HOLD TIME EFFECTS ON HIGH TEMPERATURE CRACK GROWTH RATE IN CREEP, FATIGUE AND CREEP-FATIGUE INTERACTION IN STAINLESS STEEL

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INTRODUCTION

Based on analysis of experimental data obtained by continuous observations using high temperature microscope during the creep test without interruption in vacuum[1,2] a parametric equation of high temperature creep crack growth rate was given[3] in terms of $\alpha\sqrt{a_{eff}}\sigma_g$, σ_g and temperature for 304 stainless steel. It is thermal activation type. In the present article, high temperature crack growth rate at creep-fatigue interactions and fatigue are studied on line of this consideration, and, thus, the comparison has been made between them with special reference to hold time effects. From these results we suggest that so-called frequency effect on these behaviours consists of the loading rate and the hold time effect. In fatigue the loading rate is effective, and, on the other hand, with increase of hold time the hold time becomes more predominant. The procedure in obtaining the proposed equation is also described, as it was excluded in our previous related papers[1-4].

EXPERIMENTAL DATA FOR THE ANALYSIS

The chemical composition and the mechanical properties at room temperature of 304 stainless steel used are shown in Tables 1 and 2, respectively[1]. Double edge notched specimen was used[1] as shown in Fig. 1. Tests were carried out in vacuum of 10^{-5} mmHg. Crack length was measured continuously during running the tests without stopping. The load waves were controlled as shown in Fig. 2(a)–(c) for fatigue, creep and creep-fatigue interaction tests respectively[1]. The mininum stress σ_{min} was zero and the gross section stress σ_g corresponding to the maximum value of tensile stress σ_{max} was 18.1, 19.5 and 20.9kg/mm² and test temperature was 600,650 and 700°C, respectively[1].

Table 1. Chemical Composition (wt%)

C	Si	Mn	P	S	Cr	Ni
0.094	0.56	1.28	0.027	0.013	18.0	8.81

Table 2. Mechanical properties (room temperature)

Yield stress (kg/mm²)	Ultimate tensile strength (kg/mm²)	Elongation (%)
33.6	66.3	47

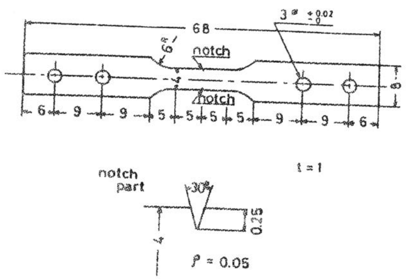

Fig. 1 Specimen shape and dimension (in mm)[1]

ANALYSIS

For the case of large scale yielding, the local plastic stress distribution near the notch or crack is characterized[5] by fracture mechanics parameter of $\beta K f(\sigma_g)$, where K=stress intensity factor $\alpha\sqrt{a}\sigma_g$, σ_g=gross section stress, a=notch or crack length, α=non-dimensional constant $f(\sigma_g)$ is increasing function of σ_g, and β is non-dimensional factor dependent of

specimen shape. Thus we believe $\sqrt{a}\sigma_g$ can be taken as one of fracture mechanics parameters involved in this case. In the present article, we used $K_{In}\equiv\alpha\sqrt{a_{eff}}\sigma_g$ taking into account of the effect of the initial notch shape, where a_{eff}=effective crack length. Using FEM[6], K_{In} is obtained by[2]

$$K_{In}/K_{IA} = 1 - 0.4\exp\{-47.3a^*/(W-a_0)\} \tag{1}$$

where K_{IA} is stress intensity factor for the plate specimen with crack on both sides and is given by[7]

$$K_{IA} = \alpha\sqrt{a}\sigma_g, \qquad a \leqq 0.7W \tag{2}$$

$$\alpha = 1.98 + 0.36(a/W) - 2.12(a/W)^2 + 3.42(a/W)^3$$

a_0=notch length; a^* = actual crack length; a=equivalent crack length = $a_0 + a^*$ and W = half width of the specimen. That is, the effective stress intensity factor K_{In} is given by[2]:

$$K_{In} = \alpha\sqrt{a_{eff}}\sigma_g \tag{3}$$

where

$$a_{eff} = a[1 - 0.4\exp\{-47.3a^*/(W-a_0)\}]^2 \tag{3a}$$

THE RELATION OF da/dt TO σ_g AND $K_{In}(\equiv\alpha\sqrt{a_{eff}}\sigma_g)$ AT SPECIFIED TEMPERATURE T

In presentation of $\log_{10}(da/dt)$ vs $\log_{10}(\alpha\sqrt{a_{eff}}\sigma_g)$ ($\equiv\log_{10}K_{In}$) with σ_g as parameter at each specified temperature, it was found that region II shows linear relationship between $\log_{10}(da/dt)$ vs $\log_{10}(\alpha\sqrt{a_{eff}}\sigma_g)$ (Fig. 4). In Fig. 5(a)–(d) an example for specific value of temperature = 650°C is shown. From these presentations at each specified temperature, the following relation is obtained:

for creep

$$\frac{da}{dt} = 8.55\times10^{-22}\,\sigma_g^{5.64}K_{In}^{9.20} \tag{4}$$

for creep-fatigue interaction (t_h=10min)

$$\frac{da}{dt} = 1.23 \times 10^{-20} \sigma_g^{4.89} K_{In}^{8.97} \tag{5}$$

for creep-fatigue interaction (t_h=1 min)

$$\frac{da}{dt} = 2.35 \times 10^{-21} \sigma_g^{5.57} K_{In}^{8.80} \tag{6}$$

and for fatigue

$$\frac{da}{dt} = 1.26 \times 10^{-8} K_{In}^{4.66} \tag{7}$$

THE RELATION OF da/dt TO $K_{In}(\equiv\alpha\sqrt{a_{eff}}\sigma_g)$ AND TEMPERATURE T AT SPECIFIED GROSS SECTION STRESS σ_g

In Fig. 6(a)–(d) an example for specific value of σ_g = 19.5 kg/mm² is shown. From these presentations at each specific gross section stress σ_g, the following relation is obtained:

$$\frac{da}{dt} = A' K_{In}^{\ n} \tag{8}$$

where A' = constant dependent of σ_g, but independent of $\alpha\sqrt{a_{eff}}\sigma_g$; n = the inclination of the straight line in the $\log_{10}$(da/dt) vs $\log_{10}(\alpha\sqrt{a_{eff}}\sigma_g)$ plot. From these presentations, as is shown in Fig. 7 n is obtained as linear to the inverse of absolute temperature T as follows:

$$n = n_1 + (n_2/T) \tag{9}$$

where n_1 and n_2 are constants.

From Fig. 6(a)–(d) $\log_{10}$(da/dt) is plotted vs 1/T as shown in Fig. 8(a)–(d). Fig. 8(a)–(d) shows that the equation of Arrhenius type is obtained as follows:

$$\frac{da}{dt} = A^* \exp(-\Delta Hg/RT) \tag{10}$$

where R = gas constant; ΔHg = apparent activaton energy for crack extension A^* = constant dependent of σ_g and $\alpha\sqrt{a_{eff}}\sigma_g$, but independent of T. The value of ΔHg obtained from the inclination of the straight line in Fig. 8 according to Eq. (10) is given as shown in Fig. 9 as follows:

$$\Delta Hg = \Delta f_1 - \Delta f_2 \ln(K_{In}/G\sqrt{b}) \tag{11}$$

where G = modulus of rigidity; b = Burger's vector; Δf_1 and Δf_2 are constants dependent of hold time t_h, respectively. From Eqs. (8) to (11), da/dt at specific value of gross section stress, σ_g = 19.5 kg/mm² is expressed as follows:

for creep

$$\frac{da}{dt} = 5.64 \times 10^{10} \exp[-\{7.82 \times 10^4 - 1.68 \times 10^4 \ln(K_{In}/G\sqrt{b})\}/RT] \tag{12}$$

for creep-fatigue interaction (t_h = 10 min)

$$\frac{da}{dt} = 2.42 \times 10^{10} \exp[-\{7.62 \times 10^4 - 1.64 \times 10^4 \ln(K_{In}/G\sqrt{b})\}/RT] \tag{13}$$

for creep-fatigue interaction (t_h = 1 min)

$$\frac{da}{dt} = 5.32 K_{In}^{\ 5.03} \exp[-\{4.92 \times 10^4 - 6.87 \times 10^3 \ln(K_{In}/G\sqrt{b})\}/RT] \tag{14}$$

for fatigue

$$\frac{da}{dt} = 1.82 \times 10^{-4} K_{In}^{\ 3.71} \exp[-\{1.48 \times 10^4 - 1.74 \times 10^3 \ln(K_{In}/G\sqrt{b})\}/RT] \tag{15}$$

THE RELATION OF da/dt TO T, σ_g AND $K_{In}(\equiv\alpha\sqrt{a_{eff}}\sigma_g)$

Using Eqs. (4) to (15) and similar analysis, da/dt is expressed in terms of $\alpha\sqrt{a_{eff}}\sigma_g$ ($\equiv K_{In}$), σ_g and T as follows:

for creep

$$\frac{da}{dt} = 2.99 \times 10^3 \sigma_g^{\ 5.64} \exp[-\{7.82 \times 10^4 - 1.68 \times 10^4 \ln(K_{In}/G\sqrt{b})\}/RT] \tag{16}$$

for creep-fatigue interaction (t_h=10min)

$$\frac{da}{dt} = 1.19 \times 10^4 \sigma_g^{\ 4.89} \exp[-\{7.62 \times 10^4 - 1.64 \times 10^4 \ln(K_{In}/G\sqrt{b})\}/RT] \tag{17}$$

for creep-fatigue interaction (t_h=1 min)

$$\frac{da}{dt} = 3.47\times10^{-7}\sigma_g^{5.57}K_{In}^{5.03}\exp[-\{4.92\times10^4 - 6.87\times10^3\ln(K_{In}/G\sqrt{b})\}/RT] \quad (18)$$

and for fatigue

$$\frac{da}{dt} = 1.82\times10^{-4}K_{In}^{3.71}\exp[-\{1.48\times10^4 - 1.74\times10^3\ln(K_{In}/G\sqrt{b})\}/RT] \quad (19)$$

From Eqs. (16) to (19) high temperature crack growth rate under creep, fatigue and creep-fatigue interaction of stainless steel can be commonly expressed by

$$\frac{da}{dt} = B_t\sigma_g^m(\alpha\sqrt{a_{eff}}\sigma_g)^{n_1}\exp[-\{\Delta f_1 - \Delta f_2\ln(\alpha\sqrt{a_{eff}}\sigma_g/G\sqrt{b})\}/RT] \quad (20)$$

where Δf_1 is apparent activation energy; Δf_1, Δf_2, m, n_1 and B_t are constants dependent of hold time t_h (For creep, t=∞; for fatigue t_h=0). Each value of them is shown in Table 3 against each hold time. From Table 3,

Table 3. The values of constant in equation (20)

	Δf_1 kcal/mole	Δf_1^* kcal/mole
Creep	78.2	85.6
t_h=10 min	76.2	84.9
t_h=1 min	49.2	51.4
Fatigue	14.8	17.0

Δf_1, Δf_2, m, n_1 and B_t is plotted against t_h in Figs. 10 to 13. The value of Δf_1, Δf_2, m and B_t are shown as the ratio to Δf_1^*, Δf_2^*, m* and B_t^* corresponding to the value for creep, respectively. From Figs. 10 to 13, Δf_1, Δf_2, m, n_1 and B_t are approximately expressed by the following formula:

$$\Delta f_1 \cong \Delta f_1^*[1 - 0.85\exp(-0.45th)] \quad (21)$$

$$\Delta f_2 \cong \Delta f_2^*[1 - 0.85\exp(-0.45th)] \quad (22)$$

$$m \cong m^*[1 - \exp(-2.1th)] \quad (23)$$

$$n_1 \cong [181.1/(th+2.2)^{2.5}] - 21.5\exp(-1.48th) \quad (24)$$

$$B_t \cong B_t^*[10^{35.5(10^{-0.544th}} - 1.2e^{-0.766th})] \quad (25)$$

CONSIDERATIONS

It can be seen from Figs. 11 and 12 that the value of n_1 and B_t shows the curve of two different trends, according to larger range and smaller range of t_h. That is, in smaller range of t_h, n_1 increases with increase of t_h, but in larger range of t_h vice versa. Also, in smaller range of t_h, B_t decreases with increase of t_h, but in larger range of t_h vice versa.

As shown in Table 3 the value of activation energy Δf_1 obtained for creep is approximately equal to that of self-diffusion[8]. On the other hand, the value of Δf_1 obtained for fatigue is the order of the activation energy for overcoming the resistance to the dislocation movement. The value of Δf_1 decreases with decrease of t_h.

From these results it may be suggested that loading frequency effect on high temperature crack growth rate consists of the loading rate and hold time effect. In fatigue the loading rate is effective, and, on the other hand, with increase of hold time the hold time effect becomes more predominant.

CONCLUSIONS

From these studies conclusions and summary are as follows:

(1) Experimental formula of crack growth rate for stage II under creep, fatigue and creep-fatigue interaction at high temperatures of stainless steel was parametrically given in terms of stress intensity factor, gross section stress and temperature.

(2) Unified experimental formula of crack growth rate for stage II under creep-fatigue interactions at high temperatures was given as a function of hold time.

(3) It is suggested that loading frequency effect consists of both loading rate effect and hold time effect.

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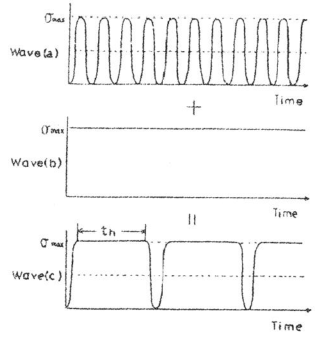

Fig. 2 Loading wave; (a) fatigue test, (b) creep test, and (c) creep-fatigue interaction test[1].

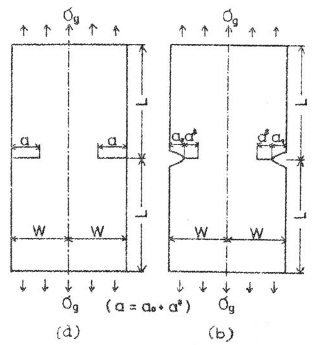

Fig. 3 (a) Cracked specimen, (b) Notched specimen[1].

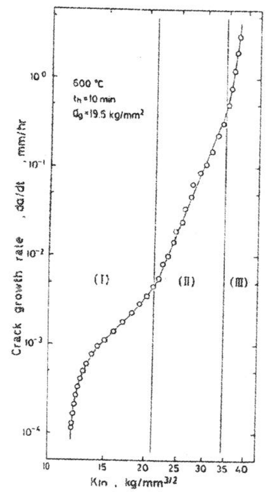

Fig. 4 Typical example of the relation[2] between the logarithm of crack growth rate and the logarithm of fracture mechanics parameter $\alpha\sqrt{a_{eff}}\sigma_g$.

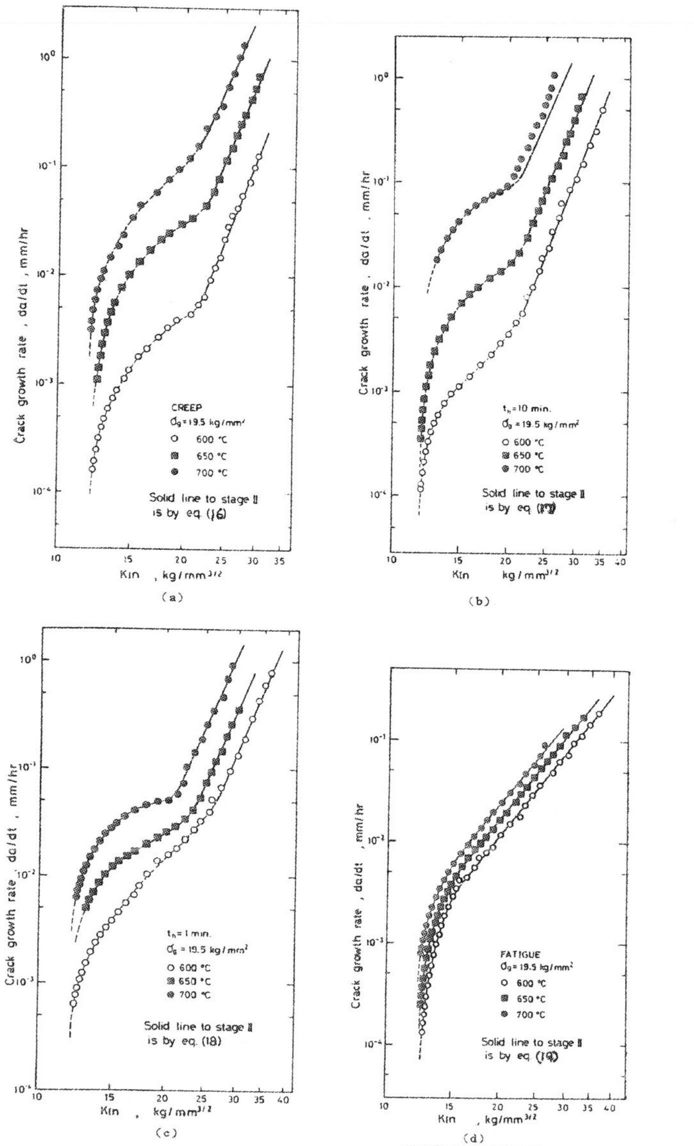

Fig. 6 Relation between logarithm of crack growth rate and fracture mechanics parameter $\alpha\sqrt{a_{eff}}\sigma_g$ with temperature as parameter at each specified gross section stress, based on experimental data in the previous papers[1,2].

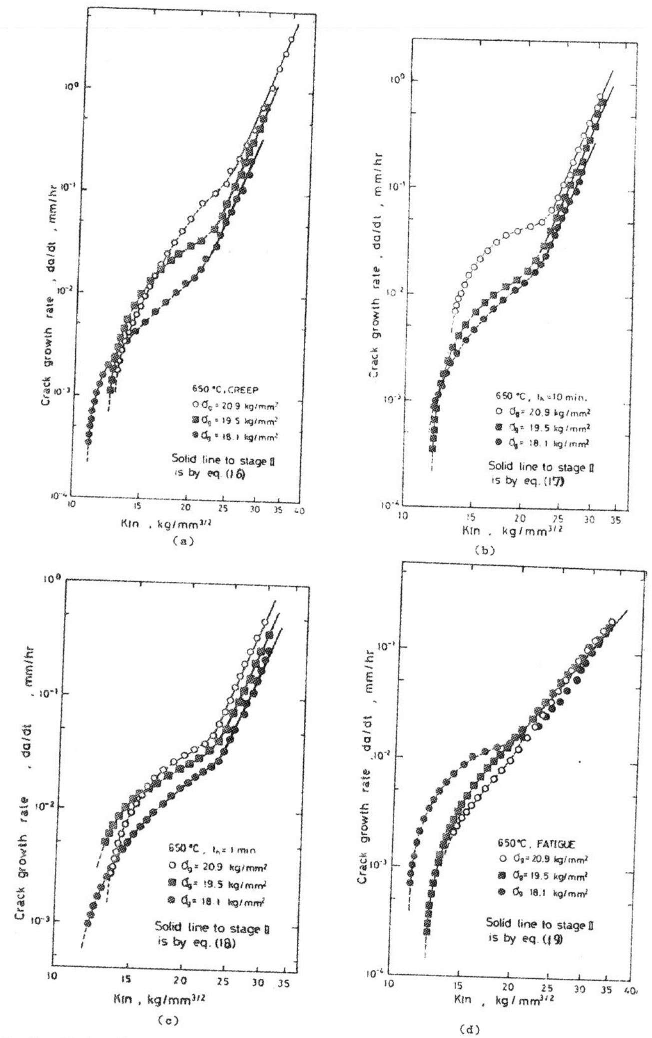

Fig. 5 Relation between logarithm of crack growth rate and fracture mechanics parameter $\alpha\sqrt{a_{eff}}\sigma_g$ with gross section stress as parameter at each specified temperature, based on experimental data in the previous papers[1,2].

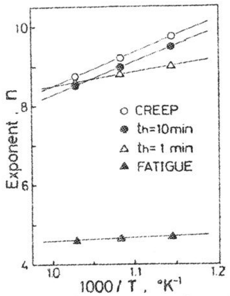

Fig. 7 A typical example of the experimental relation between the exponent n and the inverse of absolute temperature.

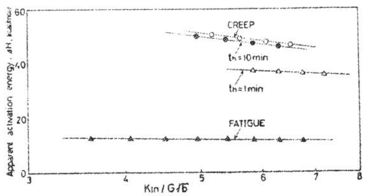

Fig. 9 The experimental relation between apparent activation energy ΔHg and $\alpha\sqrt{a_{eff}}\sigma_g$.

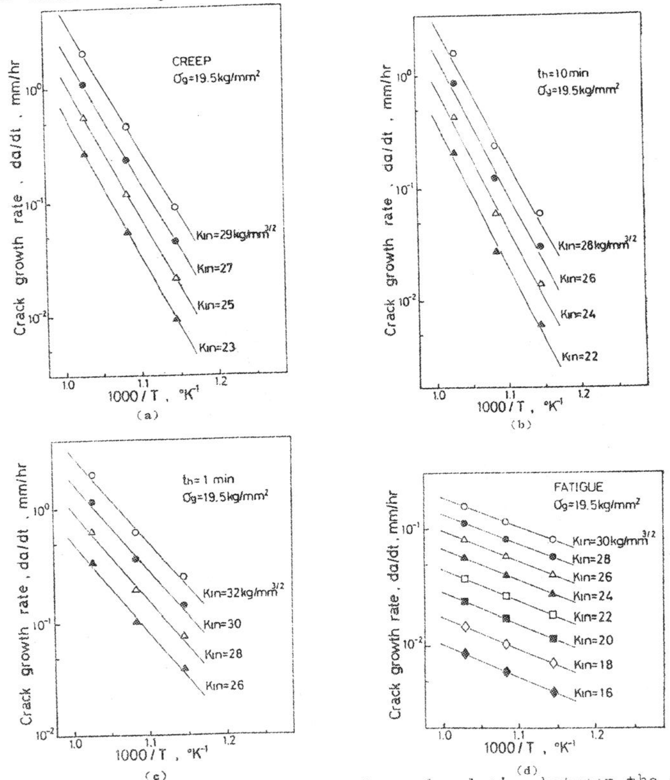

Fig. 8 A typical example of the experimental relation between the creep crack growth rate and the inverse of absolute temperature as affected by $\alpha\sqrt{a_{eff}}\sigma_g$ at specified gross section stress.

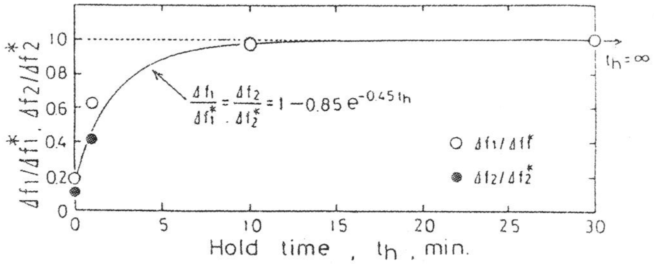

Fig. 10 The relation between $\Delta f_1/\Delta f_1^*$, $\Delta f_2/\Delta f_2^*$ and hold time t_h, respectively.

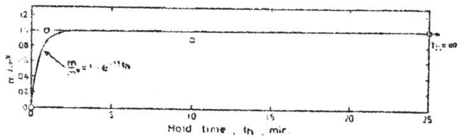

Fig. 11 The relation between m/m^* and hold time t_h.

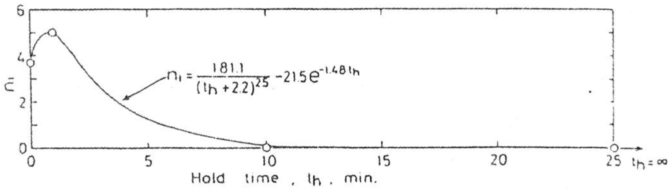

Fig. 12 The relation between n_1 and hold time t_h.

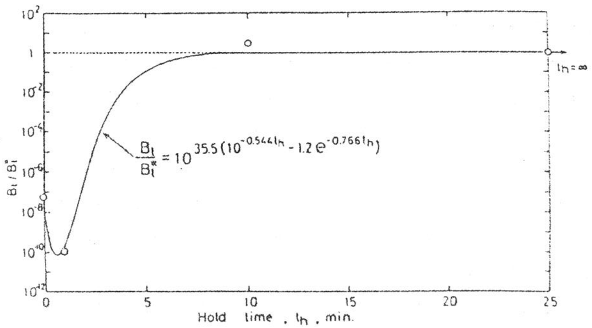

Fig. 13 The relation between B_t/B_t^* and hold time t_h.