# PREDICTION OF THE INFLUENCE OF WARM PRESTRESSING CONDITIONS ON PRESSURE VESSEL RESISTANCE TO BRITTLE FRACTURE

V.T. TROSHCHENKO and V.V. POKROVSKY

*Institute for Problems of Strength,*
*Academy of Sciences of Ukraine*
*Timiryazevskaya Str.,*
*2, 252014 Kiev 14, Ukraine*

V. Yu. PODKOLZIN

*Ternopil Instrument-Making Institute,*
*56, Ruska Str., 282001, Ternopil, Ukraine*

## ABSTRACT

The investigation has been performed on the influence of warm prestressing (WPS) on the brittle fracture resistance of structural heat - resistant steel 15Kh2MFA in two structural states and the embrittled weld metal 10KhMFT. The stability of the warm prestressing effect has been studied under cyclic loading as well as with long hold time under load at an elevated temperature. A calculation approach based on the strain criterion has been developed. It makes it possible to estimate quantitatively an increase in brittle fracture resistance after warm prestressing.

## KEYWORDS

Warm prestressing, brittle fracture resistence, fracture criterion, brittle fracture mechanisms.

## MATERIALS AND EXPERIMENTAL PROCEDURE

The tests were carried out on the 15Kh2MFA(I), 15Kh2MFA(II) steels and the Sv10KhMFT weld metal in the temperature range 293...573 K. Mechanical properties of the materials at 293 K are presented in Table 1.

Table 1. Mechanical properties of the materials

| Material | $\sigma_{0.2}$, MPa$\sqrt{m}$ | $\sigma_u$, MPa$\sqrt{m}$ | $\delta$, % | $\psi$, % |
|---|---|---|---|---|
| 15Kh2MFA(I) | 786 | 931 | 17,0 | 67,7 |
| 15Kh2MFA(II) | 1100 | 1157 | 16,1 | 67,2 |
| Sv10KhMFT | 561 | 624 | 21,3 | 66,3 |

The tests were performed on standard compact tension (CT) specimens 25 and 50 mm in thickness using a servohydraulic "SCHENCK" testing machine with the load capacity 400 kN.

The fracture toughness temperature dependence of the materials studied which govern the choice of the warm prestressing temperature and loading regimes were determined in the temperature range 293...573 K.

After constructing initial fracture toughness temperature dependences the specimens were subjected to warm prestressing and subsequent final fracture in accordance with the following schems:

1. Heating up to the temperature $T_1$; loading up to $K_1<K_c(T_1)$ where $K_c(T_1)$ is the critical stress intensity factor (SIF) at the temperature $T_1$; total unloading; cooling down to the temperature $T_3$; fracturing at $K_3 = K_f(T_3)$ where $K_f(T_3)$ is the critical SIF after WPS at $T_3$.

2. Heating up to $T_1$; loading up to $K_1<K_c(T_1)$; partial unloading down to $K_2$; cooling down to $T_3$; fracturing at $K_3=K_f(T_3)$.

3. Heating up to $T_1$; loading up to $K_1<K_c(T_1)$; cooling down to $T_3$; fracturing at $K_3 = K_f(T_3)$.

## EXPERIMENTAL RESULTS AND DISCUSSION

The problem of the warm prestressing regime effect on fracture toughness characteristics has been most extensively studed on 50 mm thick speciments.

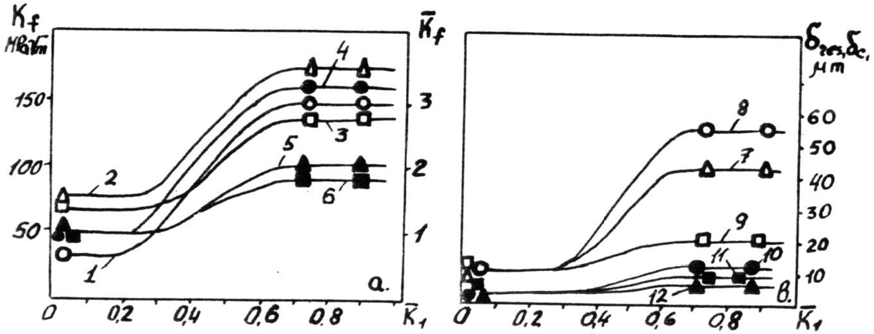

Fig.1.Relationships $K_f$ vs $\bar{K}_1$ (1-3), $\bar{K}_f$ vs $\bar{K}_1$ (4-6) - a and $\delta_c$ vs $\bar{K}_1$ (7-9), $\delta_{res}$ vs $\bar{K}_1$ (10 - 12) - b for steels 15Kh2MFA(II) - (1,4,7,10), 15Kh2MFA(I) - (2,5,8,11) and Sv10KhMFT - (3,6,9,12).

At the level of WPS $\bar{K}_1=K_1/K_c(T_1)>0.6$ no changes occur in the brittle fracture resistence with $\bar{K}_1$ variation (Fig.1a.). In the lower region of the diagram the $K_f$ value is also not sensitive to the $\bar{K}_1$ variation and correspondes to the static fracture toughness of respective alloys at ambient temperature. A point in which $\bar{K}_1 = 0.6K_c(T_3)$ is the boundary of the diagram lower region. Here $K_c(T_3)$ is the material critical SIF at 293 K. In the middle of the diagram the $K_f$ value grows continuously with an increase in $\bar{K}_1$.

The above data agree with the results obtained elswhere for the A533B-1 steel.

The shape of the diagram "critical crack tip opening displcement ($\delta_c$) and residual blunting ($\delta_{res}$) after WPS vs the level of WPS ($\bar{K}_1$)" (Fig.1b.) completely coincides with that of the $K_f$ vs $\bar{K}_1$ diagram. The $\delta$ value, as well as $K_f$, does not change with the $K_1$ increase from 0 to $0.6K_c(T_3)$. No crack blunting is observed in the given $\bar{K}_1$ variation range. With a further increase in the WPS level the crack tip would not close any longer after unloading and the radius of its blunting grows continuously along with the $\delta_c$ value up to $\bar{K}_1= 0.6$. At $\bar{K}_1>0.6$ the $\delta_c$ and $\delta_{res}$ values are practically independent of the changes in the level of WPS.

The above data allow to conclude that the crack tip blunting after WPS of the alloys studied is the factor responsible for an appreciable WPS effect.

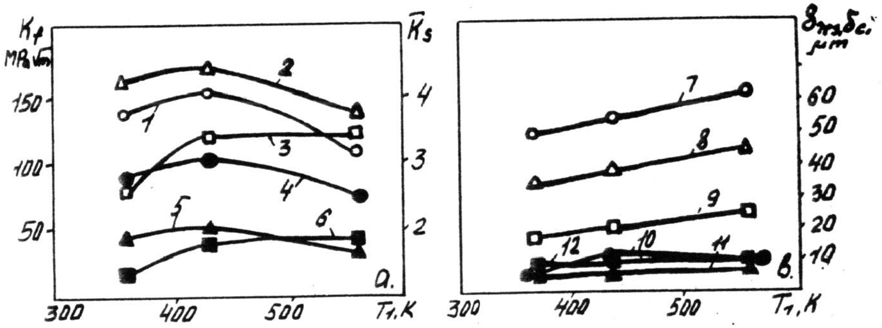

Fig.2.Relationships $K_f$ vs $T_1$ (1-3), $\bar{K}_f$ vs $T_1$ (4-6) - a and $\delta_c$ vs $T_1$ (7-9), $\delta_{res}$ vs $T_1$ (10 - 12) - b for steels 15Kh2MFA(II) - (1,4,7,10), 15Kh2MFA(I) - (2,5,8,11) and Sv10KhMFT - (3,6,9,12).

the dependence of the critical SIF after WPS ($K_f$) and the ratio $\overline{K}_f = K_f/K_c(T_3)$ on the warm prestressing temperature at $\overline{K}_1 = 0.85$ (Fig.2) proves that the maximum WPS effect is achieved at $T_1$=423 K. Note that the maximum absolute critical SIF value $K_f$ = 170 MPa$\sqrt{m}$ was obtained for the 15Kh2MFA(I) steel, while the largest relative increase in the brittle fracture resistance after WPS was obtained for a more brittle steel 15Kh2MFA(II) at the same temperature of overloading. The value $K_f$ for this steel exceeds the initial fracture toughness value 3.2 times, while for the 15Kh2MFA(I) steel 2 times only. At $T_1$ = 573 K a decrease in the $K_f$ level is observed for both structural states of the 15Kh2MFA steel which is related to an appreciably lower (compared to $T_1$ = = 423 K) value of the critical SIF $K_c$ and, hance, a lower magnitude of WPS.

Unlike the 15Kh2MFA steel, the $K_f$ value for the Sv10KhMFT weld metal does not change in the temperature range 423 K<$T_1$< <573 K and is equal to $K_f$ = 128 MPa$\sqrt{m}$ which is 1.7 times higher than the initial fracture toughness. This is explained by approximately equal levels of $K_c$ at 423 K and 573 K and, accordingly, by similar levels of $K_f$.

The brittle fracture resistance of the materials studied is shown to be practically independent of the fact whether WPS was performed with complete, partial unloading or without it (Fig.3). Thus for the 15Kh2MFA(II) steel in all three cases the $\overline{K}_f$ value varies between 3 and 3.2, for the 15Kh2MFA(I) between 1.8 and 2.1 and for the Sv10KhMFT weld metal between 1.8 and 1.9. The obtained results suggest that residual compressive stresses have no essential influence on the WPS effect for the steels considered.

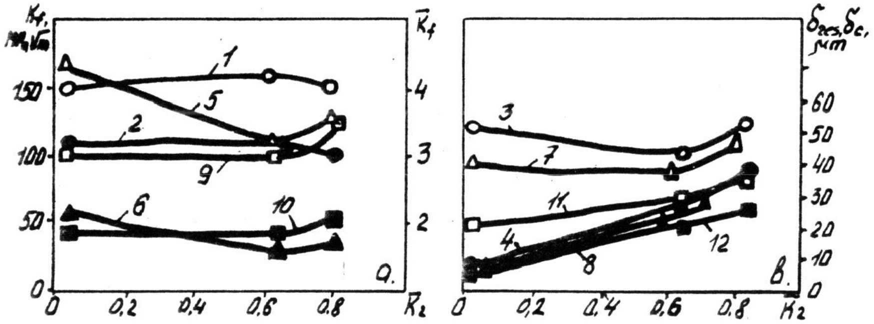

Fig.3.Relationships $K_f$ vs $\overline{K}_2$ (1,5,9), $\overline{K}_f$ vs $\overline{K}_2$ (2,6, 10), - a and $\delta_c$ vs $\overline{K}_2$ (3,7,11,), $\delta_{res}$ vs $\overline{K}_2$ - (4,8,12) - b for steels 15Kh2MFA(II) - (1-4), 15Kh2MFA(I) - (5-8) and Sv10KhMFT - (9 - 12).

In the presented paper stability of the WPS effect was studied with regard to two factors: long holdtime under load and cyclic loading.

The influence of long holdtime under static load at a temperature of WPS above the brittle-to-ductile transition temperature was studied on 25 mm thick CT specimens of steel 15Kh2MFA(II) and embrittled weld metal Sv10KhMFT.

During the experiment, the crack faces opening diplacement was measured periodically using B - 630 cathetometer (the measurement accuracy was not lower than 0.001mm).

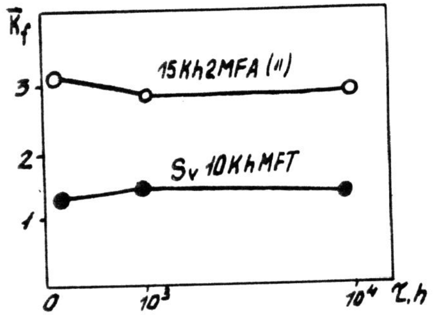

Fig.4.Dependence of the relative increase in the static fracture toughness for warmprestressed specimens on the hold time under load ($K_h$=60MPa$\sqrt{m}$, $T_h$=623K)

The results of the tests involving a single static overloading prior to holding under load (Fig.4) indicate that brittle fracture resistance of both steel 15Kh2MFA(II) and weld metal Sv10KhMFT after single static loading at a temperature above the brittle-to-ductile transition temperature is not sensitive to the holdtime under SIF $K_h$ = 60 MPa$\sqrt{m}$ at $T_h$ < 625 K over the range 0...10000 h. In this case the magnituds of the critical crack tip opening displacement does not change either.

In addition, periodic measurements (every 100 houre) revealed no noticeable increase in the crack faces opening displacement for both 15Kh2MFA(II) steel and Sv10KhMFT weld metal at holding under SIF $K_h$=60 MPa$\sqrt{m}$ at $T_h$ = 623 K during $10^4$ hours.

The analysis of the results obtained makes it possible to conclude that WPS reduces appreciably the creep strain rate due to stress redistribution at the crack tip after its blunting and at long holding under load the WPS effect does not decline if the creep crack growth onset does not occur.

The influence of cyclic loading after WPS was studied in tention of 50 mm thick CT specimens of 15Kh2MFA(II) steel. The investigations revealed that in the absence of fatique crack growth onset in the 15Kh2MFA(II) steel under cyclic loading (N = 200 cycles) a certain reduction in the fracture toughness occurs after WPS. In this case, a decrease in the $K_f$ value becomes more appreciable with an increase in the amplitude.

The analysis of the experimental results enables a conclusion to be made about the stability of the WPS effect under conditions of subsequent cyclic loading in the absence of fatique crack extension. A small reduction (3...9%) in the fracture toughness is explained by the material damage at the crack tip under the effect of cyclic load.

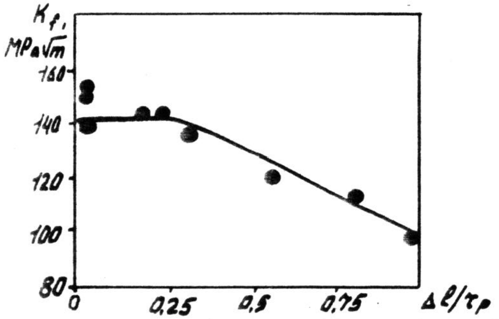

Fig.5.$K_f$ dependence on the relative value of the crack extension within the plastic zone.

In the case of fatique crack growth onset the character of the fracture toughness dependence on the number of load cycles after WPS changes (Fig.5). Irrespectively of the $K_{max}$ level, after WPS fracture toughness does not change until $\Delta l/r_p = 0.25$. When the fatique crack extends by the value exceeding $0.25r_p$, a monotonic reduction in the fracture toughness occurs down to the value $K_f = 99$ MPa√m at the boundary of the plastic zone $r_p$. The fracture toughness does not decrease down to the initial value due to the fact that the level of cyclic loading at a temperature 573 K exceeded appreciably the maximum allowable level of cyclic load ($0.6K_c$) during fatique precrack growing.

In order to determine the contribution of residual compressive stresses induced at the stage of unloading into the total WPS effect, as the crack was extending through the plastic zone $r_p$ the load was measured at which a complete crack opening occurred ($P_{op}$) that allowed the magnitude of residual compressive stresses to be evaluated indirectly. It is found that when the crack is growing through the plastic zone $r_p$, the $K_{op}$ value does not change. Considering the fact that after crack extention by the value exceeding $0.25r_p$ the fracture toughness decreases sharply while the magnitude of residual stresses does not change, it can be concluded that residual compressive stresses arising in the crack tip region at the stage of unloading after WPS have no appreciable influence on the total WPS effect.

The analysis of the data obtained revealed that the crack tip blunting makes an appreciable contribution into the WPS positive effect. In addition, crack tip opening displacement is an integral characteristic which takes into account the material yield stress variation induced by radiation, strain hardening and other factors. At the same time residual stresses arising in the crack tip region at the stage of unloading were found to have no appresiable influence on the WPS effect.

As a result of the obtained data, a criterion of brittle fracture after WPS is proposed the essence of which is in that fracture under static loading at low temperature will occur at the moment when the crack tip opening displacement value reaches the magnitude similar to that at WPS at high temperature

$$\delta_c = \delta_1 \tag{1}$$

The dependence of the crack tip opening displacement upon the applied load under plane strain conditions for a perfectly plastic material is described by the following relationship

$$\delta = 0.6\,\frac{0.6K^2}{\sigma_{0.2}E} \tag{2}$$

For a strain hardening material this dependence will be defined by the equation (Panasyuk et al., 1986):

$$\delta = \frac{0.6K^2}{\sigma_{0.2}E}\left[\frac{2/\sqrt{3}(1+\mu)(1+n)\sigma_{0.2}}{nE}\right]^n \tag{3}$$

were $\sigma_{0.2}$ is the yield stress, E is the Young modulus, $\mu$ is the Poisson coefficient, n is the strain hardening exponent.

Thus from relation (1) considering (3) an expression can be written for determining the critical SIF after WPS from the crack tip opening displacement value at unloading

$$K_f = \left[\frac{\delta_1 \sigma^f_{0.2} E_f}{0.6 Y_f}\right]^{1/2} \qquad (4)$$

where

$$Y_f = \left[\frac{2/\sqrt{3}(1+\mu)(1+n)\sigma^f_{0.2}}{n_f E_f}\right]^{n_f} \qquad (5)$$

Here $\sigma^f_{0.2}$, $E_f$, $n_f$ are the material mechanical characteristics determined at the same temperature as $K_f$.

The results obtained using the criterion proposed have been compared with those obtained by Chell's model (1981). It has been shown that the criterion proposed allows a more accurate prediction of the encrease in the material brittle fracture after warm prestressing. In addition, it makes it possible to predict brittle fracture resistance for structural elements of different thickness.

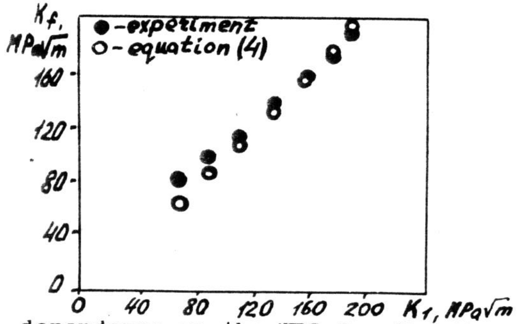

Fig.6.$K_f$ dependence on the WPS for the 15Kh2MFA steel.

Fig.6 presents the $K_f$ values for steel 15Kh2MFA(II) calculated for different $K_1$ values during WPS of 150 mm thik specimens of that steel with cracks. The analysis of those results reveals the accuracy of $K_f$ estimates after WPS which is acceptable for practical application.

## REFERENCES

G.G. Chell, J.R. Haigh and V. Vitek (1981) A theory of warm prestressing: experimental validation and the implications for elastic plastic failure criteria, Int.J.Fract., Vol. 17, P.61-81

V.V. Panasyuk, A.E. Andreykiv, V.Z. Parton (1986) Materials Fracture Mechanics. In: Fracture Mechanics and Strength of Materials. Handbook. (Ed. V.V. Panasyuk), Vol. 1., Naukova Dumka, Kiev, (in Russian).