Mechanical strength of large pressure-vessel materials in corrosive medium

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1 INTRODUCTION

In accordance with statistical data (Klemin 1971) 31 to 41 percent of the total damage of the inner surface of high-pressure-vessel shells for power equipment is associated with the formation of corrosion cracks, pittings, dimples and other flaws. Hence, it is necessary to study thoroughly the resistance of base materials used in power equipment as well as their welded joints to corrosion and fracture under conditions of static and cyclic loading and durable effect of an aqueous medium. It is of importance to conduct corrosive-mechanical testing of pearlite pressure-vessel materials irrespective of the fact that in service they are protected from the contact with an aqueous medium by the anticorrosive austenitic cladding since there exists the possibility of the corrosion resistant layer damage (Wimune 1966).

2 MATERIALS AND EXPERIMENTAL PROCEDURE

The authors studied the resistance of materials to low-cycle fatigue in an aqueous medium characterized by the parameters of high magnitude (high pressure and high temperature), as well as corrosion crack growth resistance under static and cyclic loading. The materials studied were high-temperature large pressure-vessel steels 15Kh2MFA, 15Kh2NMFA, their welded joints made by automatic welding under a layer of flux and the metal of the austenitic anticorrosive cladding made by automatic welding with the use of Sv-07Kh25N13 strip electrode for the first layer and Sv-04Kh20N10G2B electrode for subsequent layers. The last layer was in contact with a heat-transfer medium.

Low-cycle fatigue tests were conducted on tubular specimens in biaxial stress state which was attained by constant inner pressure (P = 6MPa, T = 270°C) and external tension-compression at different frequencies. During the tests the loading rate varied by 20-fold and corresponded to the frequencies of 0.00167...0.033 Hz. The water of high purity with the content of oxygen up to 0.01 mg/kg and with the

boron-content control was used as a test medium.
To evaluate the corrosion-crack growth under static loading 16×18×180 mm-beam specimens were used tested in three point bending. Due to high plasticity of the materials tested the Cherepanov-Rice J-integral method was used for the estimation of the crack growth resistance. The experimental technique is described by Nikiforchin, Ignatov, Timofeev et al. (1984). The test basis was 10^3h, while for 15Kh2NMFA steel it was considerably higher and constituted one year. Different autoclaves were used for the evaluation of the corrosion-crack growth resistance under cyclic loading. The tests were conducted with a frequency of 0.0167 Hz, at which the maximum effect of the medium on the cyclic crack growth resistance was revealed. In the course of the crack growth studies the load cycle varied to obtain the stress ratio in a load cycle from R = 0 to R = 0.7.
In the present study 1 percent H_3BO_3 solution in distilled water with the addition of KOH was used to ensure pH8. The values of pH were monitored at a temperature of 25°C.

3 EXPERIMENTAL RESULTS AND DISCUSSION

As was shown by the experiments for the steels studied and their welded joints the effect of the medium is actually absent. This is supported by the test results presented in Figure 1 from which it follows that the resistance of a pearlite steel to fracture in air and in the water with boron-content control does not change at cyclic deformation up to 820h over the life range from 10^2 to 10^4 cycles.

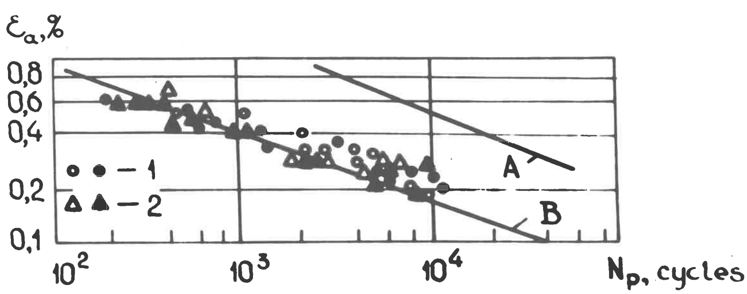

Figure 1. Resistance to low-cycle fatigue of steels 15Kh2MFA (1) and 15Kh2NMFA (2) in air (dark points), in an aqueous medium (light points) at 270°C. A,B curves obtained in air with 50 and 95 % of probability, respectively.

Similar effect was observed by Giginyak (1987). The absence of the aqueous medium effect upon fatigue strength of high-temperature pressure-vessel steels and their welds is accounted for by the formation of a protective magnetite film on the inner surface of the specimens tested. At low strains cyclic loading does practically no damage to the film. At essentially large strain amplitudes the magnetite film usually fractures but this practically does not effect

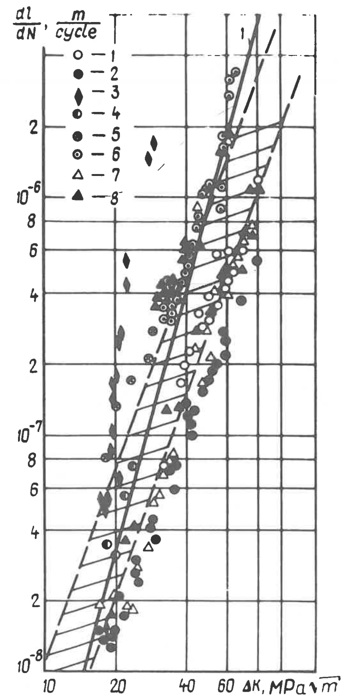

Figure 2. Fatigue crack growth rate variation in reactor's waters at 250...300°C for high-temperature steels: 1 15Kh2MFA KP60, R=0, T=250°C, δ =3 mm; 2 15Kh2MFA KP100, R=0, T=250°C, δ =3 mm; 3 15Kh2MFA KP60, R=0.7, T=300°C; δ =25 mm; 4 15Kh2MFA KP100, R=0.7, T=250°C, δ =3 mm; 5 15Kh2MFA KP60, R=0.7, T=300°C, δ =50 mm; 6 15Kh2MFA KP60, R=0.2, T=270°C, δ =50 mm; 7 15Kh2NMFA KP60, R=0, T=250°C, δ =3 mm; 8 15Kh2NMFA KP100, R=0, T=250°C, δ =3 mm.

the life of the material. The latter fact is associated with rapid healing up of the film fractures in the medium of neutral parameters as a result of which pits fail to form on the specimen surface. The absence of a free access of oxygen to the surface of the shell metal subjected to deformation is an additional guarantee that the corrosive medium will not contribute to the reduction of life.

Investigation of the aqueous medium effect on the fatigue crack growth rate in base materials and their welded joints (automatic and electroslag welding) was carried out on disk specimens which made it possible to observe visually the crack extension. These experiments conducted on compact-tension specimens of the base-metal showed that the heat-transfer medium had little effect on the resistance to fatigue crack growth with a nearly repeating load cycle.

Generalized data for steels 15Kh2MFA and 15Kh2NMFA are given in Figure 2 where the experimental results are compared with those obtained in air (shaded stripe) and with standard dependence from the ASME code (curve 1). It should be noted that for 15Kh2MFA steel at the stress ratio in a load cycle R=0.7 the fatigue crack growth rate in an aqueous medium at ΔK = 30 MPa is an order of magnitude higher than in air. These results were obtained in testing 25 mm-thick compact tension specimens. With 3 mm-thick specimens such a reduction was not observed even at a high stress ratio in a load cycle (Timofeev 1987).

In tests conducted under more severe conditions, i.e. at an aqueous medium temperature of 80°C, the medium was found to be more acidified at the crack tip in the 10 mm-thick beam specimen than the water in the autoclave. Thus, Dmitrakh, Timofeev et al. (1984) obtained pH3 at the crack tip for 15Kh2MFA steel and pH8 in the autoclave.

An improvement in the resistance of the materials studied to the fatigue crack growth with an increase in the medium temperature up to the maximum in-service one (270...290°C) is related not only to the changes in electrochemical processes but also to those in protective film properties. Under the effect of high-temperature water which contains boric acid a film is formed near the crack tip similar to that on the surface of the high-temperature steel specimens tested in low-cycle fatigue. With an increase in temperature, the solubility of magnetite reduces and the electrolyte stirring near the crack tip intensifies (Hartt, Henke, Fluet 1977) which hinders its local acidification and therefore lowers the intensity of local hydrogen embrittlement, while the penetration of hydrogen into the metal is restrained by protective oxide films. Therefore, fracture of the protective film and intensive local dissolution of the newly-formed surface are essential conditions for the crack growth under the influence of the medium. In accordance with the film theory these conditions are encountered when the deformation rate of the film does not exceed the rate of processes which cause its fracture. The data obtained by Scott, Truswell (1983) reveal the fact that under certain conditions a complete repassivation of the material at the crack tip may occur which causes a reduction in the crack growth rate.

For the tests conducted the stress ratio in a cycle was shown to have the largest effect on the crack growth rate in an aqueous medium as compared to all other service factors, such as frequency, temperature, stress ratio, the velocity of the medium. With an increase in the stress ratio from 0 to 0.7, the crack growth rate for the high-temperature pressure vessel steel in an aqueous medium can grow 15 to 20 times as compared to the same dependence in air. Basing on systematization of the experimental data on fatigue crack growth resistance in air and in an aqueous medium, the recommendations were given as to how to take into account this stage of fracture when calculating lives of structures with surface and internal manufacturing or in-service flaws. In this case it is practical to simulate the shape of the flaws which are revealed by nondestructive methods with plane defects outlined with the elliptical and circular contours as it was described in ASME Code (1978). To obtain the most conservative data on the crack extension under cyclic loading with the account taken of the location of flaws either an internal circular or surface semielliptical crack with a semi-axis ratio of 2:3 should be studied. Figure 3 presents the calculated fatigue crack growth versus conventional life curves which take into account the above-mentioned simulation procedure.

$$N_{con} = N(\Delta\sigma)^m$$

where N is the actual life spent for the crack extension from a_0 = 1 mm up to a_f evaluated from the brittle fracture condition; $\Delta\sigma$ is the range of the reduced stresses in MPa; m is the exponent in the Paris's equation. According to Timofeev, Fedorova and Zvezdin (1987) m = 2.47 for the materials tested.

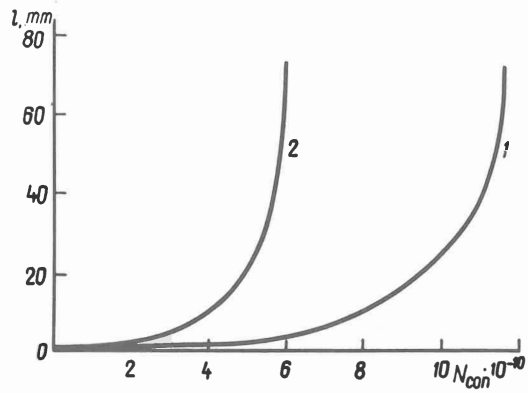

Figure 3. Calculated fatigue crack growth vs conventional life curves for inner (1) and surface flaws (2) in pressure-vessel materials.

Curve 1 presented in Figure 3 is valid for the ΔK values varying over the range from 4 to 100 MPa$\sqrt{m}$ and can be used without any correction for the evaluation of structures lives in the stage of crack extention from the internal flaw since there is no contact of a heat-transfer medium with the metal in the locality of such a flaw. Curve 2 describing the surface flaw extension is plotted with the account taken of the maximum correction for the corrosive medium effect revealed under cyclic loading with the stress ratio in a cycle R = 0.7.

No tendency to cracking was observed for high-temperature steels, their welded joints and the metal of the austenitic cladding at a temperature of 80°C when studying corrosion--crack growth resistance under static loading over a period of 1000 h. However, for both the metal of the first layer of the cladding made with the use of Sv-07Kh25N13 strip and the metal of the heat-affected zone (HAZ) of the welded joints for both steels tested under the conditions mentioned the crack extension was observed. Owing to a low crack growth rate in the HAZ metal, its reliable monitoring in the course of testing was impossible. Hence, the sensibility of a metal to the effect of a corrosive medium could be estimated only after final fracture of specimens subjected to the number of load cycles corresponding to the test basis. In this case the crack extension did not exceed 0.2mm.

At elevated temperatures (250-300°C) the tendency to crack extension for the materials tested in the aqueous medium under long-term static loading is far weaker than at a temperature of 80°C. All the data obtained mainly refer to 15Kh2MFA steel which was heat-treated to obtain different levels of strength. No subcritical crack growth was observed with 15 mm-thick compact-tension specimens tested for as long as 7000 h in autoclaves both with and without heat-transfer medium circulation. This testifies to the fact that high-temperature steels and their welded joints have no tendency to corrosive cracking.

CONCLUSIONS

The materials tested turn to be low-sensitive to the aqueous medium with the parameters of high magnitude in terms of both the resistance to the low-cycle fatigue and fatigue crack growth under long-term static loading.

Of all service factors the stress ratio in a cycle is found to have the largest effect on the fatigue crack growth rate in an aqueous medium.

At the same values of ΔK the stress ratio variation from 0 to 0.7 can result in the 10 to 15-fold increase in the crack growth rate.

Systematization of the experimentally obtained data on the fatigue crack propagation in high-temperature steels and their welded joints makes it possible to take into account the above stage of fracture in standard calculations for both internal and surface flaws.

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