FATIGUE CRACK GROWTH KINETICS AND MECHANISMS IN STEEL AT ELEVATED TEMPERATURES IN GASEOUS HYDROGEN

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Fatigue crack growth investigations of steels in gaseous hydrogen over a temperature range from 20° to 800°C have been carried out. The character and intensity of hydrogen influence on fatigue crack growth depends on the steel type, testing temperature and loading level. The revealed effects are caused by different fracture mechanisms and hydrogen influence.

INTRODUCTION

The effects of environmental variables on the fatigue crack growth behaviour of materials are among the main problems in fracture mechanics. This especially applies for the influence of hydrogen on the fatigue crack growth over a wide range of temperatures. For low temperatures (including room temperature) one can find a sufficient number of papers, but high temperature fatigue in hydrogen needs more detailed studies.

EXPERIMENTAL PROCEDURE

The experiments were performed on HK-40 steel (in wt %: C - 0.36, Mn - 0.51, Si - 1.32, Cr - 24.6, Ni - 20.64, P - 0.021 and Fe - balance). The basic mechanical properties of the material under tension are: UTS = 480 MPa; σ_{ys} = 290 MPa; R.A. = 24%; elongation = 4,3%.

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The fatigue crack growth resistance tests were done on circular ring specimens which were cut from the reforming furnace pipes 115 mm in diameter and 20 specimen working section. Taking into account the conjectural character of the stress intensity factor (SIF) use at high temperatures, the investigations were performed in the narrow range of crack length (10...14 mm). The crack closure (CC) effect was determined by using a strain gauge, which recorded the displacement along the line of load application. The tests were performed at 20°C, 200°C, 400°C, 600°C and 800°C in pure hydrogen (P_{H_2} = 0,3 MPa), "soft" vacuum (P = 0,13 Pa), and laboratory air, resp. The loading cycle parameters were: R = 0,1; f = 1 Hz (in air at 20°C: f = 10 Hz).

EXPERIMENTAL RESULTS

The fatigue fracture kinetic diagrams are plotted in terms of nominal and effective cyclic stress intensities in Fig.1-3. Obviously, fatigue crack growth (FCG) accelerates with temperature increase regardless of the type of environment. In comparison with vacuum laboratory air retards the FCG at high temperature. If one takes the CC effect into account, a conclusion can be made that such effect is stipulated by the oxidation of the crack faces during testing in air.

Hydrogen affects the FCG very ambiguously, depending on the testing temperature and on the loading level, in particular. At high SIF hydrogen accelerates FCG practically over the whole temperature range. But, if the temperature increases this effect diminishes and disappears at 800°C. On the contrary, at low SIF and temperatures up to almost 400°C hydrogen retards FCG. Thus, a temperature rise to above 400°C changes the positive influence of hydrogen into the negative one. Accounting for CC, i.e. plotting the kinetic diagram in terms of ΔK_{eff}, does not change the relative positions of nominal and effective fatigue fracture kinetic diagrams qualitatively. An exception occurs only at the higher temperatures (Fig. 3) where the FCG rate when plotted against ΔK_{eff} does not depend on the type of the environment, although such a dependence is revealed relatively toΔK.

DISCUSSION

FCG at low temperature. A negative influence of hydrogen at high SIF is a classical manifestation of "hydrogen embrittlement". It is caused by the decrease of tear resistance what is, in most cases, fractographically characterized by a great amount of cleavage on the fracture surface.

It is suggested by Stewart (1) that hydrogen induced acceleration of FCG in low-strength low-alloyed steels at low SIF values is rather due to a CC decrease than due to hydrogen embrittlement. In its turn, a small CC effect is explained by the absence of oxides on the crack faces when the crack propagates in a hydrogen environment. More recently, based on an analysis of numerous experimental data

(Romaniv et al (2)) it has been established that in the case of low-strength steels hydrogen increases the effective fatigue threshold $\Delta K_{th\ eff}$, which is received after substracting the CC effect, i.e. K_{op}, from the nominal SIF (Fig. 4). This phenomenon is explained by an increase of the shear resistance of the material as affected by hydrogen (Romaniv et al (3)). As pointed out by Schaper and Schlät (4) the concurring adsorption of residual oxygen should additionally be taken into account when explaining the effect of gaseous hydrogen on fatigue crack propagation, an effect which might be responsible for experimental inconstencies.

The results of the low temperature tests (20^o and 200^{o}C) of HK-40 steel presented here only partly proved the regularities of the hydrogen effect in increasing the $\Delta K_{th\ eff}$ level (Fig. 1). But the nominal fatigue threshold ΔK_{th} changes similarily as the effective one, a behaviour that is not typical for low-alloyed steels. This is explained by the fact that the intensive oxide formation does not assist low temperature testing of the HK-40 corrosion resistant steel. Thus, hydrogen affected strengthening (that is testified by a higher $\Delta K_{th\ eff}$ value in hydrogen in comparison with that in air) is suggested to be dominant with respect to a change of the intensity of CC what stipulates a higher nominal ΔK_{th} threshold under the conditions of low temperature FCG in hydrogen.

<u>FCG at high temperature.</u> The hydrogen influence on high temperature FCG (400^{o}C and higher) has its own peculiarities. In comparison with low temperature testing an insignificant negative hydrogen influence at high SIF values is caused by the absence of both CC and cleavage areas on the fracture surfaces. But, at low SIF hydrogen accelerates FCG. This can be explained by the absence of conditions for CC development according to the oxide formation mechanism, which at such temperatures is always more intensive in air (Oxide formation stipulates the nominal high temperature fatigue threshold increase in air in comparison with that in vacuum). But the negative hydrogen influence preserves also for the analysis of effective kinetic diagrams of FCG. Thus, the fatigue strengthening effect of hydrogen, which is peculiar to low temperatures, changes to nonstrengthening at temperature rise. In other words, hydrogen facilitates plastic deformation thus increasing the FCG rate in the near-threshold region. Such a hydrogen influence should have not only a lower, but also an upper temperature limit. At 800^{o}C the effective diagrams in hydrogen and in air practically superimpose. At this temperature hydrogen is not able to facilitate the plastic deformation, however its negative effect occurs in normal coordinates and is stipulated by low CC, because the hydrogen environment prevents the oxide formation.

<u>Mechanism of hydrogen effect on FCG.</u> At high SIF hydrogen causes a loss in material strength near the crack tip (practically up to 600^{o}C), whereas at low SIF it might either strengthen the material (at 20^o and 200^{o}C) or cause a loss in the crack growth resistance (at $T > 400^oC$). That is, there exists a certain temperature T^* where this change in the charcter of the hydrogen influence occurs: $200^oC < T^* <$

400°C. It should be noticed that especially in this temperature range hydrogen leaves the defects, including dislocations, existence of which at lower temperature was energetically advantageous. It is shown (3) that at room temperature hydrogen increases the material resistance to plastic deformation. The conclusion can be made that the strengthening action of hydrogen is stipulated by the dislocation density increase (hydrogen facilitates the dislocation generation, forming for himself energetically convenient places for precipitation).

Summing up the results we can note common and distinctive peculiarities of the mechanisms of the hydrogen influence on FCG. Independently of test temperature hydrogen weakens the bonds between the lattice atoms but the results of such influence depend on the test temperature and on the loading level. At $T < T^*$ and high SIF values all this leads to the decrease of cohesive strength, increase of cleavage fracture propensity and acceleration of FCG as a whole. At low SIF levels a facilitiated dislocation initiation and decreased dislocation mobility stipulates an enhanced shear resistance of the material and as a result - retardation of FCG. At $T > T^*$ for both high and low SIF values the weakening of lattice bonds under the hydrogen influence is accompanied by the predominating effect of an enhanced dislocation mobility, i.e. a decrease in the plastic deformation resistance of the material and, consequently, by the acceleration of FCG.

SYMBOLS USED

ΔK	=	range of stress intensity factor SIF ($MPa\sqrt{m}$)
ΔK_{eff}	=	effective range of SIF ($MPa\sqrt{m}$)
ΔK_{th}	=	threshold range of SIF ($MPa\sqrt{m}$)
$\Delta K_{th\ eff}$	=	effective threshold range of SIF ($MPa\sqrt{m}$)
β_{th}	=	ratio of the ΔK_{th} values in hydrogen to those in air
$\beta_{th\ eff}$	=	ratio of the $\Delta K_{th\ eff}$ values in hydrogen to those in air

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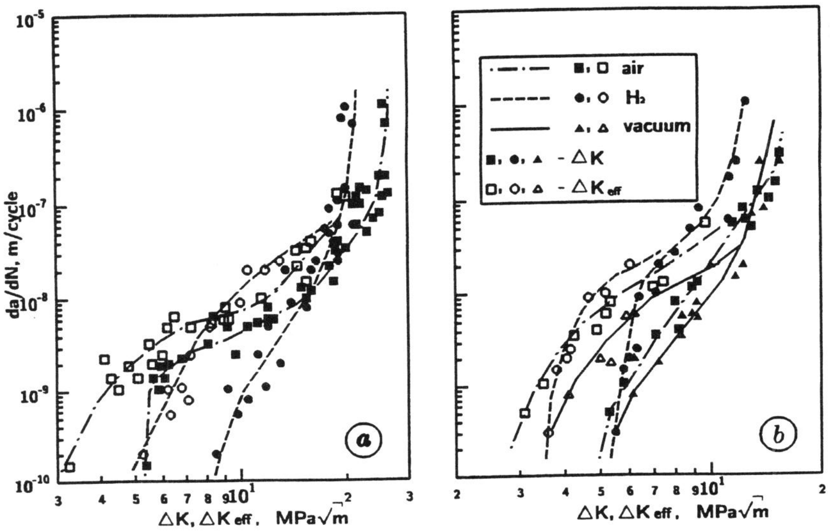

Fig.1. Dependencies of da/dN vs ΔK and da/dN vs ΔK_{eff} of HK-40 steel tested at T=20°C (a) and 200°C (b).

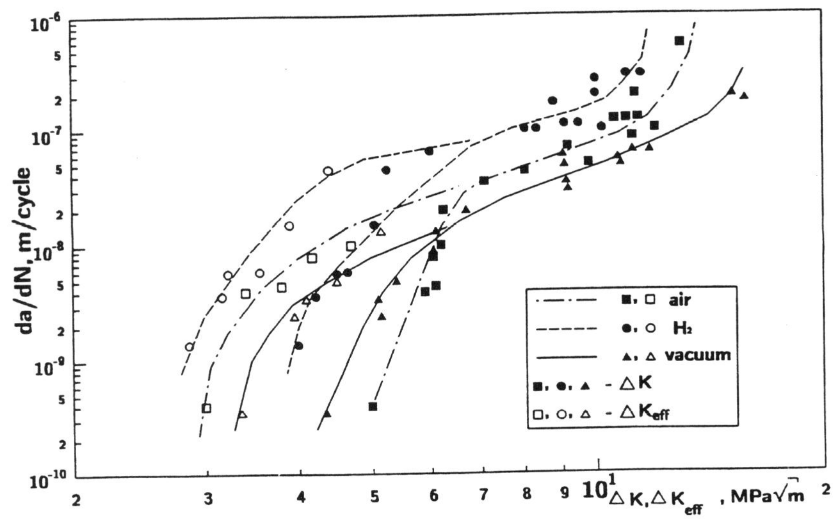

Fig.2. da/dN vs ΔK and da/dN vs ΔK_{eff} curves of HK-40 steel tested at T=400°C

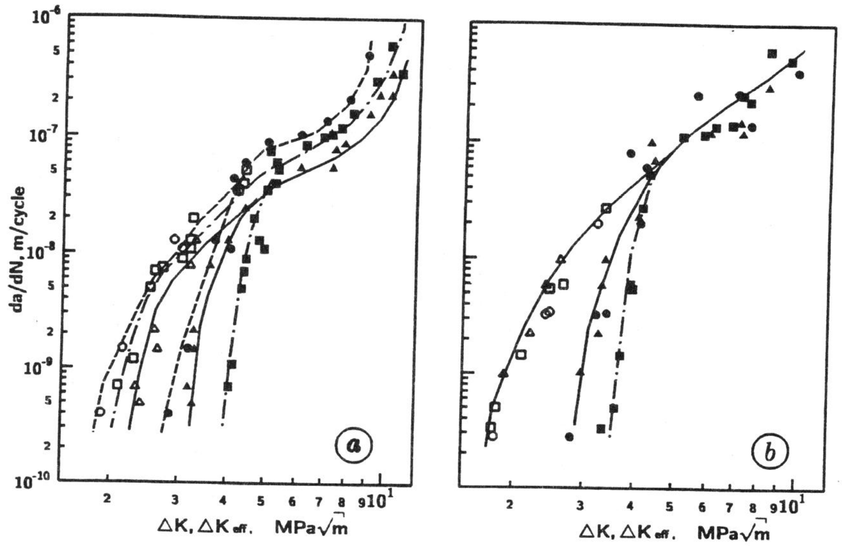

Fig.3. Dependencies of da/dN vs ΔK and da/dN vs ΔK_{eff} at T=600°C (a) and 800°C (b).

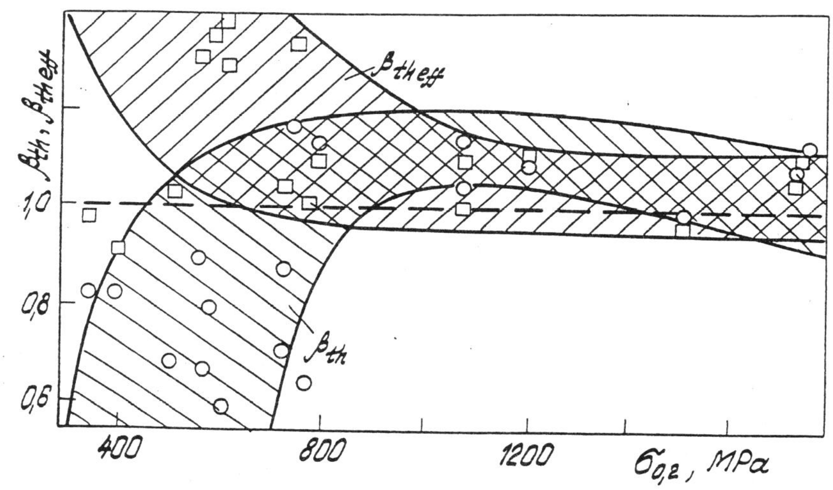

Fig.4. β_{th} vs σ_{ys} and $\beta_{th\ eff}$ vs σ_{ys} dependencies for engineering steels subjected to high frequency loading.