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Calculated and experimental estimation of preliminary loading effect at elevated temperatures on fracture toughness of pressure vessel materials

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ABSTRACT: Basing on the analysis of different factors effect on the structural materials cracking resistance after preliminary heat loading or warm prestressing (WPS), a conclusion has been drawn that the existing calculation models used for WPS effect prediction are limited, and the Chell model, which is very convenient for practical use, in particular.

The testing results on cracking resistance of the structural 15X2MFA (of different strengths steel) and 15X2HMFA steels as well as a welding 10XMFT joint after WPS are presented.

Comparison of the experimental and calculation data proved the possibility of practical application of the simplified Chell solution of the WPS effect on the structural steels cracking resistance in the wide range of loading up to the subcritical crack growth.

1 INTRODUCTION

A structure warm prestressing (WPS) is performed as a rule at temperature, exceeding operating temperature, and is aimed to increase fracture toughness of a structure, containing initial defects (the sizes of which are smaller than those, registered by NDT techniques) as well as defects, which were not casually revealed by NDT procedures. The positive WPS effect on structural material corrosion strength is confirmed by numerous experimental investigations. This positive effect after WPS is evident even in those cases, when loading at elevated temperature is lower than fracture loading by test temperature without WPS (Long 1986).

By the investigation of WPS effect on structural material fracture toughness, there main cycles of the variation of loading and temperature are usually used:

- LCF - preliminary loading at T_1 temperature; cooling to T_3 temperature; testing to failure;
- LCUF - preliminary loading at T_1 temperature; cooling to T_3 temperature; unloading; testing to failure;
- LUCF - preliminary loading at T_1 temperature; unloading at T_1 ; cooling to T_3 temperature; testing to failure.

Usually WPS temperature is selected with the aim to provide material ductile behaviour by loading; WPS level and cycle type are determined either by stresses and temperatures by structure testing or by the regimes of temperature and loading variation in a structure (for example, in pressure vessels during cooling by emergency repair).

There are several well-known models (Chell 1977, 1981; Carry 1981; Smith 1990), describing WPS influence on brittle fracture resistance. However, all of them are in some degree limited, because they base as a rule only on one or two well-known mechanisms, increasing fracture toughness after WPS (Nickols 1968). In development of residual compressive stresses at the crack tip after WPS is not enough to be taken as the main factor (as it is done in (Brazerc 1963, Harrison 1972), as it is known (Andrews 1970), that the maximum WPS effect appears in LCF cycle, when unloading and consequently residual stress field are absent. The contribution of crack blunting in crack resistance after WPS is also estimated discrepantly (Mudry 1985). The influence of strain hardening on WPS effect was investigated in (Long 1986), where due to the calculations it was

shown, that disregard of total strain hardening in Chell's and Carry's models did not sufficiently influence on results. Chell's model is recommended for practical application.

The contradiction of given results, concerning the effect of various factors on WPS attack is explained by the fact that the contribution of these factors to fracture toughness increase after WPS depends on preliminary loading level (Beremin 1981). By LUCF cycle and relatively low loading levels, the role of residual stresses becomes important. However, with preliminary loading increase, the effect of crack blunting and strain hardening also increases (Mudry 1985).

In this condition a possibility to estimate WPS effect on Chell's model as a very convenient (Chell 1980) from the practical point of view becomes by interesting high level of preliminary loading, when crack blunting and strain hardening are of great importance - the factors, which are not taken into account in Chell's model.

This paper considers the problems of Chell's model practical application to estimate WPS effect for VVER pressure vessel material.

2 CHELL'S MODEL OF WPS

Chell's model is based on the suggestion, that the main WPS effect is yield strength variation, and consequently residual zones generation. By this, the model may be used in any case of yield strength variation, while the structure is under loading - which is the result of temperature variation, irradiation affect or other factors (Carry 1981). Basing on the analysis of the development and variation of residual compressive stress and strain zones at the crack tip for various stages of loading by WPS, Chell and his colleagues (Chell 1981) showed, that WPS effect was connected with the realization of «active» plastic zone, which includes only «mobile» dislocations.

In this case WPS effect is estimated differently, depending on the characteristical size of varying plastic zone: S_1 - by initial loading at temperature T_1 and yield strength σ_1 ; S_2 - by unloading and cooling (temperature T_2 , yield strength σ_2); S_3 - by testing to failure (temperature T_3 and yield strength σ_3).

By this, three cases are possible:

$$S_1 > S_2 > S_3$$

or

$$\sigma_1/\bar{\sigma}_1 > (\sigma_1 - \sigma_2)/(\bar{\sigma}_1 + \bar{\sigma}_2) > (\sigma_3 - \sigma_2)/(\bar{\sigma}_3 + \bar{\sigma}_2) \quad (1)$$

$$S_1 > S_3 > S_2$$

or

$$\sigma_1/\bar{\sigma}_1 > (\sigma_3 - \sigma_1)/(\bar{\sigma}_3 - \bar{\sigma}_1) > (\sigma_3 - \sigma_2)/(\bar{\sigma}_2 + \bar{\sigma}_3) > (\sigma_1 - \sigma_2)/(\bar{\sigma}_1 + \bar{\sigma}_2) \quad (2)$$

or

$$S_3 > S_1 > S_2$$

$$(\sigma_3 - \sigma_1)/(\bar{\sigma}_3 - \bar{\sigma}_1) > \sigma_1/\bar{\sigma}_1 > (\sigma_3 - \sigma_2)/(\bar{\sigma}_2 + \bar{\sigma}_3) > (\sigma_1 - \sigma_2)/(\bar{\sigma}_1 + \bar{\sigma}_2) \quad (3)$$

For each case, the stress intensity factor $K_I = K_3$, characterizing fracture conditions at T_3 after WPS with unloading up to K_2 may be found from the solution of the following equations:

$$\text{Case 1} \quad K_{Ic}^2 = \bar{\sigma}_3 \left[\frac{K_1^2}{\bar{\sigma}_1} (1 - f_{32}) - \frac{(K_1 - K_2)^2}{\bar{\sigma}_1 + \bar{\sigma}_2} (1 - f_{21}) + \frac{(K_3 - K_2)^2}{\bar{\sigma}_2 + \bar{\sigma}_3} \right], \quad (4)$$

where

$$f_{32} = \Psi \left(Z = \left[\frac{(K_3 - K_2) \bar{\sigma}_1}{(\bar{\sigma}_2 + \bar{\sigma}_3) K_1} \right]^2 \right),$$

$$f_{21} = \Psi \left(Z = \left[\frac{(K_3 - K_2) (\bar{\sigma}_1 + \bar{\sigma}_2)}{(\bar{\sigma}_3 + \bar{\sigma}_2) (K_1 - K_2)} \right]^2 \right).$$

$$\text{Case 2} \quad K_{Ic}^2 = \bar{\sigma}_3 \left[\frac{(K_3 - K_1)^2}{(\bar{\sigma}_3 - \bar{\sigma}_1) K_1} + \frac{K_1^2}{\bar{\sigma}_1} (1 - f_{31}) \right], \quad (5)$$

where

$$f_{31} = \Psi \left(Z = \left[\frac{(K_3 - K_1) \bar{\sigma}_1}{(\bar{\sigma}_3 - \bar{\sigma}_1) K_1} \right]^2 \right).$$

Case 3

$$K_3 = K_{Ic}, \quad (6)$$

where

$$\varphi(z) = (1-z)^{1/2} - \frac{z}{2} \ln \left[\frac{1+(1-z)^{1/2}}{1-(1-z)^{1/2}} \right]. \quad (7)$$

where K_1 is the stress intensity factor (SIF) resulting from overload,

K_2 is the value after unloading,

K_3 is the reloaded level, when fracture takes place. It is impossible to know beforehand, which of these three cases will be realized. Therefore it is necessary to solve the equations (4), (5), (6) and then basing on the conditions (1)–(3) to define the case, being realized, for which the value K_3 is calculated fracture stress intensity factor after WPS. It should be noted, that the value K_3 is not expressed from calculated dependences quite evidently and it is necessary to use numerical methods of equation solution to find it.

The equation may be approximated with a sufficient correctness by the relation (Chell 1980, Kotilainen 1983):

$$\varphi(z) = (1-z)^2 \quad (8)$$

Then the equations (4)–(6) may be rewritten as related to K_3 .

$$\text{Case 1} \quad K_3 = K_2 + (\bar{\sigma}_3 + \bar{\sigma}_2) K_1 \left\{ \frac{(\bar{\sigma}_3 - \bar{\sigma}_2)(K_1 - K_2)^2}{2[K_1^2(\bar{\sigma}_3 + \bar{\sigma}_2)^3 - (K_1 - K_2)\bar{\sigma}_3^3]} \left[\frac{4K_{IC}^2[K_1^2(\bar{\sigma}_3 + \bar{\sigma}_2)^3 - (K_1 - K_2)^2\bar{\sigma}_3^3]}{\bar{\sigma}_3^3(\bar{\sigma}_3 - \bar{\sigma}_2)^2 K_1^2(K_1 - K_2)} + 1 \right] \right\} \quad (9)$$

$$\text{Case 2} \quad K_3 = K_1 + \frac{(\bar{\sigma}_3 - \bar{\sigma}_2) K_1}{\bar{\sigma}_3} \left\{ \frac{\bar{\sigma}_3 - \bar{\sigma}_2}{2\bar{\sigma}_3} \left[1 - \left(1 - \frac{4\bar{\sigma}_3^3}{\bar{\sigma}_3(\bar{\sigma}_3 + \bar{\sigma}_2)^2} \left(\frac{K_{IC}}{K_1} \right)^2 \right)^{1/2} \right] \right\}^{1/2} \quad (10)$$

$$\text{Case 3} \quad K_3 = K_{IC} \quad (11)$$

After K calculation on «simplified» dependences (9)–(11) it is also necessary to verify on the conditions (1)–(3) and to define the fracture stress intensity factor.

The performed analysis (Chell 1986a) of calculated dependences permitted Chell to suggest the approximated formula for the estimation of fracture stress intensity factor after warm prestressing

$$\Delta K_R = 0.20 \Delta K_U + 0.87 K_{IC} \quad (12)$$

where

$$\Delta K_U = K_1 - K_2, \quad \Delta K_R = K_3 - K_2.$$

The condition of correctness on the formula (12) is:

$$\Delta K_R / \Delta K_U \leq 1. \quad (13)$$

A program was developed for computer calculations.

The initial data for calculations are loading temperatures T_1, T_2, T_3 , material yield strength at these temperatures $\bar{\sigma}_1, \bar{\sigma}_2, \bar{\sigma}_3$ and stress intensity factors for the first two loading stages and material fracture toughness K_{IC} at T_3 temperature.

3 CALCULATION AND EXPERIMENTAL RESULTS AND THEIR DISCUSSION

Investigation results concerning WPS effect on fracture toughness of the types 15X2HMFA and 15X2MFA structural steels (of various strength level) and 15X2MFA welded joint are given together with calculation results with the use of the equations, described above. One of the investigation tasks is also to estimate the influence of before critical crack growth on WPS effect at the stage of preliminary loading. Mechanical properties and fracture toughness characteristics of investigated materials are given in Table, where K_1 the maximum value of stress intensity factor at the moment of crack starting at T_1 temperature (based on the test results of four specimens), fracture toughness characteristics were determined by compact specimens of 50 mm thickness, containing cracks. To realize conditions of plain strain at T_3 temperature, sharp notches were made on 15X2HMFA steel specimens.

The definition of K_1 parameter was performed by acoustic emission registration with AF-11 device in accordance with the procedure, published in (Smirnov 1979). Preliminary loading was carried out on three main schemes LUCF.

Mechanical properties of investigated materials.

Table.

Materials	Strength level	At +20°C				T ₁ °C	K _I ^{min} MPa√m	T ₃ °C	K _{IC} MPa√m
		UTS MPa	YS MPa	A %	Z %				
Base metal 15X2MFA	KP40	540	440	16	66	+25	—	-170	39
						+25	—	-150	42
						+25	—	-50	56
		994	889	14	65	+100	139	+20	81
						+150	139	+20	81
						+300	139	+20	81
	KP100	1199	1063	16	64	+100	127	+20	99
						+150	127	+20	99
						+300	127	+20	99
Base metal 15X2HMFA	KP80	941	816	16	68	+150	140	+20	106
						+300	140	+20	106
Weld metal (wire Cb-10XMFT)	KP60	831	692	15	62	+150	90	+20	74

Test results are given in Fig.1 as relations of K_I/K_{IC} versus K_I/K_I , characterizing the level of preliminary loading, and by $K_I/K_I > 1$ also the level of before-critical crack growth, because K_I was defined with the consideration of revealed crack growth on specimen fracture. Fig.1 indicates, that in the given coordinates practically all test results are in one scatter band. The exception is 15X2MFA (KP80) steel test results. For this steel at $T_3 = 20^\circ\text{C}$ the conditions of correctness of K_{IC} definition were not realized, and as a calculation value the relative value K_Q was taken. Besides, it is well known (Smith 1990), that by fracture under the conditions of plane strained state the positive WPS effect is sufficiently higher, than in conditions of plain strain. The same investigations were also performed in (Troshchenko 1992, Pokrovsky 1993).

It should be noted, that in contrast to the available concepts (Mudry 1985, Carry 1983), before critical crack growth does not reduce positive WPS effect at the stage of preliminary loading. It permits to select correctly T_1 temperature, preliminary loading, which should be higher than the critical T_{K2} temperature, by lower temperature fracture takes place without before-critical crack growth (Karzov 1989). T_{K2} temperature separates the range of brittle fracture from the range of quasi-brittle and tough fracture and can be determined by tests on impact bend of standard Charpy specimens with the division of fracture work on constituents (Smirnov 1992). Besides, test results indicate, that unloading degree practically does not influence on WPS effect for 15X2HMFA and 15X2MFA (KP100) steels. It permits to draw a conclusion about an insignificant residual stress influence on WPS effect in the plastic flow zone near the crack tip for these steels.

Calculated values of stress intensity factors at fracture after preliminary loading on Chell's model solution with equations (4) - (6), simplified formula (9) - (11) and approximate estimation equations (12), (13) are given in Fig.2. The comparison shows, that the best agreement with experimental results is given by calculations on «simplified» formula (Fig.2,b). It is especially evident by LUCF loading cycles. And only by the presence of significant before-critical growth the simplified solutions give lower results.

The consideration of correction on plastic zone permits to increase somewhat the exactness of estimation by the calculation of K_I^p (Fig.2,b). At the same time the correct estimation gives more conservative results even for LUCF (Fig.2,a). The greatest declining to the conservative side are obtained by the calculation on the estimation formula (Fig.2,b). It should be noted that here the correction condition for loading cycles LCF(12) is not realized.

It is recommended to calculate WPS effect on fracture stress intensity factors to perform on the dependences (9) - (11), as they are more convenient for calculations and give results close to experiment values of calculated loading by all types of loading, even by before critical crack incipient growth during preliminary loading.

Fig.1. Fracture toughness K_I/K_{Ic} dependence on preliminary thermal loading K_I/K_i :
 $\diamond, \blacklozenge$ - 15X2MFA steel (YS = 889 MPa), LUCF cycles with total and partial unloading;
 $\square, +, \blacksquare$ - 15X2MFA steel (YS = 1063 MPa), LUCF cycles with total and partial unloading and LCF cycles, respectively;
 $\triangle, \blacktriangle$ - 15X2HMFA steel LUCF and LCF cycles, respectively;
 $\circ, \bullet, \odot$ - weld metal (wire Cb-10XMFT), LUCF cycles (with total and partial unloading) and LCF, respectively.

Fig.2. Comparison of experimental data K_f^3 at fracture after WPS and calculation results on Chell's model K_f^P :
a) on exact formulas (4) - (6);
b) on simplified formulas (9) - (11);
c) on approximate formulas (12), (13)
 $\nabla, \diamond, \square$ - 15X2MFA steel (YS = 440; 880; 1063 MPa), respectively;
 $\triangle, \circ$ - 15X2HMFA steel and weld metal (wire Cb-10XMFT), respectively.
Other index same like on Fig.1.

The estimation formula may be used by LUCF cycles taking into account the conservatism of its results and that it is not necessary to have initial information about the values of yield stress for materials and the absolute level of stress intensity (in formulas only differences K_1 , K_2 , K_3). It permits to estimate WPS effect from useful loading by the presence of residual stresses in structure.

By WPS effect estimation it is necessary to take into consideration the factors which can sharply reduce WPS positive effect, strain hardening and cyclic loading between WPS stage and testing (Chell 1986b).

4 CONCLUSION

The obtained results shows the possibility of Chell's model practical application to predict WPS effect on pressure vessel steel fracture toughness in the wide range of its level up to the significant before-critical crack growth. The better agreement with experimental data is attained with the use of Chell's simplified formulas.

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