EFFECT OF HYDROGENATION AND PLASTIC PREDEFORMATION ON THE CRACK GROWTH RESISTANCE OF STRUCTURAL STEEL

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ABSTRACT: The synergistic effect of hydrogenation and plastic predeformation (PPD) on the fracture toughness and fatigue crack growth resistance in the tempered 0.4-1Cr-1Ni steel was studied. In the no hydrogenated state, PPD of steel slightly decreases its fracture toughness and increases considerably the fatigue crack growth resistance in the near threshold region of da/dN - ΔK diagram. Crack closure is responsible for the latter effect. Hydrogenation of the material drastically decreases the fracture toughness and intensifies the fatigue crack growth, especially in the middle region of da/dN - ΔK diagram. The synergistic effect of PPD and hydrogenation of the investigated steel causes the maximum decrease of crack growth resistance, both under static and cyclic loading. The possible consequences of such effect from the point of view of structural strength of drill pipe string are analyzed.

INTRODUCTION

Fracture of structural elements, which are supposed to cyclic loading in aggressive environments, is caused often by fatigue crack growth, in the first turn in place of stress concentration. Although structures in such cases are usually calculated by yield stress, one should not neglect the possibility of single overloads that cause plastic deformation of a material in the zone of constructional stress concentrators. As a result, cracks can appear in this zone. Under cyclic loads, they grow and lower the load-carrying capacity and life time. This fact demonstrates the importance of considering the effect of PPD on the static and cyclic crack resistance of such structural materials. On the other hand, it is also necessary to consider the possible hydrogenation of material in working environments, primary, at the places of stress concentration, which can, in addition, negatively effect on the fatigue crack growth. This work is directed towards studying the joint effect of hydrogenation and tensile plastic predeformation on the crack growth resistance of the steel of a drill string under short term static and cyclic loads.

EXPERIMENTAL PROCEDURE

The 40KhN (0.4C-1Cr-1Ni) steel of drill strings after hardening in oil from a temperature 840° C with subsequent tempering at 490° C (a plant technological process) has been tested. Such a heat treatment ensured a yield strength of $\sigma_{y.s.}$ = 1050 MPa and a relative reduction in area of 41 %. We chose the thickness of prismatic specimens 12×130 mm to be 2 mm, which made it possible to maximally hydrogenate the material across their thickness under conditions of cathodic polarization at room temperature. We subjected the specimens for crack resistance tests to plastic deformation by uniformly tensile them by 2 % and kept some portion of the specimens under formed for the sake of comparison. In the middle of specimens, we cut out a concentrator with a rounded 0.1 mm and a depth of 1 mm, which decreased the cross section by height.

The specimens were hydrogenated by the electrolytic method depending of the kind of mechanical testing. We subjected the specimens for fracture toughness tests with a beforehand-made crack to cathodic polarization during 3 h in a NaOH solution with pH 12.5 under current density of 10 mA / m^2. Such an electrolyte, instead of the widely used solution of sulfuric acid, did not allow the corrosive attack of a sharp fatigue crack, which could distort the test results. The great duration of hydrogenation together with a moderate current density, on the one hand, promoted a deeper hydrogen penetration into the metal and, on the other hand, prevented its damage, characteristic of cathodic polarization under the high current density. A further increase in the duration of hydrogenation had no additional influence on the crack resistance of steel. Fracture toughness tests were performed keeping to the known requirements [1]. The critical stress intensity factor K_c was determined by analyzing the diagram "tensile force F vs. crack edges displacement δ".

Fatigue crack growth resistance was estimated using cyclic loading by cantilever bending with a stress ratio R = 0 and a frequency in the 0.3 - 10 Hz. The crack length was measuremented at both lateral surfaces of the specimen with the help of the mobile microscope. The crack closure was evaluated by the compliance method. As a result, we calculated the nominal ΔK and effective ΔK_{eff} range of the stress intensity factor and built the diagrams of fatigue fracture da/dN – ΔK and da/dN – ΔK_{eff}, in conformity with the methodical recommendations [2].

In view of the possibility of hydrogen desorption in the course of test in air, we hydrogenated the specimens 3 h before the beginning and also during the fatigue experiment. For this purpose, an electrochemical cell was used that covered the working part of a specimen with crack and enabled the visual observation its growth. The electrolyte and current density of cathodic polarization were the same as in fracture toughness tests.

FRACTURE TOUGHNESS

The small thickness of the specimens gave no possibility of realizing the conditions of plane strain. The load-displacement diagrams F vs. δ in their upper part significantly deviated from linearity and their analysis [1] demonstrated a substantial plastic deformation at the crack tip, which preceded its growth. Only predeformed specimens and those hydrogenated later on were an exception. The F - δ diagrams for them remained linear up to the moment of specimen fracture and indicated about the correctness of application of the approaches of linear fracture mechanics. In this case, we manged to estimate the critical value K_{Ic}.

Comparative analysis of value of K_c for four variants of treatment of steel (Table 1) demonstrates that PPD by tension somewhat decreases its fracture toughness (from 114 to 98 MPa $\sqrt{m}$).

TABLE 1: Fracture toughness of investigated steel

K_c (K_{Ic}), MPa $\sqrt{m}$			
Initial state	After hydrogenating	After PDD	After hydrogenating and PDD
114	52	98	29

Preliminary electrolytic hydrogenation significantly reduced the fracture toughness of steel. Its value (52 MPa $\sqrt{m}$) is halved as compared with K_c of steel in the initial state (114 MPa $\sqrt{m}$). For the predeformed specimens, we fixed a still greater decrease in K_c (from 98 to 29 MPa $\sqrt{m}$), despite a lower crack resistance of deformed steel as compared with the initial state. If we take into account the joint effect of PPD and hydrogenation, these factors reduce the fracture toughness of steel of a drill string practically to one-fourth of its original value. In addition to this, the transition from fracture under conditions of a plane stress state to a fracture under plane strain testifies to the strong embitterment of PPD and hydrogenation.

FATIGUE CRACK GROWTH RESISTANCE

PPD by tension positively effects on the fatigue crack growth (Fig. 1). It increases with a decrease in the load: the threshold range of ΔK_{th} grows 1.5 times as compared with ΔK_{th} for the initial state of the material, but for high ΔK, close to the cyclic fracture toughness, the effect of PPD disappears.

The fatigue crack growth in steel for the initial state in an alkaline solution, but without cathodic polarization was beforehand estimated. The results obtained did not reveal any changes in the fatigue crack growth as compared with test in air, i.e., this environment does not affect the fatigue fracture. This fact enables us to connect henceforth the possible action of an alkaline solution under conditions of cathodic polarization on the fatigue crack growth resistance of steel just with hydrogenation of material.

Investigation of the fatigue crack growth under cathodic polarization revealed different effect of hydrogenation both by their character and intensity. This influence depends on the frequency and ΔK range as well on the state of the material (initial one or after PPD). Hydrogenation of the initial material (Fig. 1a) slightly affects the fracture kinetics, although the near-threshold crack growth becomes somewhat slower in the case of a high frequency and accelerates for greater ΔK and a lower loading frequency.

The preliminary deformed material proves to be much more sensitive to hydrogenation (Fig. 1b). The strong dependence of the fracture kinetics under an increased load on the frequency commands our attention: a greater crack growth rate corresponds to a lower frequency. The sharp jump in the rate in the middle-range part of the diagrams recorded in our experiments obviously reflects the tendency of the material to hydrogen induced cracking under cyclic loading. The ΔK range corresponding to the sharp acceleration depends on the load frequency and is minimal ($\sim$ 13 MPa $\sqrt{m}$) at the lowest frequency (curve 4).For near-threshold ΔK, hydrogenation has no negative influence if the frequency of cyclic loading is high.

Having estimated the fatigue crack closure, first of all, of low values of ΔK, we established its substantial influence on the kinetics of the investigated steel in the initial state (Fig. 1a, curves 1 and 1′). For example, the effective threshold range is $\Delta K_{th\,eff} \sim 3$ MPa $\sqrt{m}$ as against the nominal $\Delta K_{th} \sim$ 5 MPa $\sqrt{m}$. PPD practically does not affect the rate of fatigue crack growth for a given effective range ΔK_{eff}. We concluder from this that just the crack closure is responsible for the positive effect of PPD on the fatigue crack growth in steel.

Hydrogenation of the material in initial state in essence does not change the rate of the near-threshold fatigue crack growth under a high-frequency load (Fig.1a, curve 1′), if we depict the results obtained as a function of the effective range ΔK_{eff}. In other words, the presence of hydrogen has no effect on the ability of the material in front of the crack tip to resist deformation and fracture. The positive effect of hydrogenation on the crack growth rate in the case where $\Delta K \cong \Delta K_{th}$ observed early (see Fig. 1a, curves 1 and 2) can be attributed to an increase in the fatigue crack closure. One should bear in the mind that hydrogenation of material can affect the crack closure in different ways depending on the kind of hydrogenating environment in which the crack growth occurs. For example, in a gaseous environment, hydrogen in general decreases the crack closure due to the absence of oxides [3]. On the other hand, in a corrosive environment, enhancement of the crack closure owing to an increase in roughness of its fracture surfaces is possible [4].

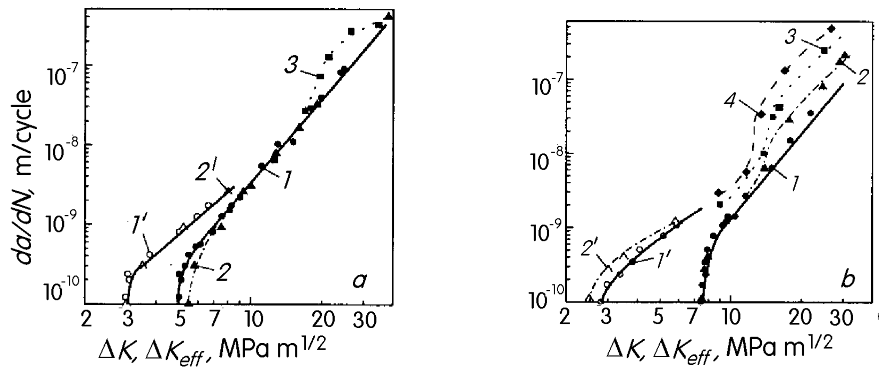

Figure 1: Dependences da/dN – ΔK (1 – 4) and da/dN – ΔK_{eff} (1′, 2′) for the no hydrogenated (1, 1′) and hydrogenated (2, 2′, 3, 4) steel in initial state (a) and after plastic predeformation (b):
1, 1′, 2, 2′ – load frequency 10 Hz; 3 – 1 Hz; 4 – 0.3 Hz.

Hydrogenation of the predeformed material slightly displaced the near-threshold part of the diagram da/dN – ΔK_{eff} to the side of the higher crack growth rates (Fig. 1b, curves 1′and 2′), i.e., it somewhat facilitates fracture. As a result, the absence of such an influence on crack growth near the threshold ΔK_{th} noted above is caused by some enhancement of the crack closure effect. Therefore, the plastically deformed material shows a tendency to hydrogen embrittlement even under conditions of a high-frequency load in the near-threshold part of diagram, which is leveled by the intensification of crack closure, i.e., by weakening of deformation of the material near the crack tip. In the case of increased ΔK, where one can neglect the crack closure, hydrogen embrittlement is more clearly manifested. Moreover, the tendency of the hydrogenated material towards hydrogen cracking is distinctly revealed in this case.

CONCLUSIONS

PPD of the investigated steel of drill string slightly lowers its fracture toughness in the absence of hydrogenation and increases the fatigue crack growth resistance for a slow asymmetry of cyclic loading. Owing to this, one should not expect a substantial negative influence of possible single overloads on the load-carrying capacity and life time of a product on the stage of crack growth. The situation becomes different, if we take into consideration the possible hydrogenation of the material in a working environment, which can significantly increase the fatigue crack growth. However, we would expect the greatest decrease in structural strength of the hydrogenated material at the places of stress concentration if they were plastically deformed before. In this case, a significant gradient of stress intensifies hydrogen diffusion into the prefracture zone, where a hydrogen concentration can be attained that much more exceeds its average magnitude. Plastic predeformation makes the material strongly sensitive to hydrogen cracking, which is especially dangerous under conditions of a long-term static load.

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