Near-Threshold Fatigue Crack Growth Behavior of SUS304 Steel at High Temperatures Using Interferometric Strain/Displacement Gage* (1st Report, Crack Closure Behavior)

Kiyotsugu OHJI**, Shiro KUBO***

Yoshikazu NAKAI****, Eiichi TAMURA*****

Shoji SHIOTANI***** and Tanoh Ange Privat KACOU*****

Interferometric strain-displacement gauge (I.S.D.G.) testing system was developed for the measurement of the crack opening displacement at high temperatures. Helium-Neon gas laser and center-cracked specimens of type SUS304 austenitic stainless steel were used. Fatigue crack growth tests were conducted at 450, 550, 650 and 700°C at stress ratios of $R = -0.1$ and 0.5. Using I.S.D.G. for the measurement of crack closure modified using platinum plate and optical filter, crack opening displacement was found to be measured with good accuracy at all temperatures tested. Results showed that crack closure was observed at $R = -0.1$, while no crack closure was observed at $R = 0.5$ even at 650°C. From the results of the measurement of fatigue crack closure in the near-threshold regime at all temperatures investigated, it was found that rapid increase and decrease in crack growth rate da/dN were observed when crack opening ratio U showed rapid increase and decrease, respectively.

Key Words: Fatigue, Crack Propagation, Crack Closure, High Temperature, Fatigue Threshold, SUS304, M(T) Specimen, Interferometric Strain/Displacement Gage

* Received 30th March, 1998. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 63, No. 610, A (1997), (Received 12th August, 1996)

** Department of Mechanical and System Engineering, Faculty of Science and Technology, Ryukoku University, 1-5 Yokotani, Oe-cho Seta, Ohtsu, Shiga 520-2192, Japan.

*** Department of Mechanical Engineering and Systems, Graduate School of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan. E-mail: kubo @ mech.eng.osaka-u.ac.jp

**** Department of Mechanical Engineering, Faculty of Engineering, Kobe University, 1-1, Rokkoudai, Nada, Kobe, Hyogo 657-0013, Japan

***** Department of Mechanical Engineering, Graduate School, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan

***** NKK Co. Ltd., 1 Koukan-cho, Fukuyama, Hiroshima 721-0931, Japan

***** Formerly, Department of Mechanical Engineering, Graduate School, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871, Japan

1. Introduction

Many studies have been conducted on fatigue crack growth behavior at high temperatures⁽¹⁾⁻⁽²⁰⁾. It has been reported that the fatigue crack growth behavior at high temperatures is classified into cycle-dependent and time-dependent ones. Threshold was found to exist in the cycle-dependent crack growth even at high temperatures. At high temperatures, oxidation on crack surface is more pronounced than at room temperature, which enhances oxide-induced crack closure⁽²¹⁾⁻⁽²³⁾ in addition to plasticity-induced crack closure⁽²⁴⁾. Crack closure which has a strong influence on crack growth rate da/dN is expected to be more significant in the near-threshold regime. Knowledge of the behavior of crack closure is then indispensable for investigating fatigue crack growth behavior near threshold at high temperatures.

Crack closure behavior can be examined from the measurement of the relationship between applied load and displacement or that between applied load and

strain at a certain point of a cracked specimen. In most measurements of crack closure employed at room temperature, displacement or strain is measured using sensors attached directly to the specimen. This method of measurement is difficult to apply to the measurement at high temperatures, since the sensors do not work at high temperatures. In interferometric strain-displacement gauge (I.S.D.G.) method^{(25),(26)}, the displacement is measured from fringe patterns formed by the beams reflected on the Vickers indentations on the specimen surface. I.S.D.G. is thought to be applicable to the measurement at high temperatures. Using I.S.D.G. for the measurement of crack closure, the behavior of the crack closure in the near-threshold regime at high temperatures is expected to be investigated.

In this study, fatigue crack growth experiments in the near-threshold regime were conducted at 450, 550, 650 and 700(°C) using center-cracked specimen of type SUS304 austenitic stainless steel. A. C. electric potential method was used for the measurement of crack length. The above-mentioned I.S.D.G. method was used for the measurement of crack closure.

2. Material and Specimen

Material used for the investigation is solution-treated type SUS304 austenitic stainless steel. Chemical composition and mechanical properties of the material at room temperature are listed in Tables 1 and 2, respectively.

Center-cracked specimens (M(T)specimen) were used. Geometry of M(T)specimen is shown in Fig. 1.

Table 1 Chemical composition of the SUS 304 steel investigated (wt.%)

C	Si	Mn	P	S	Ni	Cr	Fe
0.04	0.60	1.69	0.036	0.001	8.29	18.34	Bal.

Table 2 Mechanical properties at room temperature of the SUS 304 steel investigated

Tensile Strength (MPa)	Elongation (%)	Reduction in Area (%)	Hardness (Hb)
618	50.2	62.0	164

Fig. 1 Geometry of M(T) specimen

In the center part of the specimen, slit of about 0.2 (mm) wide and 3.0 (mm) long normal to the loading direction was introduced by electric discharge machining. Pre-cracks of about 1.0 (mm) were initiated at notch tips of the slit.

3. Experimental Procedures

3.1 Apparatus

Experiments were performed on computer-controlled electric servo-hydraulic fatigue testing machine. Specimen was heated using high frequency A.C. induction coil.

For measuring crack length, A.C. electric potential method was used. System for the measurement of A.C. electric potential is shown in Fig. 2.

3.2 Fatigue crack growth testing

Fatigue crack growth tests were conducted at 450, 550, 650 and 700(°C). Load ratio was set at -0.1 or 0.5 . Loading waveform used is sinusoidal. Loading frequency was set at 30 (Hz). ΔK decreasing test method or ΔP constant test method was used in fatigue crack growth testing. The following testing procedure was employed.

1) ΔK decreasing test was conducted until the threshold behavior was observed.

2) After the ΔK decreasing test was completed, ΔP constant test was conducted with an initial ΔK value a little higher than that at the end of the foregoing ΔK decreasing test.

In the ΔK decreasing test, ΔK value was decreased for every crack growth of 0.05 (mm) with ΔK decreasing ratio, $C(=-dK/da)$, which was set at $-0.08(\text{mm}^{-1})$ in accordance with the ASTM standard E647-91. Threshold value was identified as the ΔK for which crack growth rate da/dN was in the order of 10^{-10} (m/cycle) or smaller.

4. Laser-Based I.S.D.G.

4.1 Principle of I.S.D.G.

Principle of laser-based I.S.D.G. is shown in Fig.

Fig. 2 System for measurement of A.C. electric potential

Fig. 3 Principle of the laser-based I.S.D.G.

Fig. 4 Relationship between gage length and a distance between adjacent two fringes

3. As is shown in Fig. 3, two Vickers indentations are placed near the crack in symmetry with respect to the crack line on the specimen surface. Two indentations reflect the laser beams, which form interference fringe patterns. The positions of fringe of the maximum intensity are expressed by the following equation.

$$d \cdot \sin \alpha = \lambda \cdot n, \quad n=0, \pm 1, \pm 2, \dots \quad (1)$$

Here λ is the wavelength of laser beam, d is the distance between two indentations and α is the angle between incident and reflected beams. Similarly, the positions of fringe of the minimum intensity are expressed as,

$$d \cdot \sin \alpha = \lambda \cdot (1/2 + n), \quad n=0, \pm 1, \pm 2, \dots \quad (2)$$

As shown in Fig. 4, the distance between indentations and the sensors is denoted by L , the distance between adjacent two fringes being w . The following relation-

Fig. 5 Directions of the movement of the interference fringe patterns (a) Contribution of relative motion, (b) Contribution of rigid body motion, (c) Total movement

ship holds between two angles which correspond to adjacent two fringes.

$$d(\sin \alpha_{n+1} - \sin \alpha_n) = \lambda \quad (3)$$

Here α_n denotes the value of α for the n -th fringe. Equation (3) leads to the following equation.

$$\frac{\lambda}{d} = \sin \alpha_{n+1} - \sin \alpha_n = \cos \alpha \cdot (\alpha_{n+1} - \alpha_n) \quad (4)$$

On the other hand, w is given by

$$w = L(\alpha_{n+1} - \alpha_n) \quad (5)$$

From Eqs. (4) and (5), the following equation is obtained.

$$w = \frac{L \cdot \lambda}{d \cdot \cos \alpha} \quad (6)$$

The change in the distance between two indentations leads to movement of the fringe patterns. From Eqs. (1) and (2), the relationship for any peak point of fringe patterns between the displacement of d , Δd , and the change of α , $\Delta \alpha$, is expressed as follows.

$$\sin \alpha \cdot \Delta d + d \cdot \cos \alpha \cdot \Delta \alpha = 0 \quad (7)$$

Using $\Delta \alpha$, displacement of the fringe patterns Δx is expressed as

$$\Delta x = L \cdot \Delta \alpha \quad (8)$$

From Eqs. (7), (6) and (8), the following equation can be obtained.

$$\Delta d = -\frac{\Delta x}{w} \cdot \frac{\lambda}{\sin \alpha} \quad (9)$$

Using Eq. (9), the displacement of the distance between two indentations Δd can be calculated from the distance between adjacent two fringes w and the displacement of the fringe patterns Δx .

The movement of fringe patterns is caused by rigid body motion of specimen as well as relative motion of two indentations. As shown in Fig. 5(a), the movement of fringe patterns caused by the relative motion of indentations on upper and lower sensors has the same absolute value of Δx in opposite directions. As shown in Fig. 5(b), the movement caused by the rigid body motion of the specimen on

upper and lower sensors has the same absolute value of Δx_g in the same direction. Total movement of fringe patterns on upper and lower positions is equal to the sum of the movements caused by the relative motion and the rigid body motion as shown in Fig. 5 (c). By averaging total movements measured on upper and lower sensors, the influence of the movement caused by the rigid body motion can be eliminated to obtain Δx .

4.2 Method of crack closure measurement using I.S.D.G.

Shown in Fig. 6 is a schematic diagram of the laser-based I.S.D.G. system. He-Ne gas laser generator, mirrors and sensors were arranged as shown in Fig. 6. Wavelength of the laser was $\lambda=632.8$ (nm) and the angle between incident and reflected beams was $\alpha=42.1^\circ$. PCD linear image sensor used had 512 photo diodes of the size of 0.025 (mm) $\times$ 2.5 (mm) arranged in a row.

In this study, the I.S.D.G. method was used for the measurement of displacement at high temperatures. At high temperatures, oxide film formed on the specimen surface diffused reflection of the laser beams, and the reddish light emitted from the heated specimen deteriorated the accuracy of the observation of the fringe patterns significantly. In this study, pre-crack

Fig. 6 Schematic diagram of the laser-based I.S.D.G. system

Fig. 7 Positions of a pair of indentations

was initiated after platinum plate was attached near a notch tip. Indentations were placed on the platinum plate as shown in Fig. 7. Since the accumulation of oxide film on the surface of the platinum was not significant even at 700°C , the effect of diffusion of the reflection was small. In addition, in this study, optical filters were placed on the light paths between indentations and sensors. Specification of the filters used is listed in Table 3, where $T_{\max}$ and $\Delta\lambda_{1/2}$ denote maximum transmittance and half bandwidth, respectively. Using the optical filters, the reddish light was eliminated.

Through A/D conversion of intensity signals obtained, the relationship between intensity and sensor channel as shown in Fig. 8 was calculated. This figure shows that there are periodical maximum and minimum peaks. The data near minimum peaks were smoother than those near maximum peaks. The data of periodical minimum peaks were therefore used for the calculation of displacement. The weight function proposed by Savitzky and Golay⁽²⁷⁾ was used to determine the locations of the peaks of intensity. In this measurement, 5 or 6 peaks of intensity were observed in the fringe pattern. The resolution of displacement Δd is about 0.009 (μm).

The loading frequency during fatigue crack growth testing was set at 30 (Hz). While the fringe patterns were measured, it was necessary to hold the load. So the loading frequency during the measurement of crack closure could not be kept at 30 (Hz). In the measurement of crack closure, the displacements on 100 load levels in one stress cycle were measured. The measurement of displacement on 100 load levels in one stress cycle took about 6 seconds, which corresponded to the reduced loading frequency of 0.17 (Hz).

Table 3 Specifications of the filter

Filter	λ_0 (nm)	$T_{\max}$ (%)	$\Delta\lambda_{1/2}$ (nm)
Upper	631.9	41.0	7.5
Lower	631.0	41.2	7.6

Fig. 8 Interference fringe pattern

5. Calculation of Crack Length, Crack Growth Rate, Stress Intensity Factor Range and Crack Opening Ratio

5.1 Calculation of crack length

In this study, A. C. electric potential method was used for the measurement of crack length. Crack length was calculated from the potential drop between two points placed in symmetry with respect to the crack line on the specimen surface. The calibration equation for D. C. electric potential method was used to calculate crack length. The relationship between potential drop V and half crack length a for the center-cracked specimen (M(T) specimen) is expressed as follows⁽²⁸⁾,

$$\frac{V}{V_0} = \frac{\cosh^{-1}\{\cosh(\pi S/2W)/(\cos(\pi a/2W))\}}{\cosh^{-1}\{\cosh(\pi S/2W)/\cos(\pi a_0/2W)\}} \quad (10)$$

where W is half specimen width, S is half distance between two potential values reading probes and subscript 0 denotes initial values.

5.2 Calculation of crack growth rate

In accordance with the ASTM standard E647-91, crack growth rate da/dN was calculated as follows. Crack length data were averaged for every crack growth of 0.05 (mm). The relationship between averaged crack length and number of cycles was then approximated for 7 consecutive data points using least squares method. The slope was calculated from the approximated equation and was employed as the crack growth rate at the central point.

5.3 Calculation of stress intensity factor range

Stress intensity factor range for M(T) specimen is calculated by⁽²⁹⁾

$$\Delta K = (\sigma_{\max} - \sigma_{\min}) \cdot \sqrt{\pi a} \cdot f(a/W) \quad (11)$$

where $\sigma_{\max}$ and $\sigma_{\min}$ are the maximum and the minimum applied stress, respectively. Correction factor $f(a/W)$ in this equation is given as follows.

$$f(a/W) = \{1 - 0.025(a/W)^2 + 0.06(a/W)^4\} \cdot \sqrt{\sec\left(\frac{\pi}{2} \cdot \frac{a}{W}\right)} \quad (12)$$

5.4 Calculation of crack opening ratio

The load-displacement curve was obtained to calculate crack opening ratio U . The crack opening load was determined as the load at which the curve started to deviate from a straight line. The value of U was obtained as the fraction of the load range above crack opening load in the total load range.

6. Results and Discussions

6.1 Load-displacement curve

An example of load-displacement curve obtained for stress ratio R of -0.1 and test temperature of 650°C is shown with a solid line in Fig. 9. Similar load-displacement curves were obtained also at 450 , 550

Fig. 9 Load-displacement and load-modified displacement curves (650°C , $R = -0.1$, $\Delta K = 5.47 \text{ (MPa} \cdot \text{m}^{1/2})$)

Fig. 10 Load-displacement curve (650°C , $R = 0.5$, $\Delta K = 3.28 \text{ (MPa} \cdot \text{m}^{1/2})$)

and 700°C , which are not shown in this paper for the sake of lack of space. Modified displacement was calculated by subtracting load multiplied by a constant from displacement. The constant was chosen for the load-modified displacement curve to be parallel to the vertical axis while the crack is open. In Fig. 9, load-modified displacement relation is shown with a broken line. From Fig. 9, no hysteresis behavior is observed and it is confirmed that the effect of plasticity in cyclic loading is negligible in the present experiments.

An example of load-displacement curve for $R = 0.5$ and test temperature of 650°C is shown in Fig. 10. In this figure, load-displacement curve is almost straight. This shows that crack does not close at $R = 0.5$.

Fig. 11 Behavior of da/dN (700°C), $R=-0.1$ Fig. 12 Crack closure behavior (700°C), $R=-0.1$

6.2 Behavior of crack opening ratio

The measurements of crack closure were performed at 450, 550, 650 and 700°C in the fatigue crack growth test at $R=-0.1$. Examples of the relationship between da/dN and number of cycles, N , at 700°C are shown in Fig. 11. Also examples of the relationship between U and N at 700°C are shown in Fig. 12. In Figs. 11 and 12, (a) and (b) show the results obtained in the ΔK decreasing test and ΔP constant test, respectively.

From the results of ΔK decreasing test shown in Fig. 11(a), it can be seen that da/dN decreased with a constant value of slope in the region $N < 0.7 \times 10^5$, and it decreased with more moderate slope in the region $N > 0.7 \times 10^5$. Figure 12(a) shows that U also decreased with a constant value of slope in the region $N < 0.7 \times 10^5$, and it decreased with more moderate slope in the region $N > 0.7 \times 10^5$. Similar correspon-

dence between the behavior of da/dN and U against N was seen in the results of the tests at 450, 550 and 650°C , which are not shown in this paper for the sake of lack of space.

From the results of ΔP constant test shown in Fig. 11(b), it can be seen that da/dN increased with a constant value of slope in the region $N < 4.3 \times 10^5$, and it increased with steeper slope in the region $N > 4.3 \times 10^5$. Figure 12(b) shows that U also increased with a constant value of slope in the region $N < 4.3 \times 10^5$, and U reached 1 in the region $N > 4.3 \times 10^5$. Similar correspondence between the behavior of da/dN and U against N was seen in the results of the tests also at 450, 550 and 650°C .

As explained above, in both results of the ΔK decreasing test and the ΔP constant test, rapid increase and decrease in the behavior of da/dN against N correspond to rapid increase and decrease

in the behavior of U against N , respectively.

7. Conclusions

Fatigue crack growth tests were conducted at 450, 550, 650 and 700 (°C) using M(T) specimen of type SUS304 austenitic stainless steel. Laser-based I.S.D.G. was used for the measurement of crack closure. Applicability of I.S.D.G. to the measurement at high temperatures and the behavior of crack closure at high temperatures were investigated. The results can be summarized as follows.

(1) Using platinum plate and optical filter, laser-based I.S.D.G. was applicable to the measurement of crack closure at high temperatures.

(2) Crack closure behavior was observed at $R = -0.1$, while no crack closure was observed at $R = 0.5$ even at 650 (°C).

(3) It was found that rapid increase and decrease in crack growth rate da/dN were observed when crack opening ratio U showed rapid increase and decrease, respectively.

References

- (1) James, L.A., Stress Analysis and Growth of Cracks, Proceedings of the 1971 National Symposium on Fracture Mechanics, Part I, ASTM STP 513 (1972), p. 218-229.
- (2) Haigh, J.R., Skelton, R.P. and Richards, C.E., Materials Science and Engineering, Vol. 26 (1976), p. 167-174.
- (3) Ellison, E.G. and Harper, M.P., Journal of Strain Analysis, Vol. 13, No. 1 (1978), p. 35-51.
- (4) Smith, D.J. and Ellison, E.G., International Journal of Pressure Vessels and Piping, Vol. 50 (1992), p. 231-241.
- (5) Ohtani, R., Yamada, K., Kashiwagi, T. and Matsubara, H., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 48, No. 435, A (1982), p. 1378-1390.
- (6) Okazaki, M., Shiraiwa, F., Hattori, I. and Koizumi, T., Journal of the Society of Materials Science, (in Japanese), Vol. 32, No. 357 (1983), p. 645-650.
- (7) Sadananda, K., Nuclear Engineering and Design, Vol. 83 (1984), p. 303-323.
- (8) Kato, Y., Hasegawa, N., Matsushima, M. and Nakashima, H., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 52, No. 476, A (1986), p. 903-907.
- (9) Ohji, K., Kubo, S., Yamakawa, N. and Kuri, T., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 50, No. 454, A (1984), p. 1218-1227.
- (10) Ohji, K., Kubo, S., Kuri, T. and Nishizaki, K., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 51, No. 469, A (1985), p. 2146-2153.
- (11) Ohji, K., Kubo, S., Kinugasa, H. and Goto, T., Journal of the Society of Materials Science, (in Japanese), Vol. 37, No. 419 (1988), p. 951-956.
- (12) Ogura, K., Miyoshi, Y. and Nishikawa, I., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 52, No. 473, A (1986), p. 89-98.
- (13) Takeuchi, E., Matsuoka, S. and Nishijima, S., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 52, No. 481, A (1986), p. 2155-2161.
- (14) Nikbin, K.M. and Webster, G.A., Low Cycle Fatigue, ASTM STP 942 (1988), p. 281-292.
- (15) Webster, G.A., International Journal of Pressure Vessels and Piping, Vol. 50 (1992), p. 133-145.
- (16) Smith, H.H., Kullen, P.S. and Michel, D.J., Metallurgical Transactions, Vol. 19A (1988), p. 881-885.
- (17) Kobayashi, H. and Park, K., Journal of Japan High Pressure Institute, (in Japanese), Vol. 30, No. 1 (1992), p. 14-23.
- (18) Makhoulouf, K. and Jones, J.W., International Journal of Fatigue, Vol. 14, No. 2 (1992), p. 97-104.
- (19) Ghonem, H., Nicholas, T. and Pineau, A., Fatigue and Fracture of Engineering Materials and Structures, Vol. 16, No. 6 (1993), p. 577-590.
- (20) Ogura, K., Nishikawa, I. and Kimura, Y., Trans. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 56, No. 523, A (1990), p. 526-531.
- (21) Stewart, A.T., Engineering Fracture Mechanics, Vol. 13 (1980), p. 463-478.
- (22) Ritchie, R.O., Suresh, S. and Moss, C.M., Journal of Engineering Materials and Technology, Vol. 102 (1980), p. 293-299.
- (23) Suresh, S., Parks, D.M. and Ritchie, R.O., Fatigue Thresholds, Vol. 1 (1982), p. 391-408.
- (24) Elber, W., Damage Tolerance in Aircraft Structures, ASTM STP 486 (1971), p. 230-242.
- (25) Sharpe, W.N. Jr., Optical Engineering, Vol. 21 (1982), p. 483-488.
- (26) Sharpe, W.N. Jr. and Su, X., Engineering Fracture Mechanics, Vol. 30, No. 3 (1988), p. 275-294.
- (27) Savitzky, A. and Golay, M.J.E., Analytical Chemistry, Vol. 36, No. 8 (1964), p. 1627-1639.
- (28) Johnson, H.H., Materials Research & Standards, Vol. 5, No. 9 (1965), p. 442-445.
- (29) Tada, H., Engineering Fracture Mechanics, Vol. 3 (1971), p. 345-347.