INFLUENCE OF SUPERIMPOSED FATIGUE LOADS ON THE EFFECT OF WARM PRE-STRESSING

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ABSTRACT

The beneficial effect of warm pre-stressing (WPS) on apparent fracture toughness at low temperature is well established. Tests are usually performed with constant load during the cooling part of the load cycle. In practice load variations may occur during this part. In the present paper the effect of superimposed fatigue loading is studied experimentally. It is found that crack propagation can reduce the WPS effect considerably, and that if crack propagation occurs during cooling, the maximum load during the fatigue load cycle is the preload to be used for WPS considerations.

KEYWORDS

warm pre-stress, preload, fatigue, cleavage fracture.

PROCEDURE

The material used for the investigation was A 533B with mechanical properties according to Table 1 and chemical analysis according to Table 2. The test specimens were standard CT type with W = 60 mm and thickness 28 mm, taken from a 150 mm thick plate in the T-S direction.

TABLE 1. Mechanical properties.

Temp. ^0K	Yield stress MPa	Rupture stress MPa	Elongation %
300	510	650	16
123	870	880	11

TABLE 2. Chemical properties.

C	Si	Mn	P	S	Ni	Cr	Mo
.20	.27	.92	.009	.003	.84	.44	.59

The test temperatures chosen were room temperature, 300 ^{0}K (27 ^{0}C), for the pre-loading and 123 ^{0}K (-150 ^{0}K) for the final loading. After fatigue pre-cracking at room temperature, a thermocouple was welded to the test specimen close to the crack, and a clip-gauge was mounted in order to monitor preload load line displacement.

Preloading was done to two different levels, one just above the low temperature fracture toughness and one approximately twice as high. For the high pre-load level the load-displacement record was non-linear. For the low pre-load level it was linear, and only the load was recorded.

After preloading the clip-gauge was removed and an insulated cylindrical container was mounted around the test specimen. The test specimen was cooled by liquid nitrogen poured into the container. The rate of cooling was approximately 180 ^{0}C per hour. The test specimen was shielded so that liquid nitrogen was not poured directly onto it, in order to avoid large thermal stresses.

During cooling a fatigue load was applied, and the maximum load P_u and the load range ΔP were prescribed, Fig. 1. The frequency of the of the fatigue load was 1 Hz in all tests except test no B74, where it was 4 Hz. During the fatigue loading no displacements were recorded, and no attempt was made to record crack growth. In some tests the specimen fractured during cooling. In other tests the lower temperature was reached without fracture. In that case the load was increased up to failure, and the failure load was recorded.

Stress intensity factors are determined from the relation

$$K = \frac{P}{t\,W^{1/2}} f(a/W) \qquad (1)$$

and the J-integral from the relation

$$J = \frac{A}{t\,(W - a_0)} g(a_0/W) \qquad (2)$$

where P = load
t = specimen thickness
W = characteristic dimension of CT-specimen
a_0 = initial crack length
A = area under load-displacement curve
$f(a/W)$ = function according to ASTM E-399
$g(a_0/W)$ = function according to ASTM E-813

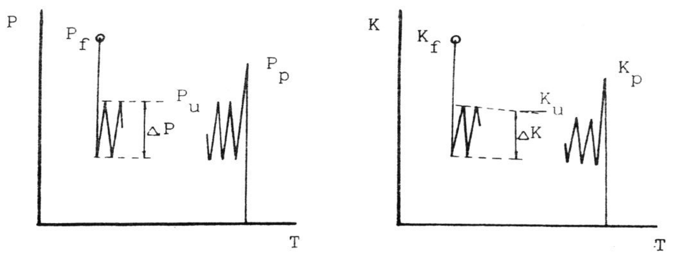

Fig. 1. Load variation during cooling.

For the low preload tests where the load-displacement curve was linear, the J-integral was determined from the relation

$$J = K^2/E \qquad (3)$$

The same relation was used to evaluate the J-integral at failure.

Due to fatigue crack growth during cooling, the crack length a varied with time, Fig. 1. The quantities K_u and ΔK were evaluated using the the mean crack length during cooling.

The limit load for the CT-specimen was determined from the expression

$$P_L = \frac{t\,b^2\,\sigma_0}{2\,W + a} \qquad (4)$$

For linear conditions to prevail, the linear dimensions of the test specimen must satisfy the requirements of ASTM E-399. With t known to be the smallest of the relevant geometrical quantities, the highest stress intensity factor for linear conditions is

$$K_{lin} = \sigma_y \sqrt{t/2.5} \qquad (5)$$

RESULTS

The fracture toughness at 123 ^{0}K determined from two tests was 55 ± 9 MPa√m. The result compares favourably with the values given by Nakamura and coworkers (1981) for the same material, Fig. 2, and also with results reported by Kotilainen (1980). The tensile properties of the present material also agrees well with the data reported by Nakamura and coworkers (1981). The maximum stress intensity factor for which linear conditions prevail are indicated in Fig. 2. The low preloads are just above the linear region.

One set of reference WPS-tests was performed without superimposed fatigue loads. The results are given in Table 3 and Fig. 3. The loading cycles were CF, LCF and LUCF, and the preloads were chosen to cover the entire range from no preload up to the limit load at preload temperature.

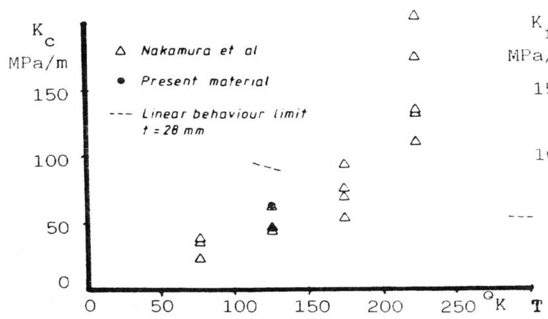

Fig. 2. Fracture toughness.

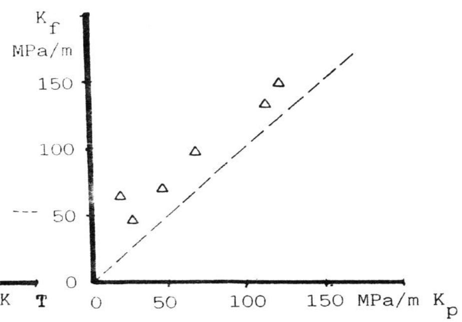

Fig. 3. WPS reference tests.

TABLE 3. WPS Reference Tests.

Spec	P_p kN	K_p MPa√m	J_p kN/m	P_f kN	K_f MPa√m	a_0 mm	Type
A78	16	20	(2)a	52	64	27.4	CF
B73	20	28	(4)a	32	46	30.2	CF
B72	32	48	(11)a	47	70	31.0	CF
B71	52	70	(25)a	72	97	29.3	LUCF
B76	90	(115)b	NR	104	132	28.0	LUCF
B75	97	(124)b	136	116	148	28.0c	LCF
(A74	88	(142)b	832	-	-	33.5d	L)

a/ J_p calculated from eq. (3).
b/ Nonlinear behaviour. K_p calculated from eq. (1).
c/ Stable crack growth during preloading, mean growth over specimen width 0.7 mm.
d/ Specimen failed due to stable crack growth. Preload equals limit load.

The results of the tests performed with superimposed fatigue loads are given in Table 4 and Fig. 4. Test types are indicated for instance LU_pC_fF where L = loading, U_p = unloading, partial, C_f = cooling, fatigue load, F = load increased up to failure.

Consider first only the points in Fig. 4a. with P_u/P_p = 1. They were obtained for different values of ΔP, in some of the tests the crack growth Δa under fatigue loading was considerable, and in some cases the specimen fractured before the final low temperature was reached. In spite of these differences the trend of data points is uniform. This indicates that that the WPS effect is not a direct function of of the load variation ΔP. The trend also coincides with that of the reference tests, cf. Fig. 3 and Fig. 4a. This indicates that the WPS effect does not depend on whether the crack is a fatigue crack or a "static" crack, only the crack length is important.

For the tests where fracture occurred before the low temperature was reached the fracture toughness at the fracture temperature is unknown. Assuming that the mechanical properties of the present material are similar to those

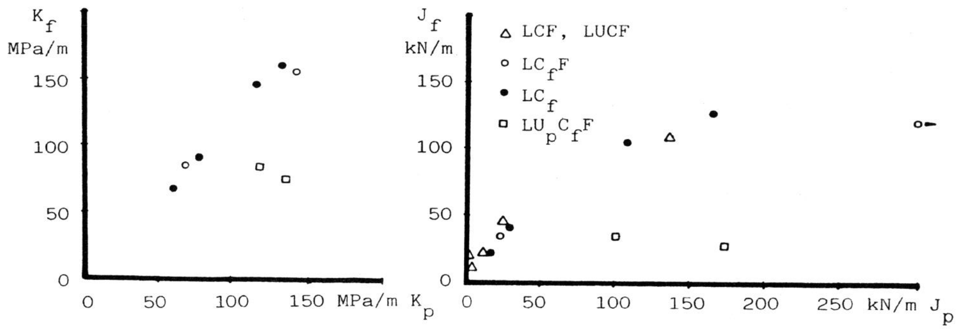

Fig. 4. Apparent fracture toughness versus preload.

TABLE 4. WPS plus Fatigue Tests.

Spec	P_p kN	K_p MPa√m	J_p kN/m	$P_u/\Delta P$ kN	$K_u/\Delta K$ MPa√m	N cycl	Δa mm	P_f kN	K_f MPa√m	a_o mm	T_f °K	Type
A76	35	60	(18)a	35/28	65/50	4120r	2.0	35	68	34.0	137	LC_f
B77	60	69	(24)a	60/13	69/15	3000	0	74	85	25.7	123	LC_fF
B78	58	78	(30)a	58/42	84/60	4120r	3.0	58	91	29.1	154	LC_f
A73	90	(119)b	109	90/50	132/73	2880r	3.7	90	146	28.9	143	LC_f
B74	90	(143)b	398	90/15	143/24	15970	0	98	156	32.3	123	LC_fF
A75	105	(134)b	166	105/45	146/63	4780r	3.5	105	160	28.0	157	LC_f
A77	86	(120)b	103	40/37	57/53	6180	0.7	58	85	29.9	123	LU_pC_fF
B79	102	(138)b	174	46/40	63/55	2016	0.5	73	77	29.3	123	LU_pC_fF

a/ J_p calculated from eq.(3).
b/ Nonlinear behaviour. K_p calculated from eq. (1).
r/ Failure during cooling.

reported by Nakamura and coworkers (1981), it can be estimated from Fig. 2 that the fracture toughness at the temperature of fracture is almost the same as that at the low temperature 123 °K. As the scatter in fracture toughness is considerable, no attempt has been made to take into account the difference in fracture toughness at fracture for the different tests.

Consider then the tests with $P_u/P_p \approx 0.5$. They had a high level P_p and a low level P_u, and the crack growth was > 0.5 mm. The stress intensity at fracture for this case is seen to be close to the values associated with the low level P_u and not with the high level P_p. This indicates that the maximum load during fatigue loading rather than the preload determines the WPS effect, when crack growth occurs during cooling.

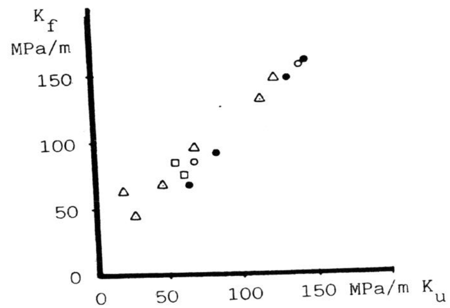

Fig. 5. Apparent fracture toughness versus K_u.

In Fig. 5 K_f is plotted as a function of K_u. All the test results follow the same trend, in spite of different load variation during cooling, crack growth and preload stress intensity. It is concluded that the maximum stress intensity K_u during crack growth is the most important parameter when the WPS effect is concerned.

DISCUSSION

The tests indicate that crack growth during the cooling portion of a WPS load cycle may reduce the beneficial preload effect considerably. Obviously this reduction comes gradually with increasing crack growth. Additional experimental work is reqired to study the WPS reduction as a function of crack growth or number of applied load cycles.

In Fig. 4b J_f is plotted versus J_p, and it is seen that for high preloads, $J_p > 80$ kN/m, the J-integral at fracture reasches a saturation level. This was also reported by Nakamura and coworkers (1981) for $J_p > 50$ kN/m, and they noticed that the preload required to reach the saturation level was the same for all WPS loading cycles tested. The observation that a saturation level exists is interesting, but the reason for this is not clear.

One possible explanation is that the small test specimen approach the limit load at preloading. For the present test series the limit load for a/W = 0.5 is 97 KN, which corresponds to J = 93 kN/m from eqs. (1) and (3). For the test series reported by Nakamura and coworkers the corresponding value is 35 kN/m. Following the assumption by Beremin (1981) that cleavage fracture occurs when plastic deformation sets in at the low temperature, the load at fracture for the LCF load cycle will be close to the preload. The observed saturation levels of 110 kN/m and 35 kN/m agree well with the limit loads. It is however not as easy to explain why all the other load cycles reported by Nakamura and coworkers show a tendency to reach a limiting value of J_f at the same preload.

Another possible explanation of the observed saturation behaviour is that the process zone reaches the critical length according to the Ritchie-Knott-Rice model for cleavage fracture. If the preload corresponding to saturation of J_f is denoted J_s, then this preload corresponds to a crack tip opening displacement of approximately

$$b_s = J_s / \sigma_o \qquad (6)$$

which for the present material is 0.080/580 = 138 μm, and for the material tested by Nakamura and coworkers is 0.050/550 = 91 μm. Ahead of the blunted crack tip there is a process zone with large strains, and with voids and holes opening up. This process zone extends approximately one crack opening displacement ahead of the crack (McMeeking, 1977). According to the model of Ritchie, Knott, Rice (1973), cleavage fracture occurrs when a critical stress σ_c is reached over a distance X_c ahead of the crack, see also Beremin (1981), Curry (1981). The critical distance X_c has been reported to be between 50 μm and 120 μm for different materials.

If the material is lightly preloaded, then the process zone b_s is smaller than the critical distance X_c, and the material within the critical distance is essentially virgin. If the material is heavily preloaded, then the process zone is larger than the critical distance, and the material within the the critical distance has had its properties changed. It is suggested as a hypothesis that the pre-load effect reaches a saturation value when the preload process zone size reaches the critical distance associated with cleavage fracture.

As a consequence of this hypothesis it may be expected that the effect of a preload is wiped out when a fatigue crack has propagated through the preload process zone. The new effective preload is then the maximum load under which the crack was propagated.

CONCLUSIONS

When load variations were imposed during the cooling part of a WPS load cycle, the following observations were made.

1. If the crack propagates due to the fatigue loading, then the maximum load during the fatigue load cycle is the preload to be used for WPS considerations.

2. The WPS effect seems independent of the load variation range of the fatigue loading.

3. The final crack length is to be used in the WPS consideration. The tests indicate that the WPS effect is independent of whether the final crack length was reached by fatigue crack growth or by static crack growth due to preload at high temperture.

4. For increasing preloads the apparent fracture toughness approaches an upper limit. A hypothesis is proposed, stating that the preload saturation value is the one which makes the process zone ahead of the crack equal to the critical distance associated with cleavage fracture in the Ritchie, Knott, Rice model.

5. It is proposed that the WPS effect is wiped out when the fatigue crack has grown through the the preload process zone. This proposal is not verified by direct experiments.

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