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Temperature Variation associated with Stable Crack Growth and the Fracture Toughness Value

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The temperature of specimens during the fracture toughness testing, varies due to the heat generation associated with a plastic flow near the crack tip. The temperature has been analyzed using a simple heat balance model and the generated heat has been calculated. Heat generation rate changes in a clear slope corresponding to the stable crack initiation. Hence, this phenomenon can be used for detecting the stable crack initiation. J-integrals were estimated based on the heat variation for three kinds of steels and were found to be close to the ones evaluated by the R curve method.

1. Introduction

Several attempts have been made to correlate the temperature changes or heat generation to the strength of materials. Wells⁽¹⁾ has demonstrated that when steel specimens are fractured in a brittle manner, the energy release rate can be estimated from temperature measurement of the fractured specimens. Recently, Wells' method was improved and adapted to measure the fracture toughness values of several steels. Measured values were well consistent with the ones estimated by other methods⁽²⁾⁻⁽⁴⁾.

Generated heat is associated with the plastic deformation of materials. Hence, the heat generation phenomenon has been studied not only to find out a relation with the fracture toughness but also to investigate phenomena which are closely related to the plastic deformation. Solid thermoplastics, the thermal conductivity of which is relatively low, have a serious problem that a generated heat during deformation increases the temperature of specimens and makes specimens soft. Müller and his co-workers⁽⁵⁾ have performed a series of tensile tests of plastics: They made precise measurements of temperatures and discussed the relation between the plastic flow of materials and generated heat. Several other investigations have been done: The temperature increase of specimens during fatigue tests provides a good estimation of fatigue limits⁽⁶⁾; the amount of generated heat in fatigue tests can be related to the amplitude of plastic

strain⁽⁷⁾; The amount of heat generation can be used as a measure of fatigue damage⁽⁸⁾⁻⁽¹⁰⁾. Successes of these investigations suggest that local plastic strain which is difficult to measure directly can be detected by a different method of heat measurement.

In the field of fracture toughness testings, up to the present, only the temperature change after specimens are fractured has been measured and analyzed. This is effective only in the case when a fracture occurs in a very short time because an assumption of instantaneous heating is made in the analysis. Therefore, the same method can not be applied to a fracture which permits stable crack growth. In the fracture process of ductile materials, plastic deformation easily occurs around crack tips considerably before fracture loads are reached. Using the field of plastic work rate around stationary and propagating cracks, temperature rise at the crack tip was calculated⁽¹¹⁾. Calculated high rise in temperature, however, can not be confirmed experimentally because of the difficulty of measuring at the crack tips without disturbing the stress field around the tips.

The fracture process around crack tips in ductile materials can be divided into two stages in sequence⁽¹²⁾: Cracks open up until a stretched zone forms; stable cracks initiate and grow. As these two stages must different natures locally, the heat associated with the plastic deformation is expected to cause a change such as the electro-potential⁽¹³⁾ or the acoustic emission⁽¹⁴⁾ does even if there is no apparent change on the load vs. loading point deflection curves or load vs. crack opening displacement curves in fracture tests.

In this paper, measurements and analyses of temperature change of specimens are reported in ductile fracture; the possibility of estimation of the stable crack initiation by temperature measurement is also discussed.

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Table 1 Chemical composition (wt. %)

	C	Ni	Cr	Mn	Mo	Si	Cu	P	S
Rotor steel	0.35	1.68	1.24	0.49	0.30	0.27	0.08	0.015	0.009
Ship steel D	0.16			0.78		0.22		0.019	0.018
Ship steel A	0.14			0.53		0.19		0.017	0.010

Table 2 Mechanical properties in a direction normal to the cracked plane

	Yield Strength MPa	Tensile Strength MPa	Elongation %	Reduction of Area %
Rotor steel	835	957	11.6	58.9
Ship steel D	240	426	35.9	65.3
Ship steel A	228	404	34.2	66.0

2. Materials and experimental procedure

Three kinds of materials were used in this experiment: a rotor steel for middle and high pressure turbine generators; ship steels of grades A and D. Chemical compositions and mechanical properties of these materials are listed in Tables 1 and 2, respectively. Specimens of the rotor steel were cut from the outer layer of the forging which was 1660 mm in diameter. Three point bend specimens illustrated in Fig. 1 were used. The specimen orientation of the rotor steel is C-R so that cracks may propagate in a radial direction. For ship steels the crack orientation was parallel to a rolled direction. All specimens were fatigue-precracked ahead of the machine slots, 0.2 mm wide and about 8 mm deep, with stress intensity factor range, ΔK , less than $9.5 \text{ MPa} \cdot \text{m}^{1/2}$ until total pre-crack length reached about 11 mm.

If a stable crack starts growing from the fatigue crack tip uniformly throughout the specimen thickness, the temperature distribution in a thickness direction may be neglected and hence subsequent analysis will become quite easy. In an attempt to make the crack growth uniform, we planned to use side grooves machined on the specimens. To examine the effect of side grooves on the stable crack growth, preliminary experiments were performed with a regular specimen and three kinds of side grooved specimens: U-shaped in 2 mm deep; V-shaped in 2 mm deep; machine slits 0.2 mm wide and 2 mm deep on both sides of the specimen ligament as shown in Fig. 2. On a regular specimen(a) and a specimen with U-shaped grooves(b) as seen in Fig. 3, cracks grew faster at the center of the crack front; at the ends of the crack front, plane stress type plastic deformation extended largely. On specimens with V-grooves(c) and with machine slits(d), crack grew almost uniformly throughout the thickness. Based on the above observation, the machine slits were grooved for all specimens after pre-fatigue cracks were induced.

The temperature during fracture tests was measured with chromel-alumel sheath thermocouples (Yamari, each wire is 0.076 mm in diameter and whole diameter is 0.5 mm) inserted into holes of 0.5 mm diameter. The temperature difference was measured between a measuring point near the crack tip and a reference point far from the crack tip where a small load was applied. Electromotive force corresponding to the temperature difference was in the order of several tens microvolts and therefore, it was amplified to be recorded. The measuring point was located at 3~5 mm apart behind the crack tip in order not to disturb the stress field around the crack tip with a hole. The fracture experiments were all done at room temperature according to the ordinary method of fracture toughness testing: Loading point deflections and crack opening displacements were measured by a differential transformer extensometer and a clip gage, respectively; the load vs. loading point deflection and load vs. crack opening displacement diagrams were recorded. A testing machine was IS-10 Shimadzu Autograph. Three increasing rates of stress intensity factor were used: $2.5 \text{ MPa} \cdot \text{m}^{1/2}/\text{s}$, one half of this, and one quarter of this. Each specimen was heat tinted at 340°C for 10 min after unloaded. Then the specimen was broken in liquid nitrogen; actual fatigue crack and stable crack lengths were measured under 20 times magnification. The crack growth less than 0.1 mm and the stretched zone width were measured under a SEM. Fatigue crack fronts were almost even throughout the specimen thickness because the side grooves machined after fatigue cracking had removed less extensive part of fatigue cracks near both sides of the specimens.

Fig. 1 Three point bend specimen (in mm).

Fig. 2 Geometries of side grooves (in mm).

Fig. 3 Growth of the stable crack in the rotor steel specimen with (a) no side groove, (b) U-shaped side grooves, (c) V-shaped, and (d) machine slits.

The pre-fatigue crack lengths were determined, however, to be an average at the center of the crack front and midway between the center and the end of the crack front on each side. Stable crack fronts were almost even for rotor steel specimens throughout the thickness but were quite rugged for ship steels. A growth amount was measured at about 0.5 mm interval along a crack front and then averaged. The J was calculated using Rice's formula⁽¹⁵⁾:

$$J = \frac{2A}{bB}$$

where A is the area under the load vs. loading point deflection curve; b is the ligament length; B is the specimen thickness. In the calculation, the actual thickness in the ligament, 10 mm, was used for B .

3. Analysis of the temperature change and evaluation of the heat generation rate

Rice and Levy have analyzed the temperature rise at the crack tip using the plastic work rate. But it would be difficult to measure experimentally the crack tip temperature. Although the heat generation is distributed around a tip as the plastic work rate is, the distribution would not make much contribution to the temperature at a point considerably distant from the crack tip. In this paper, supposing the temperature measurement at such a location, the model is simplified as: only the crack front as a line source produces heat $q(t)$ which doesn't vary along the crack front but varies only with time. In the case when the specimen volume is so large compared with the surface area that the heat convection to the atmosphere may

be neglected, the temperature at a point separated r from a crack tip can be expressed as⁽¹⁶⁾

$$\theta_1(r, t) = \frac{1}{2\pi a c \rho} \int_0^t \frac{q(\tau)}{t - \tau} \times \exp\left\{-\frac{r^2}{4a(t - \tau)}\right\} d\tau \quad (1)$$

where a , c , and ρ are the thermal diffusivity, the specific heat, and the density of the material, respectively. Values of constants used in this analysis are listed in Table 3.

The temperature of specimens changes not only due to the generated heat but also due to the thermoelastic effect and the heat convection to the atmosphere. Change due to the thermoelastic effect depends on how adiabatically the material deforms and also on the stress distribution. This change is, therefore, hardly expected beforehand. Equation (1) does not express the influence of the heat convection to the atmosphere at the specimen surface. It is mathematically possible to analyze the temperature change involving heat transfer at the surface on a real specimen having finite dimensions. However, the change would be given by the form of infinite series, which is not appropriate

Table 3 Values of physical properties used in the calculation

	Specific heat c J/kgK	Density ρ kg/m ³	Thermal diffusivity a m ² /h
Rotor steel	460	7870	0.058
Ship steel	460	7830	0.053

for an analysis of generated heat. In this paper, some assumptions are made: As a temperature change due to heat convection on surfaces takes more time than that due to heat conduction, only the former change $d\theta_2/dt$ is noted here and assumed to be proportional to the temperature at that point $\theta_1 + \theta_2$. That is,

$$\frac{d\theta_2}{dt} = -\beta(\theta_1 + \theta_2) \quad (2)$$

where β is a constant which relates to the heat transfer coefficient at the surface, surface area, volume, specific heat of the specimen, etc., and will be called a heat dissipation coefficient. Measured change θ ($=\theta_1 + \theta_2$) can be expressed taking only the difference from the initial value as

$$\theta(r, t) = \theta_1(r, t) - \beta \int_0^t \theta_1(t, \tau) \times e^{-\beta(t-\tau)} d\tau \quad (3)$$

Calculation sequence was as follows: The measured temperature θ is compensated for a loss by heat convection on a surface using Eq. (3); from θ_1 , heat $q(t)$ is calculated using Eq. (1). In solving these integral equations, numerical computation is employed: Time is divided into equal intervals, Δ ; $\theta_1(t)$ and $q(t)$ are assumed constant to be $\bar{\theta}_1(k)$, $\bar{q}(k)$ during the interval between $t = (k-1)\Delta$ and $t = k\Delta$ where $\bar{\theta}_1(k)$, $\bar{q}(k)$ are pulse functions such that they are zero at other intervals; $\theta_1(r, t)$, $q(t)$ are, then, to be approximated by the sums of $\bar{\theta}_1(i)$, $\bar{q}(j)$ ($i, j=1, 2, \dots, n$)⁽¹⁹⁾. After those discretisings, integral equations, Eqs. (1) and (3), can be solved as

$$\bar{\theta}_1(k) = e^{\beta\Delta} \left\{ \theta(k) + \sum_{i=1}^{k-1} \bar{\theta}_1(i) \times e^{-\beta(k-i)\Delta} (1 - e^{-\beta\Delta}) \right\} \quad (4)$$

$$\bar{q}(k) = \frac{1}{E_1\left(\frac{r^2}{4a\Delta}\right)} \left\{ 2\pi\alpha c p \bar{\theta}_1(k) - \sum_{j=1}^{k-1} \bar{q}(j) \times \left\{ E_1\left(\frac{r^2}{4a(k-j+1)\Delta}\right) - E_1\left(\frac{r^2}{4a(k-j)\Delta}\right) \right\} \right\} \quad (5)$$

where $E_1(x)$ is an exponential integral;

$$E_1(x) = \int_x^\infty \frac{1}{t} e^{-t} dt$$

and the functional value was obtained from its rational approximation⁽²⁰⁾. As measured temperature involved a considerable noise as shown later, a 4th~10th order polynomial was fitted using least squares regression techniques.

4. Results and discussion

4.1 Measuring of the heat dissipation coefficient β

As it was difficult to estimate the heat dissipation coefficient beforehand, the value was directly measured experimen-

tally for each specimen. Figure 4 shows an example of temperature records when the specimen temperature was raised by touching the specimen with a finger for a few seconds and then the specimen was cooled in the atmosphere. The decreasing part of the temperature change consists of two components: a change when the temperature distribution produced at the temperature rising period is made uniform and a change due to heat convection at the surface. Since the former becomes negligibly small after about the same period as the rising process required, the subsequent temperature change can be used for the estimation of the heat dissipation coefficient β . Putting $\theta_1 = 0$ in Eq. (2), the relation becomes

$$\theta_2 = \theta_0 e^{-\beta t} \quad (6)$$

where θ_0 is a constant. Circles in Fig. 5 are plots for the temperature taken from the record shown in Fig. 4 and well represented by the Relation (6). Estimated values of β for every specimen were almost invariably about 0.05 s^{-1} .

4.2 Calculation of heat

Figure 6 shows a temperature change measured in a fracture test of the rotor

Fig. 4 An example of temperature records to estimate the heat dissipation coefficient β .

Fig. 5 Temperature change converted from the chart in Fig. 4 and the Relation (6).

steel specimen which was loaded up to a peak load. From this temperature, the heat generation rate was calculated as shown in Fig. 7, in which the load vs. loading point deflection curve is also shown. On loading, the temperature decreases under the thermoelastic effect. Negative heat generation rate was obtained because a

Fig. 6 An example of temperature records during the fracture test of the rotor steel specimen at the loading rate of $1.25 \text{ MPa} \cdot \text{m}^{1/2}/\text{s}$.

Fig. 7 (a) load vs. loading point deflection curve; (b) measured temperature and the calculated change of heat generation rate for the same specimen in Fig. 6.

temperature change was analyzed without taking account of the thermoelastic effect. The value of the heat generation rate is, therefore, meaningless. Instead of the value itself, the slope change of heat generation rate will be noted. In Fig. 7(b), the heat generation rate seems to change its slope around point A, suggesting a large scale plastic deformation. The heat generation rate changes its slope again around point B. Figure 8(a), (b) shows the load vs. loading point deflection curve, the temperature curve, and the heat generation rate curve of the grade A ship steel. The same tendency of the heat generation rate as the rotor steel shows is noticed. Corresponding to the yielding of the specimen, bending points appear on the temperature and heat generation rate curves. Grade D ship steel showed the same tendency as the grade A.

4.3 J-integral and the estimation of the initiation of stable crack growth

Figures 9~11 show the R curves for three kinds of steels. For the crack-opening-stretch curve, the following was used⁽²¹⁾.

$$J = 2 \cdot \sigma_{\text{flow}} \cdot \Delta a$$

where $2 \cdot \sigma_{\text{flow}}$ is the sum of the yield and tensile strengths and Δa is the stable

Fig. 8 (a) load vs. loading point deflection curve; (b) measured temperature and the calculated change of heat generation rate for the grade A ship steel at the loading rate of $2.50 \text{ MPa} \cdot \text{m}^{1/2}/\text{s}$.

crack growth. Defining J_{IC} to be the value of J -integral at an intersection of this line with the R curve, J_{IC} values, 128, 115, and 96 kJ/m^2 are obtained for rotor steel, grade D ship steel and grade A, respectively. These values are valid as specimen dimensions satisfy the proposed size requirement⁽²¹⁾. J values corresponding to the loading up to a point B given in Figs. 7 and 8 are listed in Table 4. Empty columns are for specimens in which B point was hardly identified. The J value at B point for each specimen is quite close to the J_{IC} value for three kinds of steels. Especially, specimens which were loaded sufficiently and exhibited a large temperature change are closer to J_{IC} than others. The heat generation rate as shown in Figs. 7 and 8, when compared with values of J , suggests the fracture mechanism: After about A point, crack tip begins to open wide; a stretched zone is formed thereafter; around B point a stable crack begins to grow.

Table 4 also shows CTOD values at the

point B, which were calculated using a rotational factor according to the following equation.

$$\text{CTOD} = V_g / \left(1 + \frac{a+z}{r} \right)$$

where V_g is a crack opening displacement measured by a clip gage; z is the height of a knife edge, 0.98 mm; r is the rotational factor and 0.3 was used. The CTOD shows similar value for each specimen just as the J -integral does.

4.4 Influence of the loading rate and the location of temperature measuring

Curves in Fig. 7(b) are for the rotor

Table 4 Results of the fracture toughness test and J -integral and CTOD at the point B

	Pre-crack length a mm	Stable crack growth Δa mm	J		J_{IC} kJ/m^2	CTOD μm
			at unloading kJ/m^2	at B point kJ/m^2		
Rotor steel	10.67	0.057	76	-	128	-
	10.49	0.088	109	-		-
	10.94	0.19	156	102		74
	10.63	0.28	172	137		95
	10.40	0.43	206	137		94
	11.19	0.66	216	124		83
Ship steel D	11.37	0.068	64	-	115	-
	10.97	0.107	111	-		-
	11.18	0.21	119	82		124
	10.98	0.33	142	97		137
	10.50	0.65	177	123		171
	11.23	0.73	191	124		169
Ship steel A	11.42	0.74	215	118	96	155
	11.24	0.091	63	-		-
	11.44	0.068	89	-		-
	11.07	0.34	118	80		125
	11.34	0.35	132	-		-
	11.48	0.32	147	97		147
	11.04	0.44	166	94		138
	11.13	0.63	185	-		-
	10.91	0.72	221	106		153

Fig. 9 R curve for the rotor steel at room temperature.
 $J_{IC} = 128 \text{ kJ/m}^2$

Fig. 10 R curve for the grade D ship steel at room temperature.
 $J_{IC} = 115 \text{ kJ/m}^2$

Fig. 11 R curve for the grade A ship steel at room temperature.
 $J_{IC} = 96 \text{ kJ/m}^2$

steel under a loading rate, $1.25 \text{ MPa}\cdot\text{m}^{1/2}/\text{s}$. Under the same conditions except the loading rate $2.50 \text{ MPa}\cdot\text{m}^{1/2}/\text{s}$, a slight difference is observed in the temperature change as shown in Fig. 12. To decrease the loading rate is to allow time for heat convection to the atmosphere; the temperature will reach its minimum at early period and provide worse correspondence to the heat generation rate on a diagram. The more the loading rate increases, the better the correspondence becomes. In Fig. 12, the minimum point of the temperature seems to correspond to C point on the heat generation rate curve. At an appropriate loading rate, a temperature curve may be used instead of a calculated heat generation rate. Since the range of loading rates in this experiment is narrow after ASTM testing method E399-74, the appropriate rate can not be determined. However, too fast loading may result in the adiabatic deformation state and hence an appreciable temperature decrease due to the thermoelastic effect. This might mask the temperature change due to the heat generation.

Locations of temperature measuring were 3~5 mm apart from crack tips. Distance from a crack tip was measured after the crack front was confirmed on the fractured surface. Any location is allowable to measure the temperature as long as the actual value of r is used in Eq. (5). As a crack grows, the crack tip advances and the distance between the temperature measuring point and the line of heat generation varies. The influence of this variation, however, was not taken into consideration in this analysis because the growth amount was very small compared with the total distance. Even when a sufficient crack growth occurs, appropriate correction can be made in the value of r in Eq. (5).

Temperature difference is preferably measured. But it is possible to use the temperature itself around a crack tip although the specimen's temperature is quite

Fig. 12 Measured temperature and the calculated change of heat generation rate for the rotor steel specimen at the loading rate of $2.50 \text{ MPa}\cdot\text{m}^{1/2}/\text{s}$.

influenced by a fluctuation of the atmosphere and the analysis becomes troublesome.

4.5 Ruggedness of the stable crack growth in ship steels

Both grade A and D ship steels showed only an ambiguous slope change in the heat generation rate compared with the rotor steel. This may be caused by the difference in the manner of stable crack growth. Figure 13 shows how the stable crack grew on the grade D ship steel. Some part of the crack front grew ruggedly contrasting with the manner of the rotor steel in which the crack grew almost uniformly from the pre-fatigue crack tip as seen in Fig. 3. This ruggedness belies the assumption in the temperature analysis that the heat generation is uniform throughout the specimen thickness. Two-dimensional model of heat balance proposed here was not sufficient to catch a clear slope change of heat generation in ship steels.

Fig. 13 Rugged growth of the stable crack in the grade D ship steel.

5. Conclusions

By noting the temperature change of specimens during fracture toughness tests, the method of temperature analysis using a simple model of heat balance has been proposed. The heat generation rate calculated shows the changes corresponding to the stretched zone formation and the process of initiation and propagation of the stable crack as long as the cracks grow almost uniformly from the pre-fatigue crack tips. It has been confirmed that from the temperature measurement, initiation of the stable crack growth can be estimated. For the rotor and ship steels, the initiation of stable crack growth was estimated and the J value corresponding to the loading point was evaluated. Values were quite close to the J_{IC} values obtained by R curve method. When the unclear part such as temperature change due to the thermoelastic effect is clarified, quantitative usage of the generated heat will become possible and the value of heat itself will correspond directly to the parameters in

the fracture mechanics such as the energy release rate and the J-integral.

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