STABILITY OF THE WARM PRESTRESSING EFFECT UNDER SUBSEQUENT LOADING

V.Y.Podkolzin* and P.V.Yasniy*

In the present paper stability of the warm prestressing effect was studied with regard to two factors most important from scientific and practical standpoints: long hold-time under load at an elevated temperature and cyclic loading (both without a fatigue crack growth onset and with its extention by different magnitudes).

INTRODUCTION

The warm prestressing (WPS) appears to be one of the most effective methods of raising the brittle strength of structural materials. Investigations carried out earliar by the authors showed that WPS of 15Cr2MoV steel which is used for the manufacturing of the shells of WWER reactors gives the possibility to increase its fracture toughness under static loading in the region below the brittle-to-ductile transition temperature in 2...3 times (Figure 1).

At that time the problem of WPS effect stability under the influence of the subsequent operating loading is not investigated enough. This work deals with the investigation of this problem concerning the materials and operating regimes of the WWER reactors.

* Department of Theory of Materials,
Ternopil Instrument Making Institute.

RESULTS AND DISCUSSION

The influence of the long-term static loading under high temperature on WPS effect was investigated in the three schemes using the compact specimens of 25 mm thickness of embrittled 15Cr2MoV steel. In scheme No 1 the cracked specimen was under cyclic loading. When the loading was removed the specimen was heated and stayed in unloaded state during 5 hours. Then it was cooled and the static fracture toughness was determined according to ASTM Standards. In scheme No 2 when the cyclic loading was removed the specimen was heated, statically loaded and it was under this loading during 5 hours. Then it was cooled and fracture toughness was determined. In scheme No 3 when the cyclic loading was removed, the specimen was heated up to 573 K and subjected to single static overloading. Then the specimen was cooled and subjected to long-term static loading under high temperature. After it the static fracture toughness was determined. The time of the long-term static loading varied from 5 to 10^4 hours. It exceeds the operating time of the WWER reactor between its scheduled repair.

In all three cases the cyclic loading and the final fracture toughness testings under the static loading were carried out at 293 K, preliminary static overloading at 573 K, the long-term static loading at 623 K. The level of the cyclic loading was $K_{max} = 32$ MPa$\sqrt{m}$. These regimes coinside with the operating regimes of WWER reactors. Long-term static loading veried from 0 till 60 MPa$\sqrt{m}$ which is equal to stress intensity factor at the tip of the crack of 35 mm depth under hydrostatic testing of the reactor shell.

As it follows from Figure 2 when the value K_h is increased from 0 till 32 MPa$\sqrt{m}$ the increasing of the brittle strength of 15Cr2MoV steel appears. The further increasing of the long-term static loading level leads to the substantial decreasing of the static fracture toughness. The level of the cyclic loading before the long-term static loading (K_{max} = 32MPa$\sqrt{m}$ = $0.7K_{Ic}$) was over the value determined in standards which caused the raising of the fracture toughness (as compared with the initial K_{Ic}) under testing in scheme No 1. The raising of the brittle strength under raising the K_h level up to 32 MPa$\sqrt{m}$ is explained by the fact that the crack tip radius is increased because of the creep deformation (when the creep crack extension is not available).The decreasing of the fracture toughness under the further increasing of the long-term static loading level is because of the growing of creep crack and caused by the decreasing of the crack tip radius.

The testing in scheme No 3 are shown in Figure 3. As it is seen the brittle strength of 15Cr2MoV steel is not sensitive to the long-term static loading under the load level $K_h = 60$ MPa $\sqrt{m}$ at temperature $T \leq 623$ K within 0...10^4 hours. As it follows from Figure 3 the level of δ_f for the given steel does not change when the time of subjecting to loading was changing from 0 till 10^4 hours. Besides, the periodical measurements (in every 100 hours) showed that the increase of the crack opening under long-term static loading did not occur.

The results obtained showed that WPS decreases greatly the creep deformation rate, and WPS effect under long-term static load is stable when the creep crack growing is absent. It is known that the creep deformation rate is a function of stresses in the crack tip region. In this case stresses normal to the crack plane are of importance. WPS leads to the initial crack tip blunting which can be spoken about the notch. In this case the changing of stresses appears which leads to the creep deformation rate decreasing.

The stability of the WPS effect under the long-term static loading is explained by the fact that when the creep crack growing is absent, the creep deformation can only increase the crack tip radius which leads to the further increasing of the brittle strength of the material.

The influence of the cyclic loading after WPS was investigated using the compact specimens of 50 mm thickness of embrittled 15Cr2MoV steel. During the first stage the cracked specimens were heated up to 423 K and statically loaded up to $K = 0.85K_{Ic}(T)$, were $K_{Ic}(T)$ - stress intensity factor at the temperature T. Then the specimen was unloaded, heated up to 573 K and subjected to the cyclic loading. The value of the cyclic loading was equal to the real operating regimes of the WWER-440 reactor and was K_{max} = 32; 55.8 ; 64.4 MPa$\sqrt{m}$. While testing the fatigue crack growth magnitude within the plastic zone which appeared during WPS was controlled. After that the specimen was cooled to 293 K and subjected to the static fracture toughness testing according to standards.

The investigations carried out showed that (when the fatigue crack growth is not available) in 15Cr2MoV steel under cyclic loading (ΔN=200 cycles) some decreasing of the fracture toughness after WPS takes place (Figure 4). In this case a decrease both in the K_f value becomes more appreciable with an increase in the amplitude. The analysis of the results of experiment allows to make the conclusion about the WPS effect stability under cyclic loading in the case when the fatigue crack growth is absent. A small decreasing (3...9%) of the fracture toughness is explained by the material damage (embrittlement) at the crack tip under cyclic loading.

In the case when the fatigue crack growth occurs the way of dependance of the fracture toughness after WPS on the number of the load cycles changes. The dependance of K_f on the value of $\Delta l/S_1$ under the cyclic loading is shown in Figure 5. As it follows the fracture toughness after WPS does not change up to $\Delta l/S_1 = 0.25$, which is the same as the results obtained by Chell (1). It is explained by the specific character of the interaction of the deformation fields of the initial crack blunted as the result of WPS and the short fatigue crack which was initiated from its tip. When the fatigue crack is grown more than $0.25S_1$ the decreasing of the fracture toughness take place. In our case the decreasing of the fracture toughness till the initial level does not take place because the level of cyclic loading at 573 K exceeded greatly the maximum allowable level during the fatigue precrack growing.

The mesurment of the critical crack tip opening showed that the way of dependance δ_f - $\Delta l/S_1$ coinside strictly with the way of dependance K_f - $\Delta l/S_1$ (Figure 5).

To determine the contribution of residual stresses which appeared at the stage of unloading in the total WPS effect when the fatigue crack was growing through the plastic zone S_1, the value of the loading under which the whole crack opening took place (P_{op}) was measured. It allows to estimate indirectly the value of residual stresses. As it follows from Figure 6 when the fatigue crack growing through the plastic zone S_1 the value of K_{op} is stable. As it was mentioned earlier the fracture toughness after the fatigue crack growth in more than $0.25S_1$ decreases greatly but the value of the residual stresses does not change. It allows to make the conclusion that the residual stresses which apeared at the crack tip region during the unloading after WPS do not influence the total warm prestressing effect.

SYMBOLS USED

K_f = Critical stress intensity factor after WPS.

K_{1c} = Critical stress intensity factor under plane-straine conditions.

K_{max} = Maximum stress intensity factor in a cycle.

K_h = Stress intensity factor during holding under load.

δ_f = Critical crack tip opening displacement after WPS.

Δl = Crack increment.

S_1 = Plastic zone after overload

REFERENCES

(1) Chell, G.G., and Haigh, J.R., Int. J. Press. Vess. Piping, Vol.23, 1986, pp. 121-132.

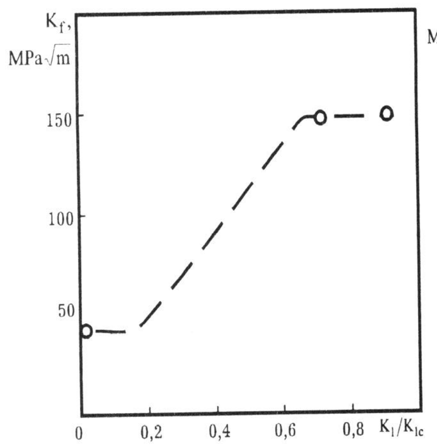

Figure 1. Relationship K_f versus K_1/K_{1c}

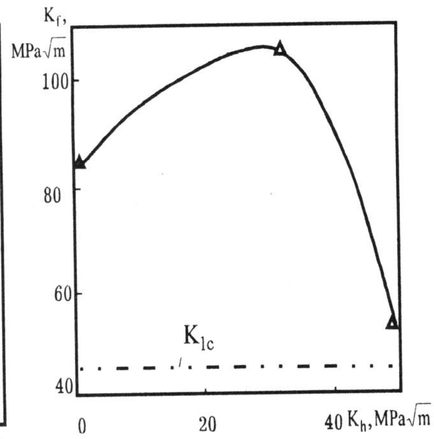

Figure 2. Relationalship K_f versus K_h.

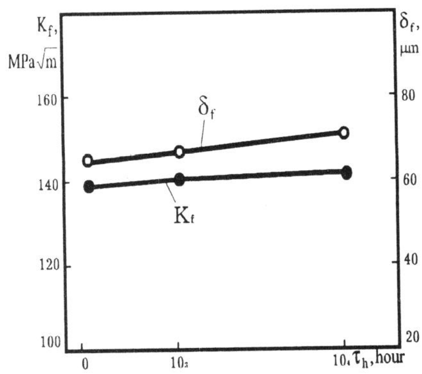

Figure 3. Relationship K_f and δ_f versus τ_h

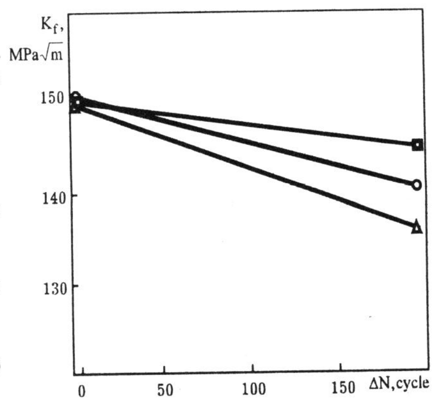

Figure 4. Relationship K_f versus ΔN

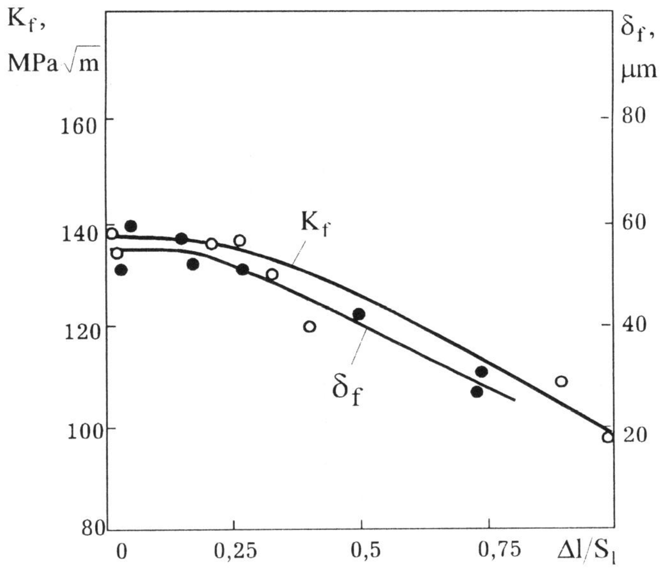

Figure 5. Relationalships K_f and δ_f versus $\Delta l/S_1$

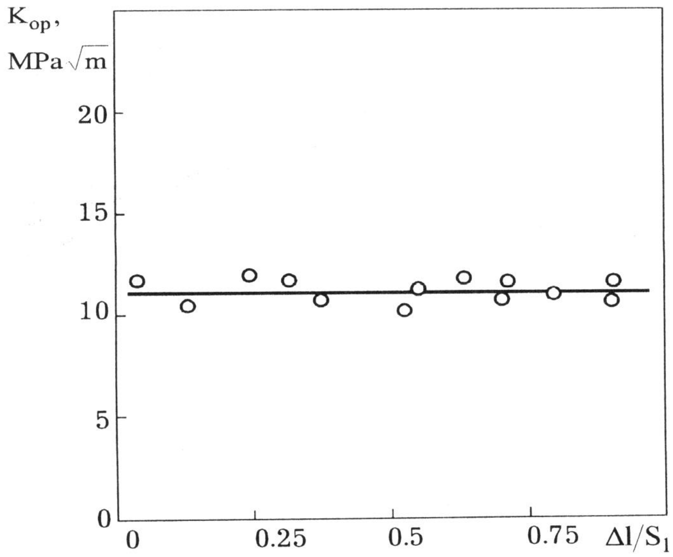

Figure 6. Relationship K_{op} versus $\Delta l/S_1$