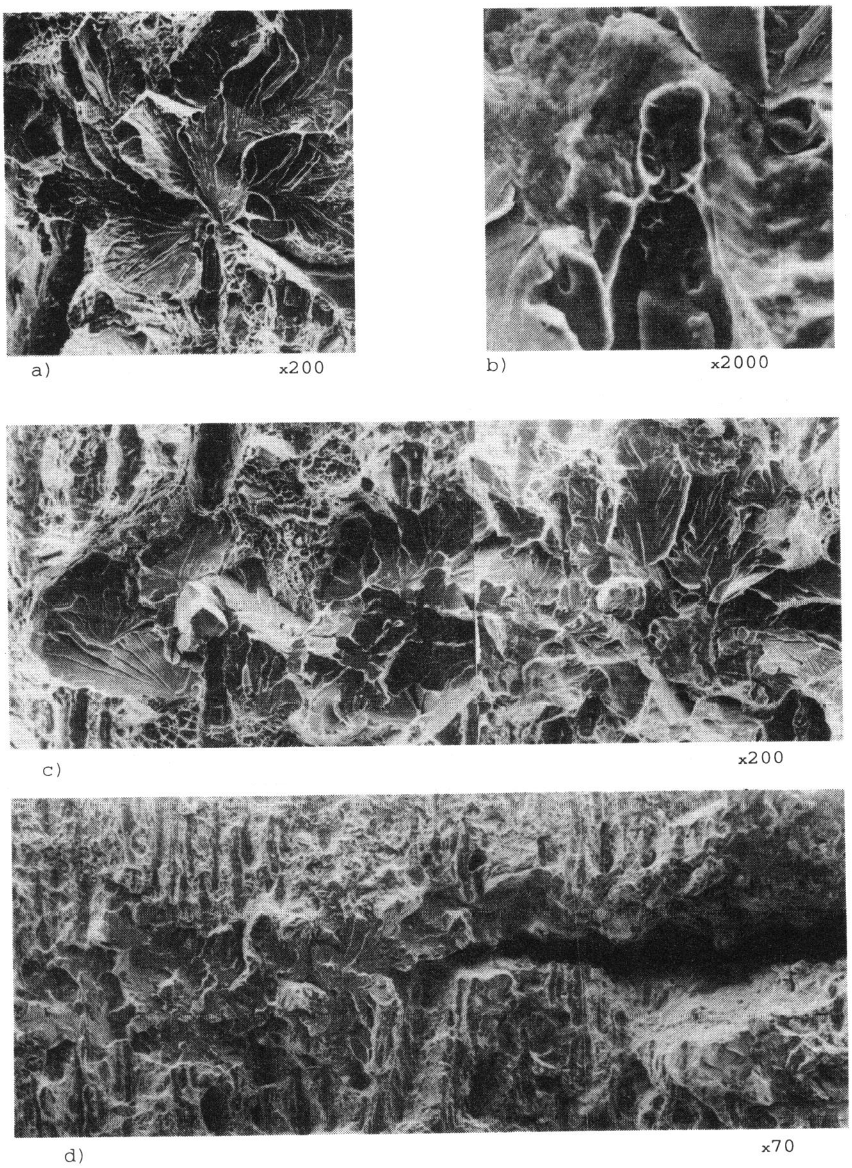

Figure 1. Damage accumulation near sulphide tips in the pipe 1 (a,b- embrittled zone, c- zones coalescence, d- crack initiation).

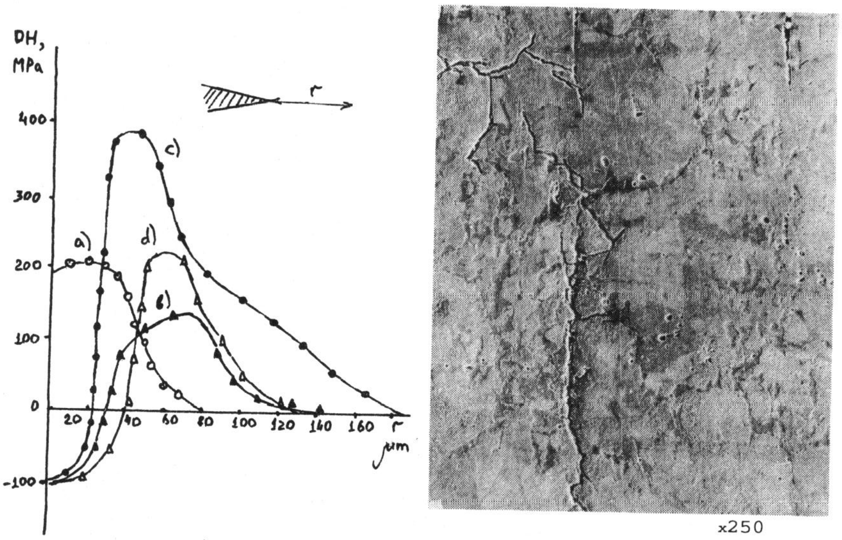

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Figure 2. Knoop's microhardness distribution after 100 (a),150 (b), 200 (c) and 400 (d) hours and microcracks of hydrogen delamination.

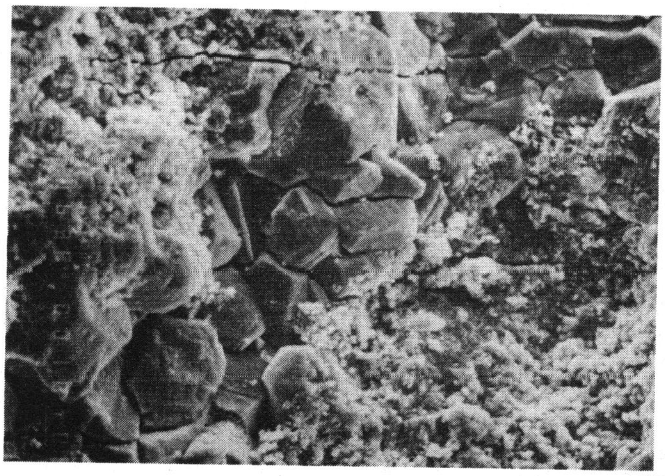

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Figure 3. Intergranular damage accumulation and crack initiation in steel 4 along the former austenite grain boundaries.