Experimental Research of Warm Pre-Stressing Effect

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ABSTRACT
To research toughening of materials is a noticeable subject. Warm pre–stressing (WPS) discussed in this article is one method of toughening and it is concluded that WPS–effect can prevent crack propagation in PWR pressure vessels during a loss of coolant accident (LOCA).

The experiment of simulating WPS process during LOCA was completed in this article to research WPS–effect and its influence factors.

1 INTRODUCTION

Increasing fracture resistance of a structure is important. The present research shows that the mechanism of toughening of materials is different according to the difference of material properties and external conditions.

There are three major aspects in the research of the fracture resistance rise: establishment of its simplified model, experimental research of its effect, theoretic calculation.

The research of WPS–effect is being paid more and more attention because of its importance to nuclear reactor safety.

2 BACKGROUND

Accidents of nuclear reactor happened ever and again in past several ten years. LOCA is one major kind of them.

The pressure vessel is in a state of high temperature (about several hundred degrees, and there is some temperature difference among different reactors) when the nuclear reactor is in a normal state. Cold water is poured into the vessel (about thirty degrees) during LOCA. So there is a great difference of temperature between the inside and outside surface of the vessel, and a great thermal stress between them. The smaller

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the temperature difference as time goes on, the smaller the thermal stress afterwards.

The above–mentioned process was simplified into three stages for convenience:

1) The load was applied at working temperature which was higher than transformation temperature T_t of the material used to make the vessel. A large plastic zone is formed at the tip of a crack by the load.

2) The temperature was lowered and the load was decreased. Both processes could be carried out simultaneously or separately. The load could be removed completely or not.

3) The load was increased until break occured at a lower temperature than T_t. Fig.1 showed a typical process of WPS. (Fig.1)

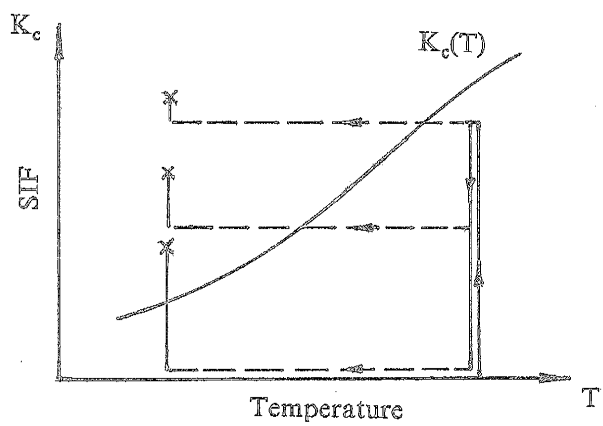

Fig.1 A typical process of WPS
"×" stands for a break point.

It is known that fracture toughness K_c of a material drops as temperature drops, and there is so–called T_t. At this temperature a little variation of temperature will lead to a great variation of K_c value. It is also known that in the vessel there is great thermal stress and low temperature which means low value of K_c at the beginning of LOCA. So K value of crack tip is probably bigger than K_c value at the same temperature. If it resulted in crack propagation, the consequence would be disastrous.

A large number of experiments proved that the crack never extended even though the K of the crack tip exceeded the K_c at the same low temperature during LOCA, and it had nothing to do with unloading process. This is called WPS–effect.

3 EXPERIMENTAL INVESTIGATION

The material used in our experimental research is 18MnNiMoNb which was used to make pressure vessels of Qinshan nuclear reactor in China. Three–point–bend specimen was prepared with this material. Chemical compositions of the material were listed in Tab.1.

Table 1. Chemical compositions of the material (%)

material	C	Si	Mn	Ni	Mo	S	P	Nb
18MnNiMoNb	0.2	0.33	1.45	0.8	0.55	0.025	0.02	0.04

The material was normalized at 930℃ for four hours firstly, water quenched after being heated at 880℃ for two hours secondly, and tempered at 640℃ finally. Mechanical properties of the material were listed in Tab.2

Table 2. Mechanical properties of the material

material	$\sigma_{0.2}(kg/mm^2)$	$\sigma_b(kg/mm^2)$	α	n	$E(kg/mm^2)$
18MnNiMoNb	47.6	61.9	8.46	6.52	2.06×10^4

The size of the specimen was listed in Tab.3.

Table 3. Size of speciments unit: mm

test	1	2	3	4	5	6	7	8	9	10	11	12
W	15.06	15.053	15.06	15.06	15.06	15.06	15.06	15.063	15.07	15.067	15.07	15.06
B	7.53	7.517	7.527	7.52	7.513	7.533	7.527	7.513	7.52	7.51	7.513	7.52

The specimens underwent a fatigue process, and fatigue cracks occured. The frequency of fatigue loading was about 100Hz. Test machine was Amsler high frequency fatigue test machine of electromagnetic resonance type. Other experimental conditions were listed in Tab.4.

$K_c$values were measured at different temperature without WPS process, and listed in Tab.5. $K_c\sim T$ curve was lined in Fig.2.

$T_t$was about−86℃ which was also obtained from the curve or experimental data.

Table 4. Fatigue load and cycles

test	1	2	3	4	5	6	7	8	9	10	11	12
P_{ave}(kg)	600	190	180	180	170	180	230	170	250	200	300	170
P_{min}(kg)	200	40	20	20	20	20	40	20	40	20	80	20
P_{max}(kg)	1000	360	340	380	360	360	400	340	500	420	540	380
N_{fati} (Ten thousand)	0.6	2.2	4.7	6.6	5.1	5.3	4.4	7.1	3.1	2.9	1.0	4.7

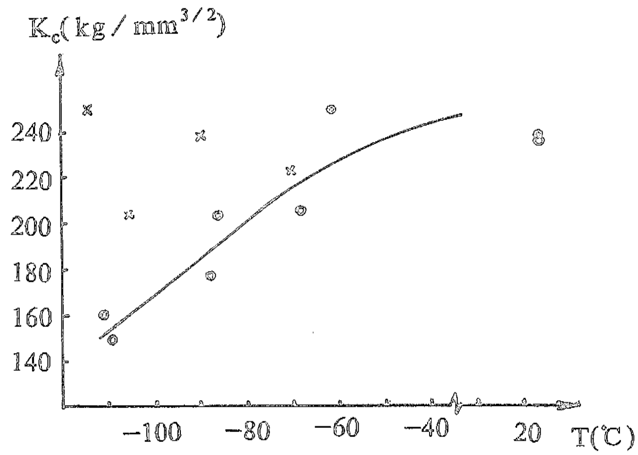

Fig.2 "×" stands for a break point
"o" stands for a point on K_c−T curve

Other specimens except those listed in Tab.5 were loaded at room temperature. The load was about 0.7~ 0.8 times P_f at 24℃ (P_f: failure load at correspanding temperature). A large plastic zone appeared at crack−tip, but the crack didn't extend. Then the load was removed. The load was applied again leading to failure in lower temperature. Shimadzu Autograph DDS−25T test machine was used in failure experiment.

In the experiment, mixed liquid composed of alcohol and liquid nitrogen made a low temperature environment. To maintain temperature constantly, liquid nitrogen was mixed continuously during experiment. Specimens were put into mixed liquid. Experimental apparatus were shown as Fig.3.

Table 5. $K_c(T)$ value S = 60mm

test	3	5	11	6	10	7	4	8
P_f(kg)	700	700	693.3	620	593.3	466.7	413.3	473.3
a(mm)	7.13	7.153	7.45	7.043	7.043	7.77	7.493	7.15
T(℃)	24	24	−60.9	−68.5	−68.5	−87.5	−109.5	−111
K_c(kg / mm$^{3/2}$)	234.7	236.1	247.7	203.9	203.9	176.3	148.7	159.5

Fig.3 Exprimental apparatus

Failure values K_f (T) were measured with the specimens that had been pre–loaded, and listed in Tab.6. In the table 6,

Table 6. $K_f(T)$ values after WPS–process S = 60mm

test	P_f(kg)	△P	a(mm)	T_f(℃)	K_f(kg / mm$^{3/2}$)	△K
2	655.3	90	7.24	−70	225	11
9	606.7	87	7.92	−91.4	239.9	37
12	593.3	85	7.287	−105	205.3	28
1	820	≈100	6.7	−114	251.7	62

$$\triangle P = \frac{P_p}{P_f}\Big|_{T=24℃} \times 100\% \qquad (1)$$

$$\triangle K = \frac{K_f - K_c}{K_c}\Big|_{T=T_f} \times 100\% \tag{2}$$

P_p was the pre–load, P_f was the failure load. T_f was the temperature at failure.

4 CONCLUSIONS AND DISCUSSION

It is proved by experiments WPS–effect is existent and marked in certain environment.

On the basis of the above experiment, the main factors influenced WPS–effect are $\triangle P$ and $\triangle K_c$ ($\triangle K_c = K_c|_{T=T_1} - K_c|_{T=T_f}$, T_1 is the pre–loading temperature.) The larger $\triangle P$ or $\triangle K_c$ is, the larger WPS–effect is.

The popular viewpoint of WPS–effect is that: the plastic zone of crack tip formed at higher temperature transformed into reverse pressure zone. It resulted in variation of stress distribution at crack tip and the toughening of materials.

WPS can improve the apparent fracture resistance of a pressure vessel, and crack growth during LOCA isn't dangeous.

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