The Limit State of Heat Resistant Steel After Combined WPS

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ABSTRACT

The results of combined warm pre-stress (WPS) effect on crack tip opening displacement (CTOD) and critical stress intensity factor (SIF) of 15Kh2MFA heat resistant steel study were presented in paper [1]. The influence of the combined WPS on the critical SIF of 15Kh2MFA steel is governed by two factors, namely, the CTOD and changes in the cleavage stress. The dynamic creep at high temperature (623 K) is initiated at the crack tip that leads to CTOD increasing. On the other hand, an additional cyclic component decreases the cleavage stresses comparing with static loading conditions at the same plastic strain.

The aim of this work was the combined WPS effect on crack growth resistant of 15Kh2MFA steel investigation based on nonlinear fracture mechanics characteristics: critical CTOD and J-integral.

The influence of SIF range ΔK=10.0…30.0MPa√m on the critical CTOD and J-integral under combined WPS was studied by compact-tension 19 mm thickness specimens testing at T_1=150°C and 350°C.

Simultaneous superposition of an additional cyclic component on static tension at T1=350°C leads to the critical Jf of 15Kh2MFA steel increasing (up to 13%) comparing with the critical J-integral after static WPS at the same SIF values K1(Fig.1). Here $K_1=K_1/K_{1c}$, K_1—SIF at pre-stress temperature T_1; K_{1C} — fracture toughness at 20°C.

The J_f dependence on SIF range ΔK can be described by one curve in the case of ductile crack growth absence. In the opposite case we obtained the bigger data scatter. This is conformed by the experimental data at ΔK=20 and 30MPa√m, and WPS ductile crack extensions 0,47mm and 0,63mm accordingly (Fig.1). The critical J_f depends insignificantly on SIF range ΔK=10-30MPa√m, when ductile crack extension does not occur.

On the other hand, an additional cyclic loading at 150°C, that is close to ductile-brittle transition temperature, decreases critical J_f of 15Kh2MFA steel up to 1.5 times comparing with the steady static WPS. This J_f decreasing after combined WPS occurs at the different SIF K_1 =0.6-1.01.

The additional cyclic loading during static overloading at the temperature T_1=623K increases both elastic-plastic δ_{epf} and plastic δ_{plf} critical CTOD. The δ_{epf} and δ_{plf} values were reducing with SIF ΔK increasing after combined WPS at K_1=423K. The same tendency retains at the different SIF under overload K_1.

The J_1 increasing raises the critical SIF K_f regardless of the type of loading and temperature. However, an additional cyclic loading during static overloading at the same J_1 value reduces the critical SIF K_f at T_1=150°C and increases it at 350°C.

The combined WPS at T_1=150°C and the same J-integral J_1 reduce the critical SIF K_f in comparison with steady static WPS. However, the critical SIF increases after combined WPS at the temperature K_1=350°C. A conclusion was made that an additional cyclic loading at higher temperature (350°C), induces a creep at the crack tip and, therefore, the crack tip blunting.

The WPS has the similar effect on the critical SIF K_f versus K_{J1} dependence calculated using J-integral.

INTRODUCTION

The influence of combined warm preloading stress (WPS) on the current and residual crack tip opening displacement (CTOD) as well as resistance quasi-brittle fracture of the heat resistant steel is investigated in papers [1,2]. The main idea of the combined WPS method is the cyclic load adding at the stage of the static tension overloading. It was shown up, that the character of an additional cyclic component influence on the critical stress intensity factor (SIF) of 15Kh2MFA steel depends on a rate of the overloading at the temperature T_1 and on brittle critical temperature.

The main goal of the present work was the investigation of combined WPS influence on reactor steel quasi-brittle fracture, based on the nonlinear fracture mechanics approaches.

The experimental investigations were carried out using 15Kh2MFA steel after the heat treatment simulated the material radiation embrittlement at the end of nuclear reactor operation term. The chemical structure, heat treatment modes, 15Kh2MFA steel mechanical properties characteristics and experimental techniques of combined WPS influence on fracture resistance investigation at unaxial tension of cracked compact specimens, are described in details in papers [1,2]. The deformation diagrams of 19 mm thickness compact specimens in loading - notch faces displacement coordinates were registered during tests. The cracked compact specimen notch faces displacement was interpreted to the displacement along a loading line according to technique [3]. The maximum levels of loading and displacement during combined loading were used for estimation. The diagrams P-v were used for J-integral and stress intensity factor K_J

determination. The elastic plastic deformation work A_c was calculated for J-integral determination. The ratio of work A_c to the specimen net cross-section area value with a correction factor α=2.44 was used for J-integral calculation [4].

$$J = \frac{\alpha \cdot A_c}{t(W-l)} \tag{1}$$

where *l*-length of a crack; t, W - thickness and width of a specimen accordingly. The critical SIF K_{jf} for the plane strain state was calculated using the critical J-integral (after WPS) J_f obtained [5].

$$K_{Jf} = \sqrt{\frac{J_f E}{(1-\nu^2)}} \tag{2}$$

RESULTS AND DISCUSSION

The influence of overloading temperature (T_1=150°C, 350°C), maximum SIF K_1 and SIF range (ΔK=10.0…30.0MPa√m) at overloading on critical J-integral J_f at the temperature 20°C at 19mm thickness compact specimens unaxial tension were investigated (here $\Delta K = K_{max} - K_{min}$, K_{min}, K_{max} - minimum and maximum SIF of a cycle). An additional cyclic loading at tension deformation condition at T_1=150°C increases J_f of 15Kh2MFA steel up to 30% (at ΔK=20.0MPa√m) in comparison with the critical J_f after the static WPS at the same values of relative SIF K_1 (here $K_1 = K_1/K_{1c}$ - SIF and fracture toughness of the material at overloading temperature T_1 accordingly)(fig. 1a). The similar dependences were obtained during the amplitude range SIF ΔK at combined WPS influence on relative J_f value of 15Kh2MFA steel investigation (here $J_f = J_f/J_{fc}$, J_f - critical J-integral at overloading temperature T_1; J_{fc} - J-integral at temperature 293K) (Fig.1b).

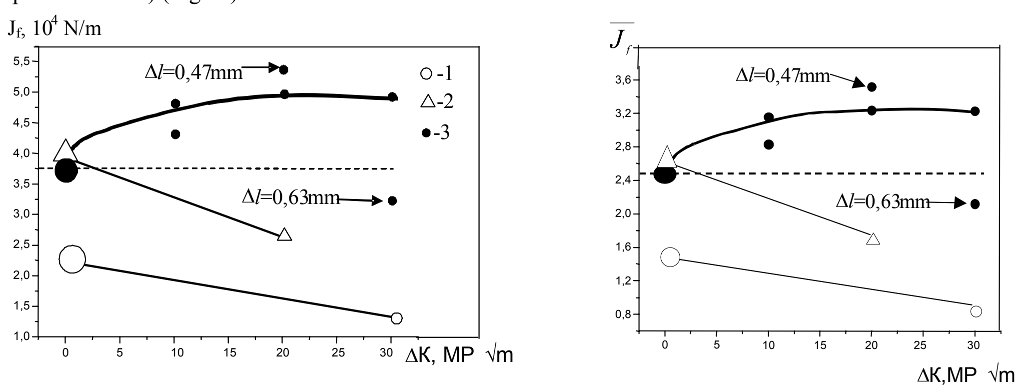

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Fig. 1.Relation of critical J_f-integral (a) and relative $\overline{Jf}$ -integral of steel 15Kh2MFA at T=20˚C from scope ΔK combined WPS. $\overline{K}1$=0,67(1), 0,80… 0,82 (2), 0,82…1,01(3), T1=150˚C (1,2); 350˚C (3). (Large badges - static load).

The critical J_f - integral (J_f - integral) experimental data of 15Kh2MFA steel at different values of SIF range ΔK during overloading at 150°C can be described by one dependence, if ductile crack propagation does not occur. The ductile crack propagation availability (0.47mm and 0.63mm) leads to certain data deviation from the dependence. Moreover, the critical J_f practically does not depend on SIF range ΔK=10.0…30.0MPa√m in the case of ductile propagation crack unavailability. On the contrary, combined WPS at the temperature 150°C which is close to the critical temperature of steel fracture toughness (393K) reduces the critical J-integral value of 15Kh2MFA steel in 1,5 times in comparison with the static WPS. Unlike the static loading, J_f value decreasing after combined loading was obtained for different SIF values K_1=0.67…1.01.

The elastic-plastic critical crack tip opening (CTOD) δ_{epf} and plastic CTOD δ_{plf} in steel 15Kh2MFA dependence on ΔK at both static and combined WPS at the temperature WPS T_1=150°C and 350°C are presented in a fig.2.

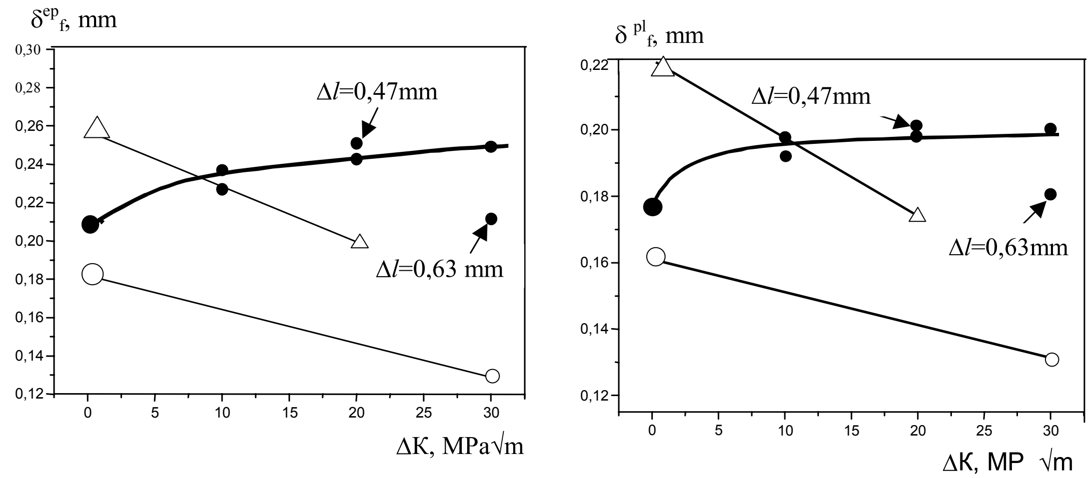

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Fig. 2. Relation of elastic-plastic critical COD δ_{epf} (a) and plastic critical COD δ_{plf}(b) in steel 15Kh2MFA of ΔK at temperature 20˚C (designation to look Fig. 1).

The cyclic component adding on the overloading stage at the temperature T_1=350°C increases the elastic-plastic critical CTOD δ_{epf} and plastic critical CTOD δ_{plf} in comparison with static WPS. CTOD δ_{epf} grows with SIF range increasing from 10.0 to 30.0MPa√m at combined WPS at T_1 = 350°C. However, δ_{plf} remains almost constant. Elastic-plastic δ_{epf} and plastic δ_{plf} at 20°C decrease after combined WPS at the temperature T_1=150°C with ΔK increasing. This dependence was observed for different SIF values at an overloading. The influence of crack tip opening value at the overloading δ_{epf} (T_1=150°C and 350°C) on critical SIF K_f at specimen failure (T_3=20°C) was also investigated. The experimental dependences of critical SIF K_f on elastic-plastic crack tip opening at WPS δ_{epf} at overload temperature T_1=150°C and 350°C as well as the dependence for the temperature 350°C calculated using the equation [6] are presented in a fig.3

$$K_f = \sqrt{\frac{\delta_1 \cdot \sigma_{0,2} \cdot E}{0{,}6 \cdot Y}}$$

Where

$$Y = \left(\frac{\frac{2}{\sqrt{3}} \cdot (1+\nu)(1-n) \cdot \sigma_{0,2}}{n \cdot E} \right)^n \tag{3}$$

For 15Kh2MFA steel at the temperature 20°C the yield stress is $\sigma_{0.2}$=1100MPa√m; the deformation strengthening parameter of deformation diagram n=0,1; E=2.10^{5}MPa; ν=0,3.

The critical SIF of 15Kh2MFA steel increasing with increase of elastic-plastic crack open tip at WPS is observed for all temperature - load WPS modes investigated.

The adding of a cyclic component (ΔK=20, 30MPa√m) at WPS displaces K_f - δ^{ep}_1 dependences downward for T_1=150°C, and upward for T_1=350°C comparing the data for static WPS. It means that the critical SIF after combined WPS K_f is higher for T_1=350°C and lower for T_1=150°C at the same δ^{ep}_1 values at overload stage. This opposite character of combined WPS influence at different temperatures of overload could be explained by more considerable deformation strengthening of a material as well as larger residual stress at combined WPS for T_1=350°C compared with static WPS.

Vice versa, an additional cyclic loading at the temperature T_1=150°C leads to the material softening at the crack tip vicinity and, as a result, reduces brittle strength and critical SIF K_f compared with static WPS. It is confirmed by results of the temperature of combined deformation influence on a cleavage stress of 15Kh2MFA steel investigations [7].

The calculations made using equation (3) gives a little bit lower critical SIF after combined WPS value for T_1=350°C compared with the experimental data at the same temperature. Fig. 4 presents the dependence of critical SIF K_f on the value of residual crack tip opening δ_{res} after static and combined WPS at overload temperatures T_1=150°C and 350°C.

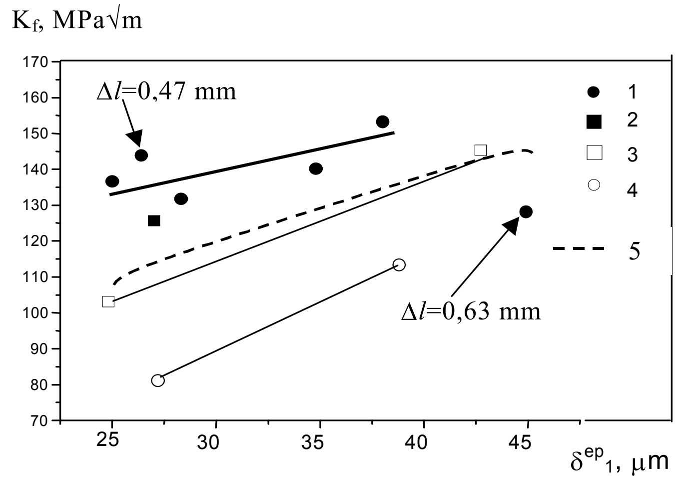

Fig. 3. Relation of critical SIF K_f steel 15Kh2MFA at temperature 20˚C from size crack-opening displacement at static (2,3) and combined WPS (1,4) at temperature T_1=350˚C (1,2) and 150˚C (3,4) (1-4 — experiment, 5 — calculations in formula (3) at T_1=350˚C and combined WPS) [6].

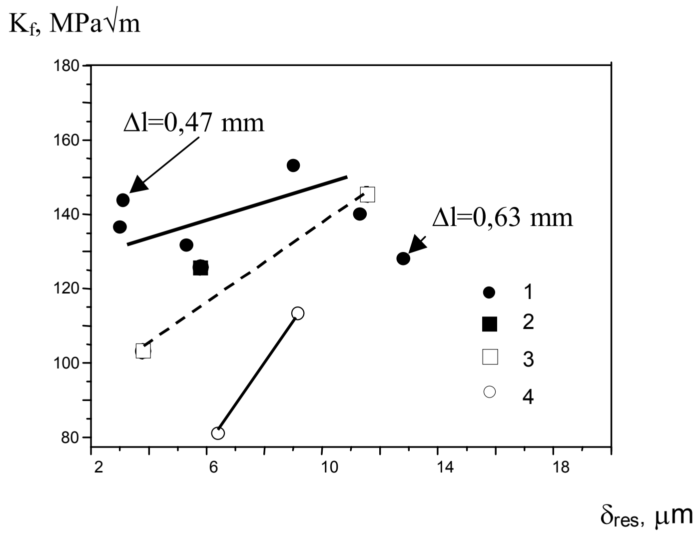

Fig. 4. Relation of critical SIF K_f steel 15Kh2MFA at 20˚C from crack tip opening displacement residual δres after static (2, 3) and combined WPS (1, 4) at temperature T_1=350˚C (1, 2) and 150˚C (3, 4).

Generally, the critical SIF K_f of 15Kh2MFA steel increases with the residual crack open tip after an overload increasing independently of the WPS temperature T_1 and the type of an overload (static or combined). It is necessary to note, that more essential K_f increasing is observed at the WPS temperature T_1=150°C. The additional cyclic component during the overloading at T_1=150°C essentially reduces, and at K_1=350°C increases the critical SIF K_f in comparison with the static WPS at the same level of elastic-plastic crack tip opening. The dependences of critical SIF K_f on the J-integral value J_1 for WPS at temperature T_1=150°C and 350°C are given in fig. 5. It is shown that J_1 increasing leads to the critical SIF K_f increasing independently on a type and temperature of WPS. The combined WPS at the temperature T_1=150°C, at the same J-integral J_1, leads to critical SIF K_f reduction in comparison with static WPS, and, on the contrary, at T_1=350°C leads to the certain increasing. Probably, it could be explained by the following: the additional cyclic component at the high temperature (350°C) promotes the creep process initiation at the crack tip vicinity, and, consequently, increases crack tip blunting.

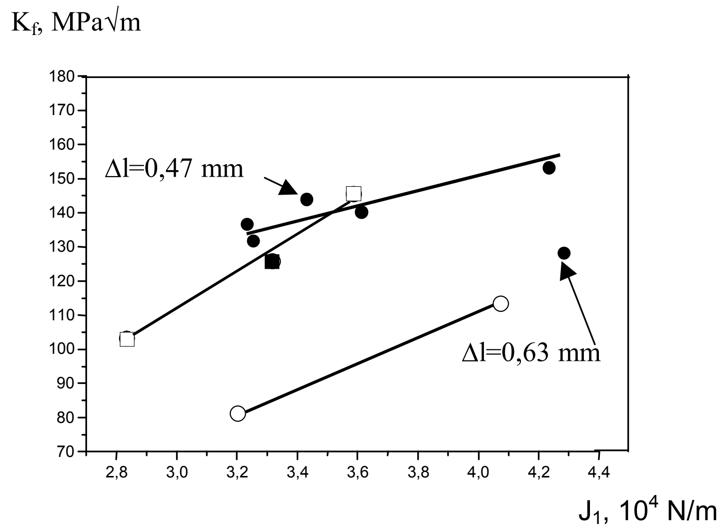

Fig. 5. Relation of critical SIF K_f from size J-integral J_1 in an interval overloading (designation to look Fig. 4).

The combined WPS influence on the dependence of critical SIF K_f on SIF K_{J1}, determined via J-integral using the equation (2) for plane deformation conditions is the same (fig. 6).

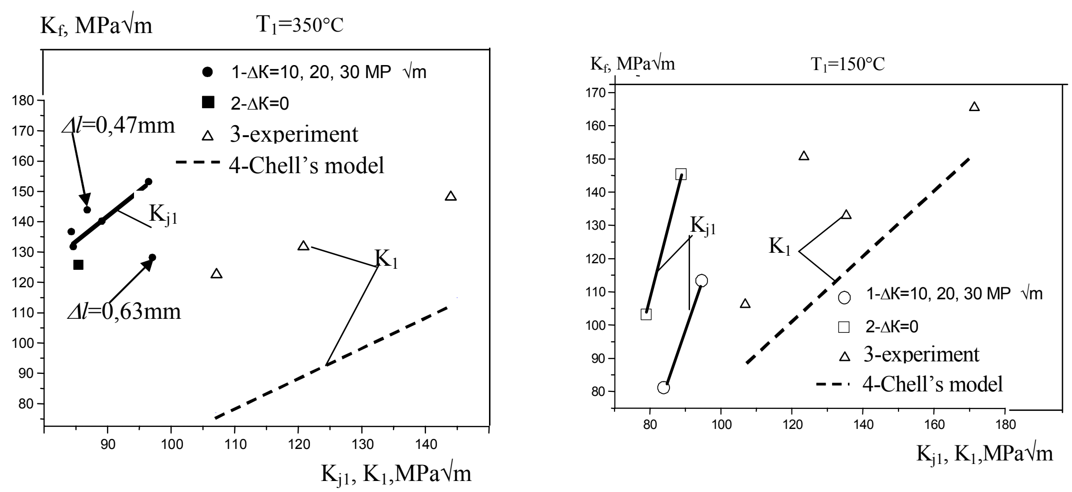

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Fig. 6. Relation of critical SIF K_f steel 15Kh2MFA at 20˚C from SIF K_{J1} and K_1 at static (2) and combined WPS (1), at temperatures overloading T_1=350˚C -(a) and 150˚C -(b); 3 – experiment, 4 – calculation by Chell's model at static loading [8, 9].

The critical SIF K_f dependence on critical elastic-plastic δ_{epf} and plastic δ_{plf} of 15Kh2MFA steel at the temperatures WPS T_1=150°C and 350°C is presented in a fig. 7. All experimental data of the critical elastic-plastic crack tip opening displacement are in the same scatter band and can be described by one dependence for both WPS temperatures and modes (fig. 7, a).

The K_f difference at the different test conditions (temperature and loading mode) is a little bit larger for the critical SIF K_f dependence on plastic δ_{epf} experimental data.

The calculated curve (5) obtained by the following equation (4) [10] is shown in fig.7 for comparison with experimental data.

$$\delta = \beta \frac{\left(1-\nu^2\right)K_1^2}{E\sigma_{0,2}} \qquad (4)$$

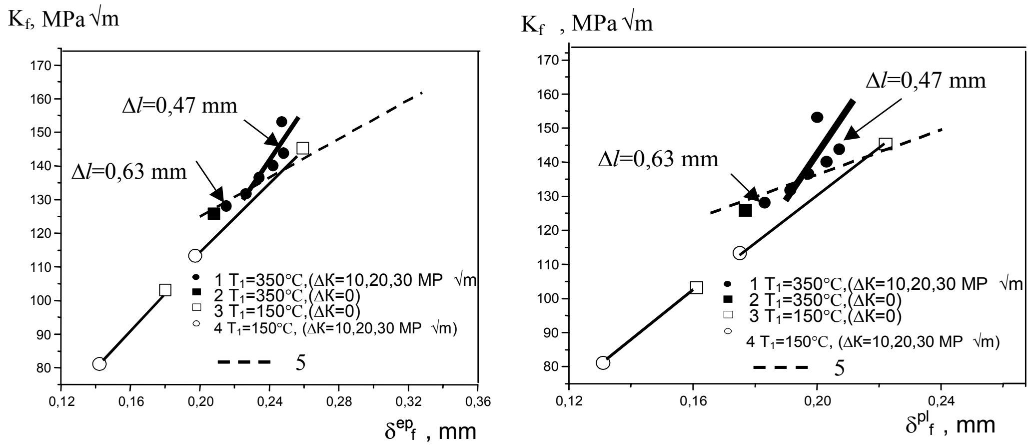

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Fig. 7. Relation of critical SIF K_f of elastic-plastic δ_{epf}-(a) and plastic δ_{plf}-(b) critical crack-opening displacement in steel 15Kh2MFA at temperature WPS T_1=150˚C and 350˚C ; 5 — calculations in formula (4).

The best correspondence between the calculated curve (4) and experimental results was obtained for K_f dependence on the critical elastic-plastic crack tip opening δ_{epf} using factor β=3.0 and for K_f dependence on the critical plastic crack tip opening δ_{plf} using factor β=2.57.

Generally, the critical SIF K_f of 15Kh2MFA steel increases with critical elastic-plastic crack tip opening δ_{epf} as well as critical plastic crack tip opening δ_{plf} increasing.

CONCLUSION

1. An additional cyclic loading during the static tension at overload stage essentially influences a boundary state of cracked bodies. The character of its influence on critical SIF of 15Kh2MFA steel depends on the temperature of the previous loading to critical brittleness temperature ratio.
2. The combined WPS reduces the critical value of J-integral of 15Kh2MFA steel up to 1,5 times in comparison with static WPS at the temperature of the previous loading 150°C, which is close to the material critical brittleness temperature (T_K=393K). The J_f decreasing after the combined overload, comparing with static one, is observed for different K_1=0.67…1.01.
3. The combined WPS at the temperature 350°C which is essentially higher then the critical brittleness temperature of 15Kh2MFA steel increases the critical J-integral J_f value up to 30% as well as the critical elastic-plastic crack tip opening δ_{epf} up to 14% in comparison with the static WPS.
4. All experimental data of the critical elastic-plastic crack tip opening displacement are in the same scatter band and can be described by one dependence regardless of WPS temperatures (150˚C, 350˚C) and modes (combined, static)

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