THERMOCYCLING IN HYDROGEN ENVIRONMENT AS SIMULATION METHOD OF PIPELINE STEAM STEEL'S DAMAGES

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The paper is aimed to prove the efficiency of a method of thermocycling in hydrogen environment for acceleration of degradation of steam pipeline steels. Fatigue threshold changes for a steel that have been aged in service and laboratory conditions, respectively, are analysed. According to the experiments, $\Delta K_{th\ eff}$ decreases when the operation time or number of thermocycles in hydrogen increases, and this value is proposed be used as a parameter of material degradation due to ageing. Inversion of the effect of hydrogen dissolved in the steel on $\Delta K_{th\ eff}$ in relation to the degradation degree is shown.

INTRODUCTION

Serviceability of power plant components operating at high temperature is most often evaluated from the creep behaviour data. However in last decades, much attention has been paid to the material damage without significant residual deformation. The expert conclusions by Mann and Garnsey (1) for some strainless fracture regard them as negative effect of hydrogen. On the other hand, it has been known that the properties degradation occurs during high temperature operation of steel components. It is caused by changes in microstructure and damage development. The experience of the service damage inspection proves that during the first stages of operation, structural changes determine the degree of degradation. Only on the last operation stages, the processes of damage development start to prevail. The structural changes in the service conditions are occurring during dozens of thousands of hours. However the proposed by Nykyforchyn et al (2) laboratory express-method of the high temperature ageing of steels allows to achieve the same structural changes during one week. Its principal point is in thermocycling of specimens in a hydrogen medium. The method is based on the facts that equilibrium concentrations of hydrogen which is dissolved in metal at different temperatures are different, i.e. a higher solubility

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corresponds to a higher temperature, and the reduction of the hydrogen mobility because of the temperature decrease.

This paper continues the previous investigations (2) and is aimed to ground the usefulness of thermocycling in hydrogen as an effective and fast way to achieve the degradation of steam power plant pipeline steels.

EXPERIMENTAL DETAILS

A steam pipeline Cr-Mo-V steel with a composition of 0.1C, 1.1 Cr, 0.26 Mo, 0.17V, 0.26 Si, 0.54 Mn after having being used during different operation times τ_{op} (48, 110, 140, 190 thousand hours) and subjected to the laboratory treatment simulating material degradation have been studied. The tensile properties of the steel in virgin state are: $\sigma_{UTS} = 470$ MPa, $\sigma_{YS} = 280$ MPa, $\varepsilon = 29\%$, $\psi = 75\%$. To simulate the operation-induced degradation the specimens were exposed to high-rate thermocycling in gaseous hydrogen at a pressure of 0.3 MPa and a temperature range of 100...570°C. The peculiarities of the express-method of ageing are described in detail in (3). Two kinds of laboratory aged specimens at the same regime are considered and compared: just after the ageing treatment and after the outgassing of hydrogen (the aged specimens have been kept 1 hour in air at the maximum temperature of a thermocycle).

The degree of material degradation was evaluated by measuring crack propagation rates, da/dN in 180x22x7 mm beam specimens subjected to cantilever bending at the room temperature. The load frequency and ratio were 10 Hz and 0, respectively. The crack size was measured on both lateral sides with optical microscopes of 0.01 mm tolerance. The fatigue crack closure was evaluated using the compliance technique. Strain-gauge transducer was fixed at the crack tip level and was periodically transferred during the crack growth.

TEST RESULTS AND DISCUSSION

The results of the investigations of service and laboratory ageing (outgassed specimens) effects on the fatigue threshold at room temperature are presented in Fig. 1. The effect of ageing was evaluated by a relative change of the fatigue threshold of the degraded metal in comparison with that in the virgin state, i.e. with the parameters β_{op}, $\beta_{eff\ op}$, β_{tc}, $\beta_{eff\ tc}$. Regardless of the ageing method the parameters ΔK_{th} and $\Delta K_{th\ eff}$ are sensitive to the steel degradation, but only $\Delta K_{th\ eff}$ decreases constantly with increase of τ_{op} and n. This proves that this parameter unambiguously indicates high temperature degradation of steel both in operation and in hydrogen thermocycling. Changes of $\beta_{eff\ op}$ and $\beta_{eff\ tc}$ show that approximately the same steel degradation degree is achieved after 190 thousand hours of operation and after 100 thermocycles in hydrogen. However, the degradation rates at these two ageing modes are different on the different ageing stages. This can be seen from different rates of $\Delta K_{th\ eff}$ decrease for two methods of degradation. The change rate of $\beta_{eff\ op}$ at the first stage of the operation (up to 140 thousand hours) is approximately 10^{-6} h^{-1}, but at the end it achieves 4 10^{-6} h^{-1}. For the laboratory ageing, change rates of $\beta_{eff\ tc}$ are 4 10^{-3} h^{1}

and 5 10^{-4} h^{-1} for $n \le 33$ and $n > 33$ respectively. Hence, in service ageing, the $\Delta K_{th\ eff}$ decreases mainly at the final stage of the operation, from 1.4×10^5 to 1.9×10^5 h, and in laboratory it happens at the first part of the thermocycling. Possible reason of these differences is that in the real service conditions the damage develops faster because of additional sustained loading. Their appearance is conditioned by achieving a certain amount of microstructural changes. Therefore the development of mechanical damages falls into the final operation stage when a certain level of structural degradation is achieved. During the laboratory ageing procedure, specimens are not loaded. The internal stresses appear only after rapid cooling in hydrogen and are formed to equilibrate the inequilibrium hydrogen concentration in metal. These stresses are maximum in a cooled specimen, when the high temperature mechanism of degradation is impossible. In addition, a possibility of low temperature hydrogen cracking should not be ignored. The investigated steel in virgin state should not be sensitive to such an effect of hydrogen, but this can be a case for a aged steel.

The results above concern the outgassed material in which there is not mobile hydrogen. It allows to investigate the influence of microstructural changes and possible damages on the $\Delta K_{th\ eff}$ parameter, which has been assumed to be an indicator of the materials mechanical state. It is also interesting to investigate the effect of dissolved hydrogen in the aged metal. The diagrams da/dN - ΔK and da/dN - ΔK_{eff} for the specimens tested just after the thermocycling and outgassing are showed in Fig. 2. The major effects are observed in the threshold region of the loading. Here hydrogen has almost no effect ($n = 100$) or causes the displacement of the da/dN - ΔK diagrams in direction of lower crack growth rates ($n = 13$). However, the effect of hydrogen in the threshold da/dN - ΔK_{eff} region is ambiguous: it retards fracture after 13 thermocycles and accelerated after 100.

The data presented in Fig. 3 allow to compare the threshold parameters of the hydrogenated and outgassed specimens at different of values of n. The results show an ambiguous effect of dissolved hydrogen on the ΔK_{th}, $\Delta K_{th\ cl}$ and $\Delta K_{th\ eff}$ parameters depending on n. The positive effect of hydrogen has a maximum at 13 thermocycles, in this case the values of ΔK_{th}, $\Delta K_{th\ cl}$ and $\Delta K_{th\ eff}$ are the highest. At $n = 33$ the positive effect of hydrogen on ΔK_{th} and $\Delta K_{th\ cl}$, decreases and the effect on $\Delta K_{th\ eff}$ changes to negative. Crack closure gives a considerable contribution to the ΔK_{th} increase by hydrogen: the hydrogenation increases $\Delta K_{th\ cl}$, especially at a small number of thermocycles. It can be caused by increase of the fracture surface roughness. Concerning the $\Delta K_{th\ eff}$ change, we can argue that it is the one from where we can judge the effect of material hydrogenation on the fracture resistance at the crack tip. The increase of $\Delta K_{th\ eff}$ due to hydrogen after 13 thermocycles is typical for low alloy steels at high frequency loading and ambient temperature as has been shown by Nykyforchyn (4). It can be explained by hydrogen-induced increase of the resistance of microplastic deformation in the prefracture zone. The decrease of $\Delta K_{th\ eff}$ due to hydrogen effect, which is observed after 33 and 100 thermocycles, is typical for high strength steels. It means that from the point of view of the hydrogen effect on the effective fatigue threshold, the steel degraded in laboratory conditions is comparable to high strength steels, while such an integral parameter as hardness is insensitive to the changes caused by ageing in hydrogen. This is should be taking into account in selection of parameters for evaluation the serviceability of structural components.

CONCLUSIONS

1. $K_{th\ eff}$ parameter detects unambiguously high temperature degradation of steel during operation and thermocycling in hydrogen and can serve as an indicator of the amount of material degradation due to the ageing.

2. Inversion of the effect of hydrogen dissolved in the metal on the $\Delta K_{th\ eff}$ depending on number of thermocycles in hydrogen, which determines the metal degradation degree, has been found.

SYMBOLS USED

β_{op} $= \Delta K_{th}\,(\tau_{op} > 0) \,/\, \Delta K_{th}\,(\tau_{op} = 0)$

$\beta_{eff\ op}$ $= \Delta K_{th\ eff}\,(\tau_{op} > 0) \,/\, \Delta K_{th\ eff}\,(\tau_{op} = 0)$

β_{tc} $= \Delta K_{th}\,(n > 0) \,/\, \Delta K_{th}\,(n = 0)$

$\beta_{eff\ tc}$ $= \Delta K_{th\ eff}\,(n > 0) \,/\, \Delta K_{th\ eff}\,(n = 0)$

da/dN = fatigue crack growth rate (m/cycle)

ΔK_{th}, $\Delta K_{th\ eff}$ = nominal and effective ranges of threshold SIF (MPa $\sqrt{m}$)

$\Delta K_{th\ cl}$ $= \Delta K_{th} - \Delta K_{th\ eff}$ = ineffective SIF range (MPa $\sqrt{m}$)

n = number of thermocycles (cycle)

σ_{UTS}, σ_{YS} = ultimated tensile strength and yield stress (MPa)

ε, ψ =elongation and reduction of cross-section area (%)

τ_{op} = operation time (hour)

U_{th} $= \Delta K_{th\ eff} \,/\, \Delta K_{th}$ = crack opening ratio

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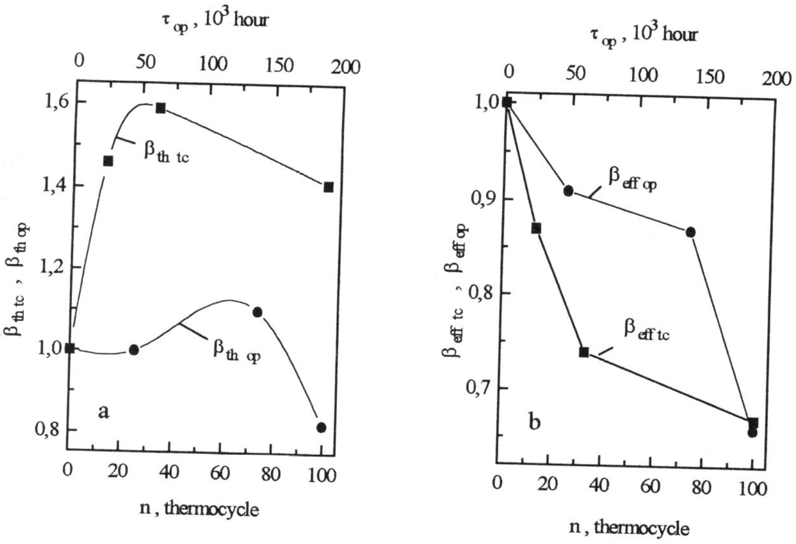

Figure 1 Influence τ_{op} and n on the $\beta_{th\,op}$, $\beta_{th\,tc}$ (a) and $\beta_{eff\,op}$, $\beta_{eff\,tc}$ (b).

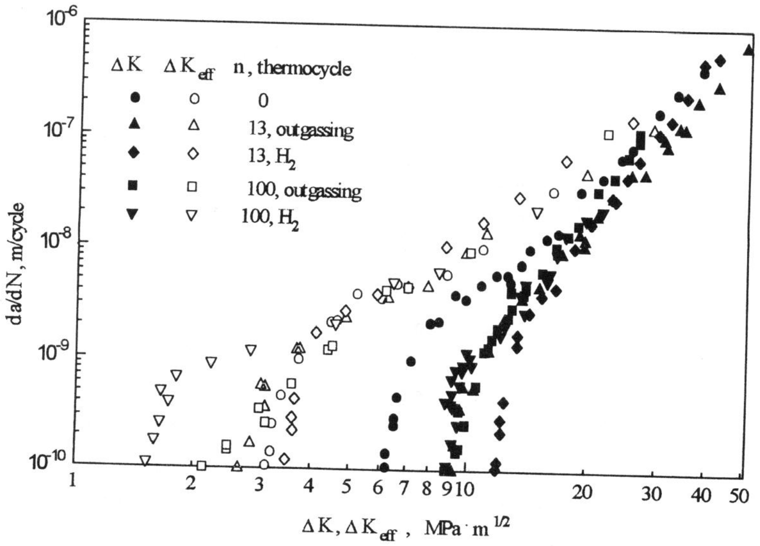

Figure 2 Influence of the hydrogenation on the fatigue crack growth rate.

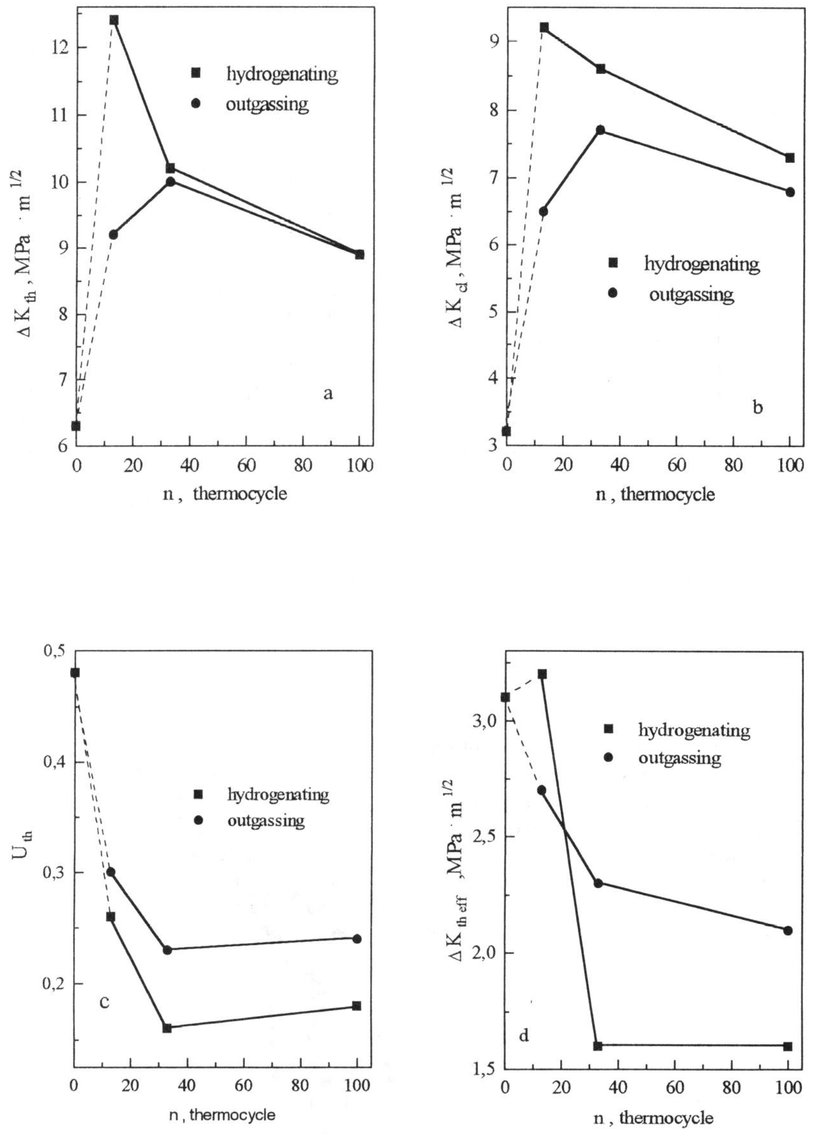

Figure 3 Influence of the hydrogenation on the threshold parameters of the fatigue crack growth.