THE EFFECT OF POWER PLANT ENVIRONMENT ON FATIGUE CRACK GROWTH OF PIPE STEELS

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ABSTRACT

The paper presents the experimental results of corrosion fatigue crack kinetics of three types of steels: carbon (0.2C); Cr-Mo-V and 18Cr12Ni. The effect of parameters cyclic loading and environments on corrosion fatigue failure of steels has been studied. It has been revealed that in the low-frequency (below 0.04 Hz) loading region, the cycle frequency is of no substantial effect on corrosion-fatigue crack-resistance of steels investigated, while the R ratio affects the rate of crack growth mostly in the near-threshold (low-amplitude) region. Water chemistry conditions of real power plants were simulated by different water solutions.

KEYWORDS

Pipes ,steels, cyclic testing, water environment, crack, kinetics.

INTRODUCTION

The operating experience with large power plants gives evidence that major failures of components are due to initiation and propagation of cracks (Karzov, et al.,1982). For example, power plant pipes exposed to 623 K more frequently exhibit failures dealt with crack-like defects on the inner surface, generally of corrosion-fatigue nature (Nakhalov,1983). Therefore,for ensuring reliability of power plants, characterization of both manufacturing and operational defects and their effects in cyclic loading and corrosive environmentare of great importance.Solution of such problems will contribute to improved methods of prediction of life of power equipment and procedures of in-service metal inspection. Though much has been done in the field of fatigue failures, lack of experimental data is felt with regard to large power plants. The present paper is an attempt to bridge the gap.

MATERIALS AND TEST TECHNIQUE

As test specimens use was made of ϕ 273x36, 325x45 mm and 500 mm I.D. conventional as-received pipes of carbon 0.2C and low-alloyed Cr-Mo-V perlitic steels, and austenitic steel 18Cr12Ni, respectively, widely used in power industry. All steels meet applied specifications for chemical composition, mechanical properties and structure. Compact tension precracked specimens of 25 mm thick were tested on lever machines specially designed for low-frequency cyclic testing in corrosive environment.

Comparative air tests were made on machines of electromechanical type. Perlitic steels were tested in deionized water cleaned at power plant ion-exchangers (pH=7, electrical conductivity of 1.0 µS/cm maximum) and in ammonia solution (pH=9, electrical conductivity of 10 µS/cm maximum). The stainless steel was tested in simulated PWR primary circuit water (1% H_3BO_4 solution + KOH of up to pH=7 + NH_3 5 mg/kg of up to pH=8 + Cl^- 5 mg/kg). The corrosive environment test temperatures were 353, 523 and 548 K.

The 353 K tests were made in plastic chambers incorporating special appliances for providing adequate loading and measurements and visual observation of the specimen. The major part of experiments was accomplished in static environment, while a limited number of tests was performed for the stainless steel at $8.3 \cdot 10^{-5}$ m^3 /s flow through each chamber . In 523 and 548 K test conditions, use was made of specially designed installation with a natural-circulation circuit. The circuit contained two interconnected loops each of which incorporating high-pressure test chamber and heater. The installation also comprises compensating volume, water treatment and make-up unit and measurement system. The use of the "piston effect" compensating device and no gland sealings in the test chambers ensured high accuracy in maintaining preset loads during the experiment. Also, water samples were taken and pH value and electrical conductivity of the environment were monitored. Tests were conducted at R ratio of about 0.15 and 0.65, trapezoidal wave in the frequency range of cyclic loading f= 0.04 - 0.0008 Hz.

The specimen crack length was determined by crack opening displacement: in the high-pressure chambers using a specially developed displacement transducer of the induction type, and in plastic chamber (θ =353 K) - using external transducer. The calibration curve for the given distance between measurement vector displacement (transducer axis) and loading axis for the specimen was derived numerically with subsequent correction for experimental data statistics.

RESULTS AND DISCUSSION

Carbon Steel (0.2C). Kinetic dependences of crack growth rates

(da/dN) vs. peak-to-peak stress intensity factor (Δ K) in deionized water (pH=7) and in aqueous ammonia solution (pH=9) in 353 K tests, as well as in air tests at 298K are shown in Fig.1.

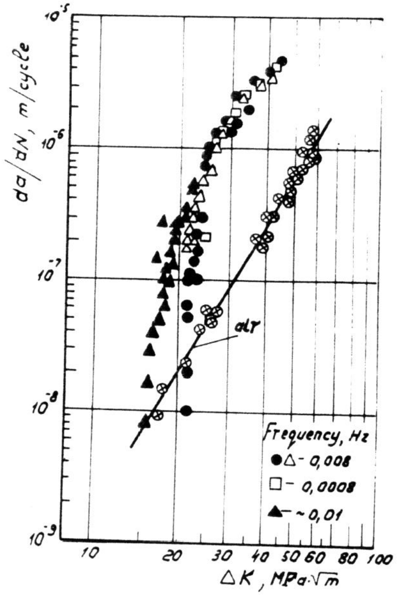


Fig.1.Kinetic diagrams of corrosion-cyclic crack resistance of carbon steel in deionised water (● , ▲) and in ammonia solution (Δ ,□) at different loading frequencies and R ratios (Δ ,□ ,● - R =0.10 -0.15; ▲ - R = 0.65); ⊗ - air tests (298 K, R =0.05).

The effect of each of the above environments is characterized by over than 10-fold increase in crack growth rate, with no significant differences between deionized water and ammonia solution experiments. The change of cyclic loading frequency by an order (from 0.008 up to 0.0008 Hz) is of no marked effect on characteristics of corrosion-cyclic crack-resistance of steel. Increase in R ratio from 0.10-0.15 up to about 0.65 causes increased crack growth rate of steel largerly at initial section of da/dN - ΔK curve. At middle section of the curve (at ΔK>20 MPa·√m),the difference between experimental data for different R ratios are found to be smoothed.

Fig.2.illustrates corrosion-fatigue crack growth rates for carbon steel in ammonia solution (pH=9) at 353 and 548 K with comparison for 573 K air results. With increasing environment temperature from 353 K up to 548 K marked reduction of crack growth rate of steel was observed. Hence, the intensifying effect of the environment on steel fatigue failure to a great extent decreases with increasing temperature which is proved by the results of 573 K air tests.

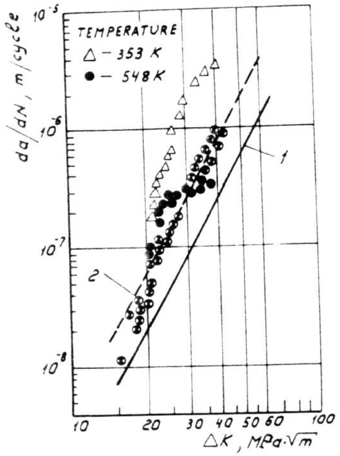
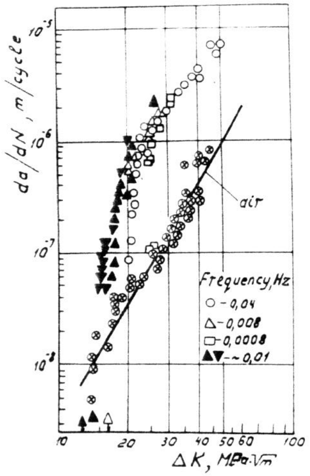


Fig.2. Kinetic diagrams of cyclic crack resistance of carbon steel in ammonia solution at 353 K (Δ) and at 548 K (●) and in air:
1 - at 298 K;
2 ,(⊗) - at 573 K.

Low-Alloyed Steel. Fig.3. shows kinetic diagrams of cyclic crack resistance for deionized water, 353 K tests at different cyclic loading and for 298 K air tests. Comparison of test results for deionized water (353 K) and ammonia solution (353 and 523 K) and for air at 573 K is shown in Fig.4. The data give evidence on substantial intensification of steel fatigue failure under the effect of water. The change of frequency of cyclic loading in the considered range (0.04 - 0.0008 Hz) produce no marked effect on steel corrosion crack resistance, at least, on middle portion of the curve. It is possible that the observed effect of reduced crack growth rate on the initial portion of the cur- ve with decreasing frequency of cyclic loading down 0.0008 Hz is associated with the effect of initial value of Δ K on typical form of the kinetic diagram at the start of the tests. The increased R ratio is accompanied by increased crack growth rate in the near-threshold region of the kinetic diagram (da/dN- - Δ K) i.e., the initial section shifts toward low-amplitude loading. Comparison of the results for steel in water of two compositions (Fig.4.) demonstrates weak tendency to reduced resistance to fatigue crack growth with decreasing value of pH=9 (ammonia solution) down pH=7 (deionized water). The environment temperature effect is manifested in reduced rate of corrosion-fatigue of cracks with increasing temperature from 353 K up to 523 K. In view of that according to the data of Panasyuk and Romaniv (1982) the temperature curves of crack growth rate for alloyed steels in water increase monotonously up to 373 K, one may conclude on the existence of the extremum of such curves in the temperature range of 373 - 523 K. It is probably associated with the change of the mechanism of the intensifying effect of the environment on steel fatigue failure.



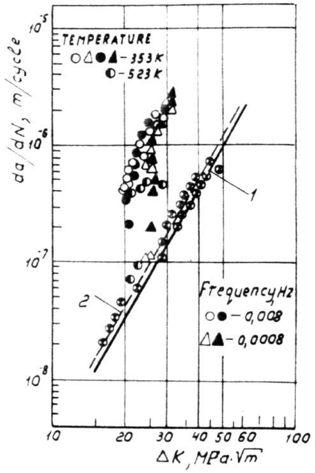
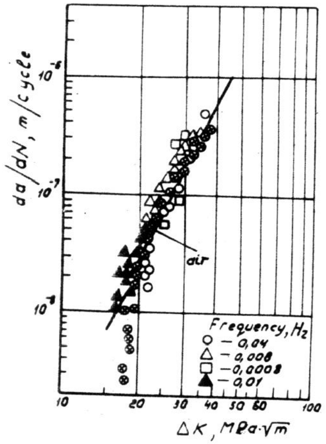


Fig.3. Effect of frequency and R ratio of loading cycle on kinetic diagrams of crack growth rate of Cr-Mo-V steel in deionized water: (○, Δ, □) - R = 0.15; (▲) - R = 0.62; (▼) - R = 0.67; (⊗)-air test results - R = 0.05.

Fig.4. Kinetic diagrams of Cr-Mo-V steel fatigue failure in deoinized water - pH = 7 (○, Δ - θ = 353 K), ammonia solution pH=9 (●, ▲ - θ = 353 K; ◐ - θ = 523 K) and in air (1 - θ = 298 K; 2, ⊗ - θ = 573 K).

Corrosion-Resistant 18Cr12Ni Steel. Kinetic curves of crack growth rate of steel in reactor water with Cl^- 5 mg/kg content, derived with consideration of the effect of cyclic loading and environment parameters are shown in Figs.5. and 6., respectively. The PWR water produces insignificant stimulating effect on kinetics of fatigue cracks of Cr-Ni steel. The results of static environment tests at 353 K, 0.04 Hz (Fig.5.) for crack growth rates are almost the same as for air tests. With decreasing frequency of cyclic loading down 0.008 Hz, the intensifying role of environment is manifested more strongly: crack growth rate in steel increases as high as 1.5 time as compared to air test results. A few tests at 0.0008 Hz prevents unambiguous conclusion with regard to the effect of very low loading rates on corrosion-cyclic crack resistance of steel. The increased R ratio from 0.12 up to 0.62 results in insignificant shift of the near-threshold region of the kinetic diagram toward the low-amplitude region and is simultaneously accompanied by larger scatter of the experimental data. The latter may be associated with higher crack tip branching at high average cycle load observed during the experiment. The efficiency of intensifying effect of corrosive environment on steel fatigue failure is increased with the presence of flowing water in the specimen region: crack growth rate in forced circulation tests is almost as high as 2 times as compared to static environment (Fig.6.). It may be due to activation of electrochemical reaction in the failure region because of easier "transport" of participating ions. The results of steel tests in high-temperature environment evidence that temperature change from 353 to 548 K is accompanied by about two-fold increase in the crack growth rate. Taking into account reduced 18Cr12Ni steel corrosion-cyclic crack resistance with increasing environment temperature from 298 up to 353 K, obtained earlier (Dmytrakh et al., 1989) one may conclude that propagation of fatigue failure of Cr-Ni steels under the effect of environment is thermally activated process.



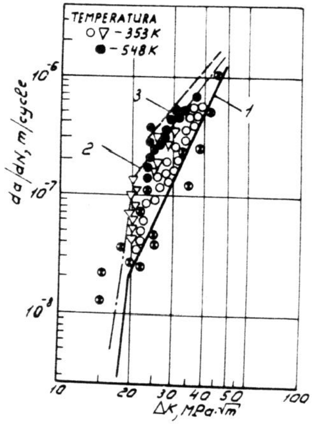


Fig.5. Effect of frequency and R ratio on corrosion-cyclic crack resistance of 18Cr12Ni steel in reactor water at 353 K (○,△,□ - R=0.12; ▲ - R=0.62); ⊗ - results of air tests (R =0.10).

Fig.6. Diagrams of 18Cr12Ni steel cyclic crack resistance in reactor water at 353 K (○ -static environment; ▽,2 - flowing environment) and at 548 K(●,3 -natural circulation) and in air: 1 - at 298 K; ⊕ - at 548 K.

CONCLUSIONS

1. Fatigue crack growth resistance of carbon and low-alloyed steels in chemically deionized water (pH=7) and ammonia solution (pH =9) are substantially lower than in air, with no considerable difference between the results in above aqueous environments. In the frequency range of cyclic loading from 0.04

to 0.0008 Hz, frequency produce no marked effect on steels corrosion-cyclic crack resistance.

2. The PWR primary circuit environment produces moderate intensifying effect on Cr-Ni steel fatigue crack growth. Reduced frequency of cyclic loading from 0.04 down 0.008 Hz was found to somewhat increase the sensitivity of steel crack resistance to the effect of environment. The efficiency of stimulating effect of corrosive environment on crack growth increases with intensive water flowing in the specimen region.

3. Increasing R ratio from 0.15 up to 0.65 results in larger rate of corrosion-fatigue crack growth for all investigated steels mostly in the near-threshold region of crack resistance kinetic diagrams (da/dN - ΔK).

4. The nature of environment temperature effect on crack resistance kinetic diagrams is qualitatively different for perlitic and austenitic steels. If for the first grade of steels, increased corrosion-cyclic test temperature from 353 up to 523-548 K is accompanied by marked reduction of the intensifying effect of environment on the rate of crack growth, then for austenitic steel similar temperature rise intensifies the role of environment being the crack kinetic activating factor.

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