First online: 7 July 2017

A Method for Detecting an Unexpected Application of a Hazardous Load During Operation

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***Abstract*-A method for detecting the application of an unexpected dangerous load was investigated. An acceleration behavior of crack growth due to the application of overload and or underload during fatigue crack growth test with constant stress amplitude was observed. In some cases, the acceleration of crack growth brings catastrophic failure in machine structure. Therefore, it is useful for machine maintenance to know whether an unexpected load was applied or not by doing a daily inspection. In the present study by using center-crack specimen, a simple method of detecting the application of overload or underload was investigated. Such an unexpected load can be detected by the waveform of the function of stress and strain in the vicinity of the crack.**

Keywords- Fatigue; Acceleration of Crack Growth; Dangerous Load; Detecting Method

I. INTRODUCTION

The fatigue crack growth rate would vary from an expected situation when stress amplitude fluctuates. It is well known that the crack growth decelerates or accelerates when an overload or an underload is applied during the crack growth test with constant stress amplitude [1-8]. The focus of the present study is the acceleration behavior of fatigue crack growth. If the crack growth rate becomes higher, a machine structure or equipment will be in a dangerous situation.

The crack growth rate after overloading and underloading is related to the formation of residual stress in front of the crack tips. The crack opening stress is affected by the residual stress conditions. It is well known that the crack growth rate can be summarized with effective stress intensity range ΔK_{eff} [1-8]. The crack growth can be evaluated by the ΔK_{eff} to know whether the crack growth rate accelerates or decelerates after applying overload or underload. Therefore, to understand the crack growth behavior, the crack opening and closing behavior should be evaluated.

The acceleration of crack growth is dangerous because there is the possibility of catastrophic failure in machine structure due to unstable crack growth. If cracks grow stably, the crack length after definite loading cycling can be predicted under the application of a crack growth law. In that case, the applied load can be evaluated or measured. When an unexpected load is applied during machine operation, it is important to know whether a dangerous overload or underload is applied or not. In the present study, the main objective is to detect the application of an unexpected load which leads to the acceleration of the crack growth. The crack initiation from a notch can be detected by using a strain gage during the operation [9, 10]. That method was applied to detect the application of the overload during fatigue test with constant stress amplitude in the previous study [11]. This work was improved in the present study, and was understood that crack opening and closing behavior is strongly related to the acceleration of crack growth. In this paper, it shows the effectiveness for detecting a dangerous load by evaluating the relationship in the variation between local strain and applied stress.

II. MATERIAL AND CRACK GROWTH TESTING PROCEDURE

The material used for the experiment was 0.15% carbon steel. This is called JIS-S15C in Japan (JIS = Japanese Industrial Standards). The chemical compositions and mechanical properties of the material are shown in Table 1. A center-cracked type of specimen was employed in this experiment. Fig. 1 shows the specimen geometry and the positions where strain gages were pasted on. Dimensions of the specimens are 20 mm in length and 4 mm in width. A notch of 3 mm in length was cut in the center section of the flat part of specimen by electric discharge machine. Then the specimens were polished by emery paper and metal polisher. Before the main experiment, about 1 mm of crack was introduced from both sides of the notch root by a pull-push hydraulic fatigue testing machine. The initial crack length of the present specimen is about 4 mm which includes notch length of 3mm.

After annealing at 600˚C for 1 hr in a vacuum furnace, strain gages were pasted on the specimen surface as shown in Fig. 1 to detect an unexpected load application. The fatigue crack growth tests were carried out using a hydraulic testing machine with a constant loading frequency of 10Hz with negative stress ratio R= -1 in laboratory room conditions. Fig. 2 shows the overview of the equipment used for testing. Overload or underload was applied when the crack length reached about 6 mm.

DOI: 10.5963/AMSA0601002

This crack length is defined as including the notch length. The crack opening and closing stresses were measured by using the strain gages. Crack length was measured by an optical microscope which was connected to an image display system device to make it easy to measure the crack length.

TABLE 1 CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES OF 0.15% CARBON STEEL (σ_s; YIELD STRESS [mpa], σ_b; ULTIMATE TENSILE STRENGTH [mpa], ψ REDUCTION OF AREA [%])

Chemical composition [wt., %]									Mechanical properties [MPa, %]		
C	Si	Mn	P	S	Cr	Ni	Cu	Fe	σ_S	σ_B	ψ
0.15	0.30	0.50	0.013	0.013	0.19	0.05	0.14	Bal.	283	449	60

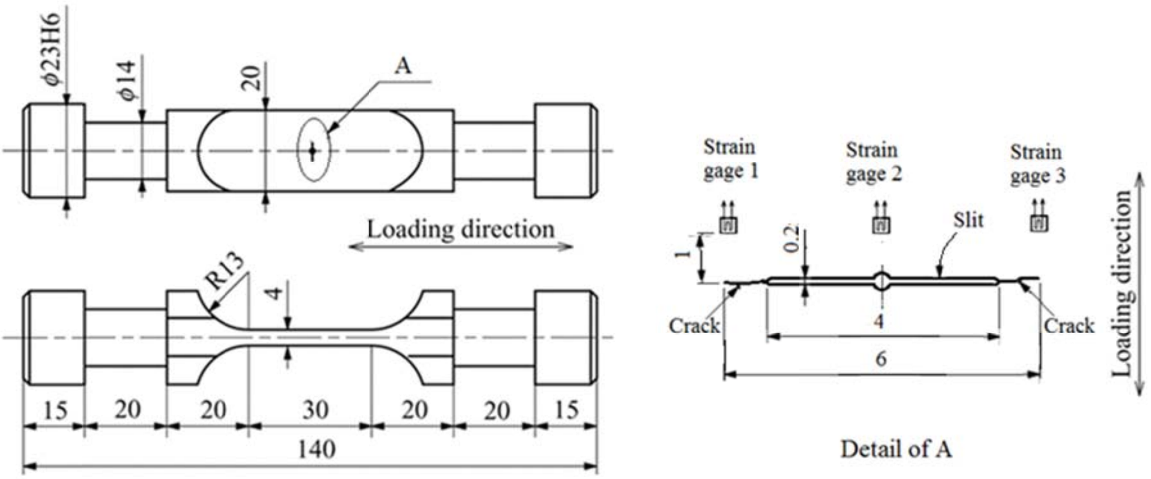

Fig. 1 Geometry of the specimen and position of strain gages (Unit: mm)

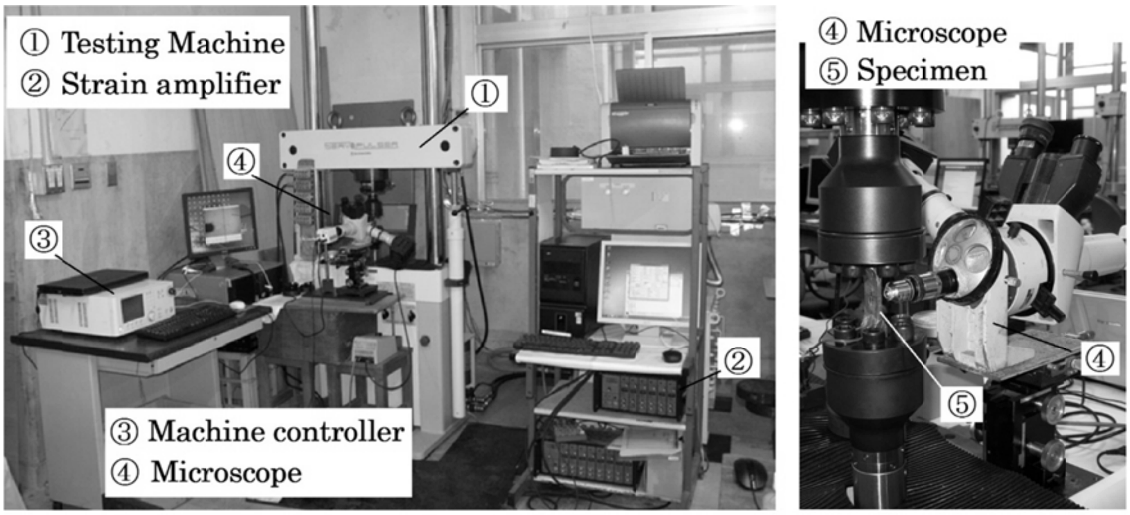

Fig. 2 Equipment used for testing

III. METHOD OF MEASURING CRACK OPENING AND CLOSING STRESSES

There are some methods of measuring crack opening and closing stress. The "Unloading elastic compliance method" was measured which was proposed by Kikukawa et al. [12]. Fig. 3 shows the schematic representation of that method of the present study. Due to the applied stress level and positions of pasted strain gages, the hysteresis loops of stress - strain curve showed different shapes depending on the elastic-plastic behavior. First of all, the gradient C of the stress σ - strain ε relation on unloading stage within a range of $0.9\sigma_{max}$ - $0.6\sigma_{max}$ was measured. Then the following strain function was calculated,

$$H_i = \varepsilon_i - C\sigma_i \tag{1}$$

Where, C = $\Delta\varepsilon_i/\Delta\sigma_i$ in the range of $0.9\sigma_{max}$ - $0.6\sigma_{max}$ on unloading stage, and the subscript 'i' shows the measurement position of strain as shown in Fig. 1.

As shown in Fig. 3, the points of crack opening and closing stress are measured by the turning points or changing points of curvature of $\sigma - H$ loop [5, 12]. In some cases, the minimum value of H coincides with the crack opening stress. Where, σ_{op}

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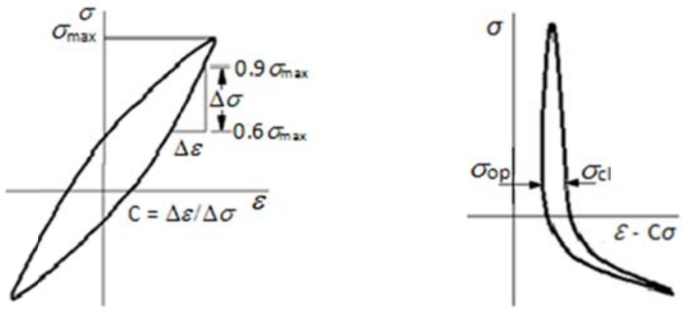
represents crack opening stress and σ_{cl} crack closing stress.



(a) (b) (c)

Fig. 3 Schematic representation of the measurement of the crack opening and closing stresses; (a) Original stress – strain loop, (b) σ vs. H in the case of $\varepsilon_e > \varepsilon_p$, (c) σ vs. H in the case of $\varepsilon_e < \varepsilon_p$; Where, ε_e is elastic strain and ε_p plastic strain

IV. RESULTS AND DISCUSSION

There are some cases of machine failure related to metal fatigue [13, 14]. It is well known that the specimen does not fail immediately after the fatigue crack initiation. Thus, even if a fatigue crack is initiated, the machine structure can be available for work on condition that the fatigue cracks growth behavior is safe or the fatigue crack stops growing [14, 15]. So, some machines were in operation for a limited term though a crack initiated in the equipment. When the crack length is measured and crack growth behavior is predicted by the crack growth law during operation when an unexpected load is not applied, the machine is controlled under safe conditions. However, once an unexpected load is applied, the crack growth behavior changes. Sudden stopping of machine operation is affected by the loading conditions. The occurrence of an earthquake is expected to bring damage to machine structure. Such possible cases of unexpected load applications had better be considered.

In the present study, the acceleration of crack growth behavior was confirmed after the application of overloading and underloading during fatigue test with a center-cracked specimen with constant amplitude. Then a method of detecting the application of such an unexpected load was examined.

A. Crack Growth Behavior

The crack growth behavior after the application of overload and or underload was examined. After the application of such a load manually, the fatigue test was continued under the same testing conditions as that before the application. The following are conditions of manual load application; the case of overload and underload are σ_{ou} =185 MPa & -185 MPa, -185 MPa & 185 MPa, -113 MPa & 113 MPa and the cases of single underload are σ_{ul} = -113 MPa, -185 MPa. Because it is known that the acceleration behavior tends to occur when the underload is applied in the cases of negative stress ratio [7, 8], the loading conditions of the present investigations was chosen. Now, the order of underloading and overloading was not affected by the tendency of the crack growth. Hereinafter, those loads are called unexpected load or unexpected stress, conveniently. Also, the symbols of unexpected stress are defined as follows, σ_{ul} is underload, σ_{ol} overload and σ_{ou} overload and underload. The crack growth test was performed with constant stress amplitude σ_a = 86 MPa with stress ratio R = -1.

Fig. 4 shows the relationship between half-crack length a and number of stress cycles N. A series of fatigue tests were carried out to investigate the crack growth behavior. The crack growth behavior with the application of unexpected load was compared with that without unexpected load (which is the baseline of the present study's data). The arrow shows the application point of such unexpected load. In comparison with the baseline, the crack growth rate accelerated when the applied unexpected load was over some critical stress level. In the present study, the acceleration of crack growth was observed when σ_{ou} = ±185MPa and σ_{ul} = -185MPa. In the case of σ_{ul} = -113MPa, the crack growth rate was almost the same as that of the baseline. In the case of σ_{ou}= ±113MPa, the crack growth decelerated from the base line.

Fig. 5 shows the relationship between the crack propagation rate da/dN and stress intensity K at maximum stress. It is clear that the crack growth rate is higher than the baseline when the unexpected load was applied with σ_{ou} = ±185MPa and σ_{ul} = -185MPa.

B. Detecting the Application of Dangerous Load

To detect the application of a dangerous load, the crack opening and closing stresses was measured. Because the crack growth rate is evaluated well by using the effective stress intensity range which is determined by the crack opening or closing stress, even if fluctuating stress is applied [1-8]. When the crack opening and closing stress level became lower than the baseline case after applying an unexpected load, the crack growth rate became higher than the baseline case. On the other hand, the higher level stresses of the crack opening and closing bring a lower crack growth rate after applying an unexpected load.

DOI: 10.5963/AMSA0601002

Such behavior of cracks can be applied to the detection of the application of a dangerous load. So, the crack opening and closing was measured by using the loop and waveform of the stress σ and strain function *H* shown in Eq. (1). Figs. 6 and 7 show the loop and waveform of σ and *H* in the cases of overload and underload application. Figs. 8 and 9 show those in the case of a single underload application. The loop and waveform shapes were compared before and after the unexpected load was applied. Their change is strongly related to the crack opening and closing behavior.

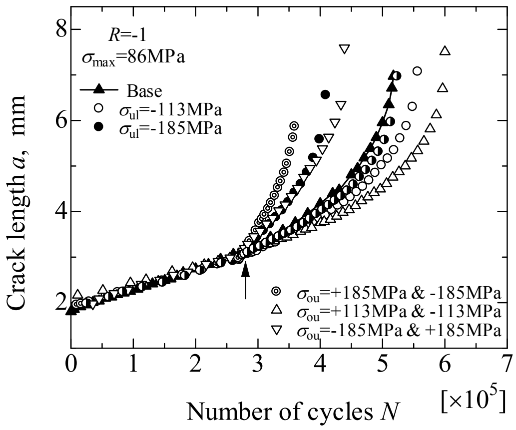


Fig. 4 Crack length a vs. Number of cycles N

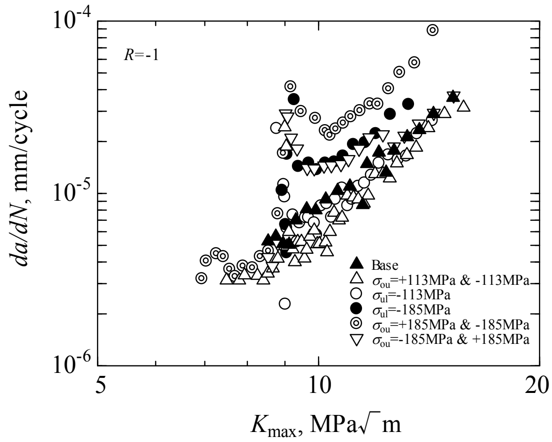


Fig. 5 da/dN vs. K_{max}

Fig. 6 shows the case of σ_{uo}= -113MPa and 113MPa. Now, the data was taken at N = 313760 and a= 3.10mm before applying an unexpected load, and at N = 322000 and a= 3.15mm after that. In the other cases, the data were detained in almost the same situation as the case of Fig. 6. As shown in Figs. 4 and 5, the crack growth was not accelerated after applying unexpected load. Also, the crack opening and closing stress were measured as shown in Fig. 3. It is understood from the loop of σ- H (Figs. 6 (a1) and (b1)) that the crack opening and closing stresses keep the value close to 0 MPa before and after the overload. When the crack opening and closing stresses hardly varied before and after applying an unexpected load, the crack growth did not accelerate after applying that. Whether a dangerous unexpected load was applied or not was examined by using the waveform shape of the strain function *H* after spending some time on the application of unexpected load. It is found that the crack opening and closing stresses were determined by the time where the waveform of strain function *H* showed the changing. The dotted lines show the times of crack opening and closing. In the case of Fig. 6, that waveform hardly changed and the local maximum point and the turning point of the waveform of *H* were crack opening and closing points.

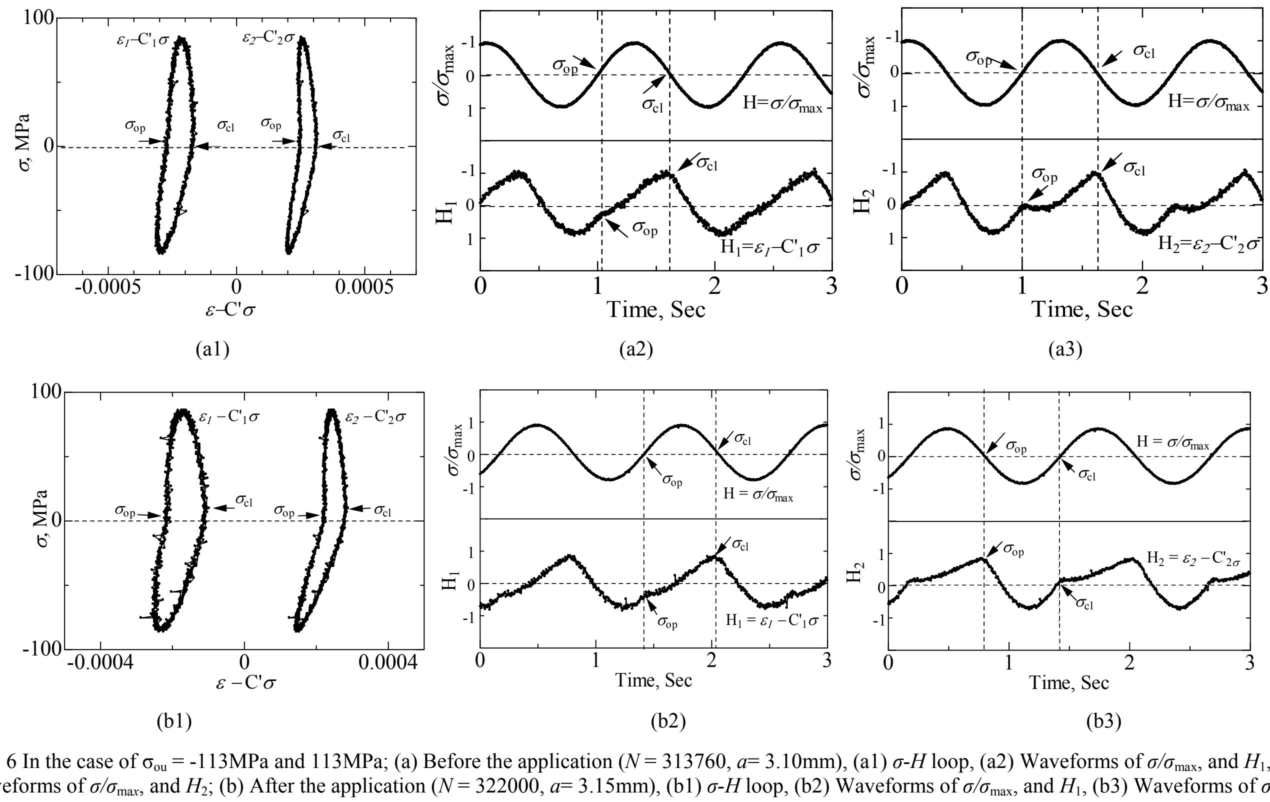


Fig. 6 In the case of σ_{ou} = -113MPa and 113MPa; (a) Before the application (N = 313760, a= 3.10mm), (a1) σ-H loop, (a2) Waveforms of σ/σ_{max}, and H_1, (a3) Waveforms of σ/σ_{max}, and H_2; (b) After the application (N = 322000, a= 3.15mm), (b1) σ-H loop, (b2) Waveforms of σ/σ_{max}, and H_1, (b3) Waveforms of σ/σ_{max}, and H_2

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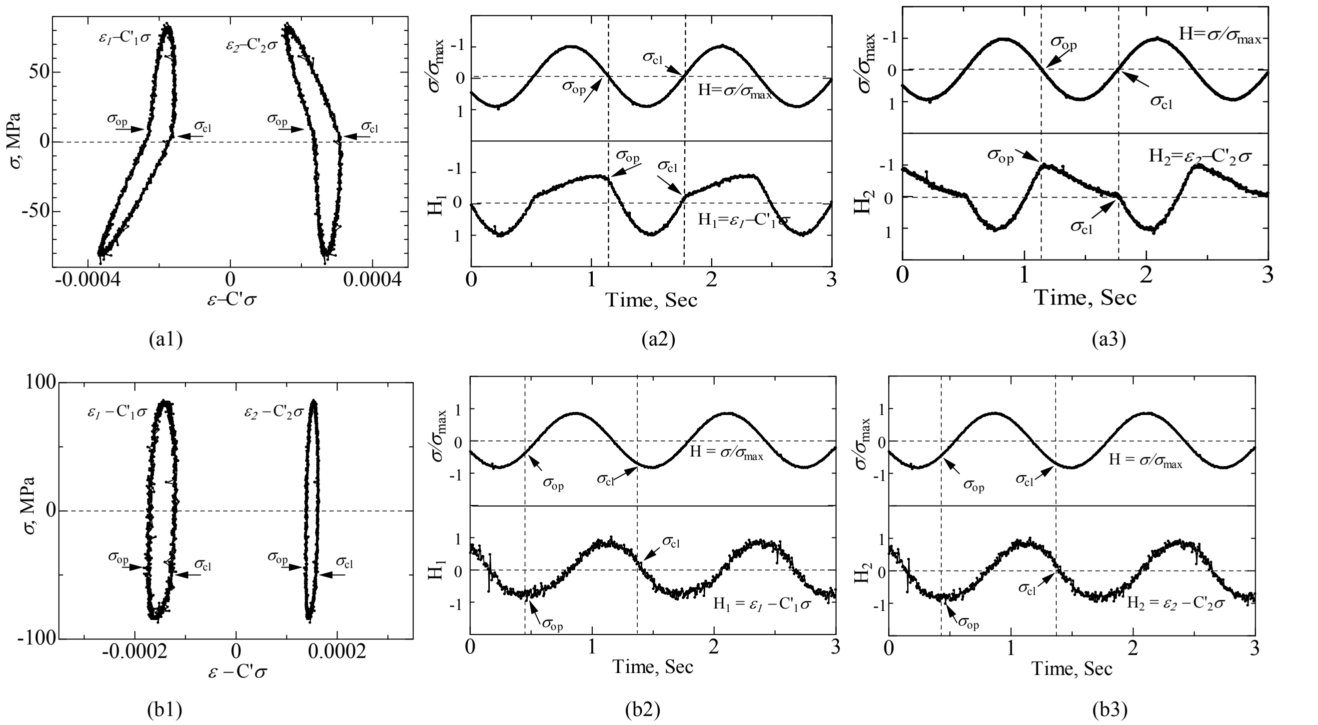

Fig. 7 In the case of σ_{ou} = -185MPa and 185MPa; (a) Before the application (N = 269005, a= 3.10mm), (a1) σ-H loop, (a2) Waveforms of $\sigma/\sigma_{\max}$, and H_1, (a3) Waveforms of $\sigma/\sigma_{\max}$, and H_2; (b) After the application (N = 272609, a= 3.20mm), (b1) σ-H loop, (b2) Waveforms of $\sigma/\sigma_{\max}$, and H_1, (b3) Waveforms of $\sigma/\sigma_{\max}$, and H_2

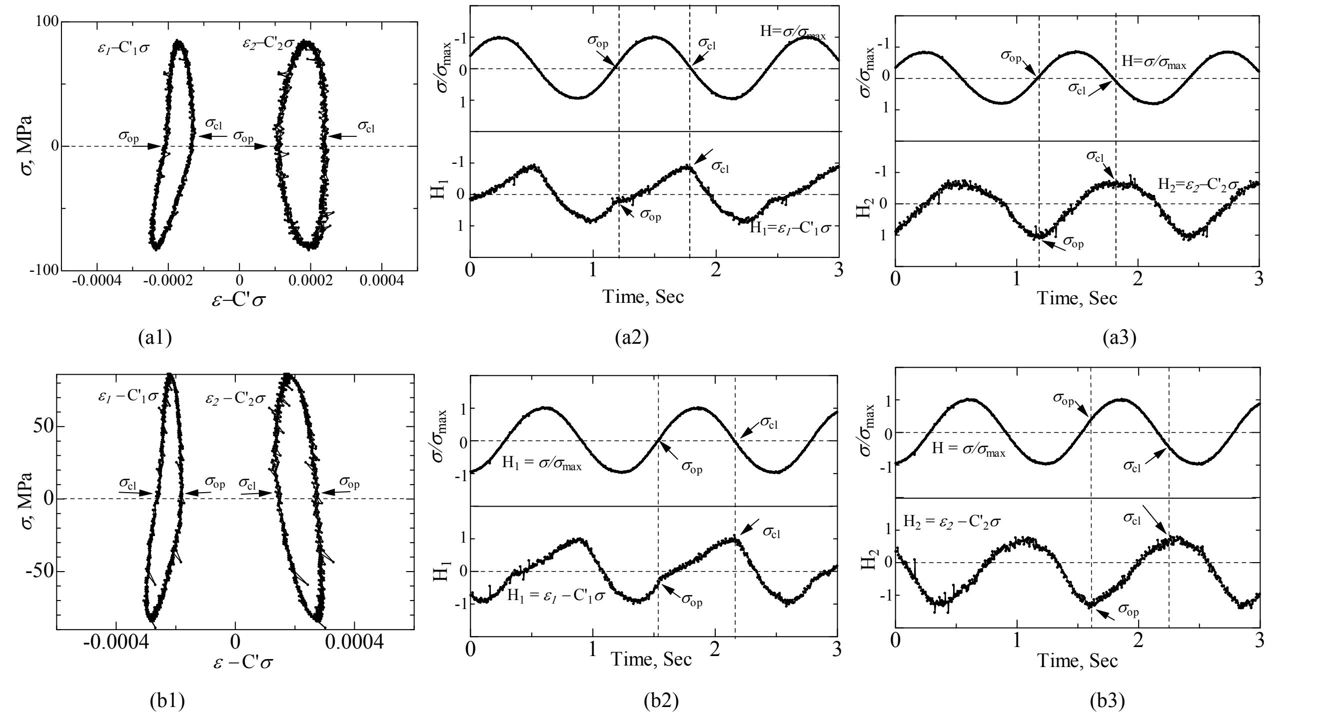

Fig. 8 In the case of σ_{ul} = -113MPa; (a) Before the application (N = 20000, a= 3.10mm), (a1) σ-H loop, (a2) Waveforms of σ/σ_{max}, and H_1, (a3) Waveforms of σ/σ_{max}, and H_2; (b) After the application (N = 28506, a= 3.13mm (b1) σ-H loop, (b2) Waveforms of σ/σ_{max}, and H_1, (b3) Waveforms of σ/σ_{max}, and H_2

DOI: 10.5963/AMSA0601002

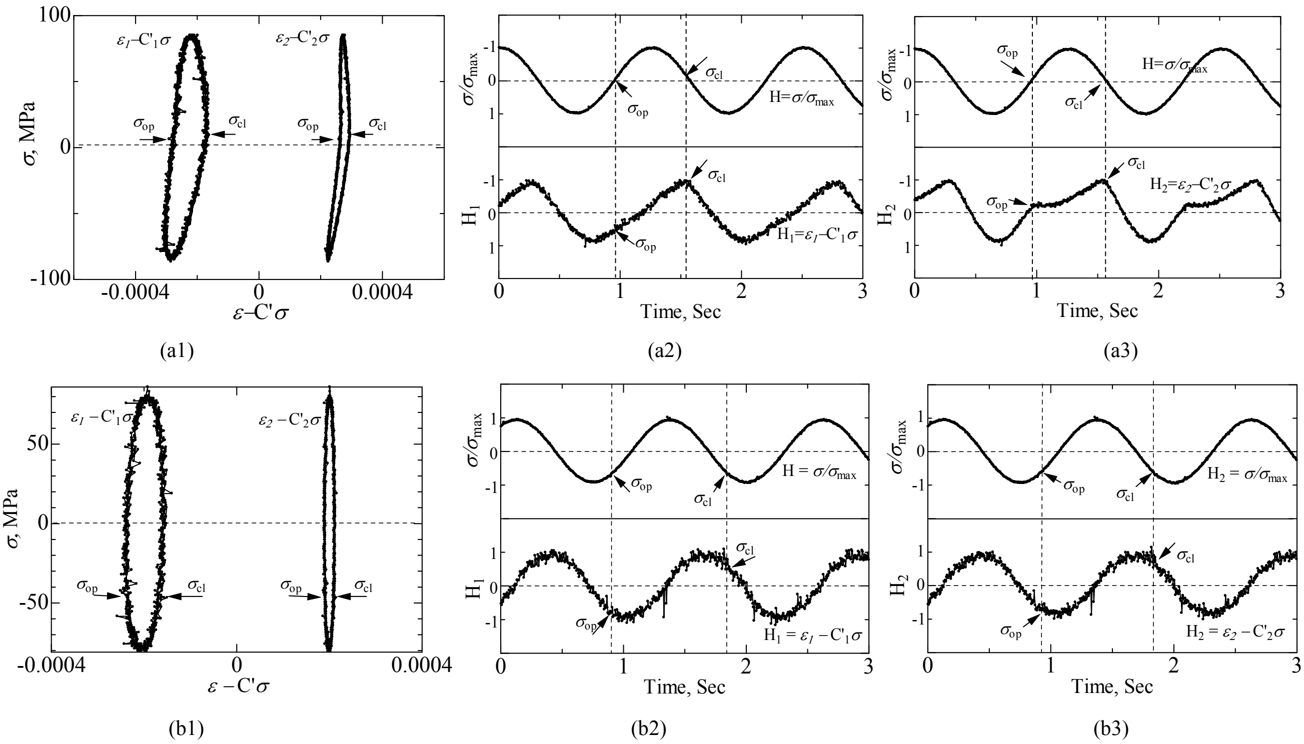

Fig. 9 In the case of σ_{ul} = -185MPa; (a) Before the application (N = 240110, a=3.10mm), (a1) σ-H loop, (a2) Waveforms of σ/σ_{max}, and H_1, (a3) Waveforms of σ/σ_{max}, and H_2; (b) After the application (N = 241108, a=3.13mm), (b1) σ-H loop, (b2) Waveforms of σ/σ_{max}, and H_1, (b3) Waveforms of σ/σ_{max}, and H_2

Fig. 7 shows the case of σ_{uo}= -185MPa and 185MPa. Since the crack growth accelerated after applying an unexpected load, the detection of changes in the loop and waveform is very important to detect the crack growth acceleration. It is found that the loop and waveform of σ and H after applying an unexpected load were changed from those before applying an unexpected load. Before applying an unexpected load, the loop and waveform were almost the same as the case of Fig. 6 (a). However, in the case of Fig. 7, the crack opening and closing stress moved to the negative stress level. Also, it is expected that the crack tip was fully opened just after applying unexpected load. In the case of Fig. 6 (b), the shapes of the waveform H are different from a sine waveform. However, in the case of Fig. 7 (b), the turning points in the waveform H are not clear, and the waveform of this is closer to a sine waveform than the case of Fig. 6 (b). Therefore, the application of a dangerous unexpected load by inspection of the waveform could be detected.

Human health can be checked by the electrocardiogram. The waveform of strain function could be detected, like the electrocardiogram, continuously; then whether the dangerous load was applied or not can be detected. Therefore, it is better to continuously check the strain waveform for the purpose of inspecting machine health.

Similar results were obtained in the cases of Figs. 8 and Fig. 9. A single underload was applied in those cases. It is known that the acceleration of crack growth tends to happen in the case of applying an underload rather than in the case of applying an overload [10]. The purpose of the present study is to investigate a simple method of detecting the application of a dangerous load. In the present stage of the study, it is found that the application of a higher level of overload and underload bring an acceleration of crack growth, and those loads can be detected by the waveform of a strain function. In the future, the detailed condition of acceleration of fatigue crack growth will be investigated.

C. Observation in the Vicinity of Crack Tip

The acceleration and deceleration of crack growth are related to the residual stress conditions in front of the crack tips. The residual stress conditions are related to the applied stress amplitude, stress ratio, and unexpected load levels. Also, crack tip deformation is related to the residual stress conditions [7, 8].

Fig. 10 shows the observation results of the crack tip. In the case of acceleration of the crack growth (σ_{ou} = -185MPa and 185MPa), from the comparison of the situation of the crack tip before (Fig. 10 (b1)) and after (Figs. 10 (b2) and (b3)) applying an unexpected load, it is observed that the crack tip was once blunted and sharpened again. As discussed by Makabe et al. [8], when the opened crack was closed again, residual tensile stress was created in front of the crack tip. Now, the arrow shows the position of crack tip in Fig. 10. In the case where the crack tip was not blunted much after applying an unexpected load as shown in Fig. 10 (a), compressive residual stress was created in front of the crack tip. One of the mechanisms of crack growth acceleration and deceleration after applying an unexpected load is shown in the present paper. In future, the residual stress and strain distributions in the vicinity of the crack will be calculated, then a more effective method of detecting dangerous loads will be discussed.

DOI: 10.5963/AMSA0601002

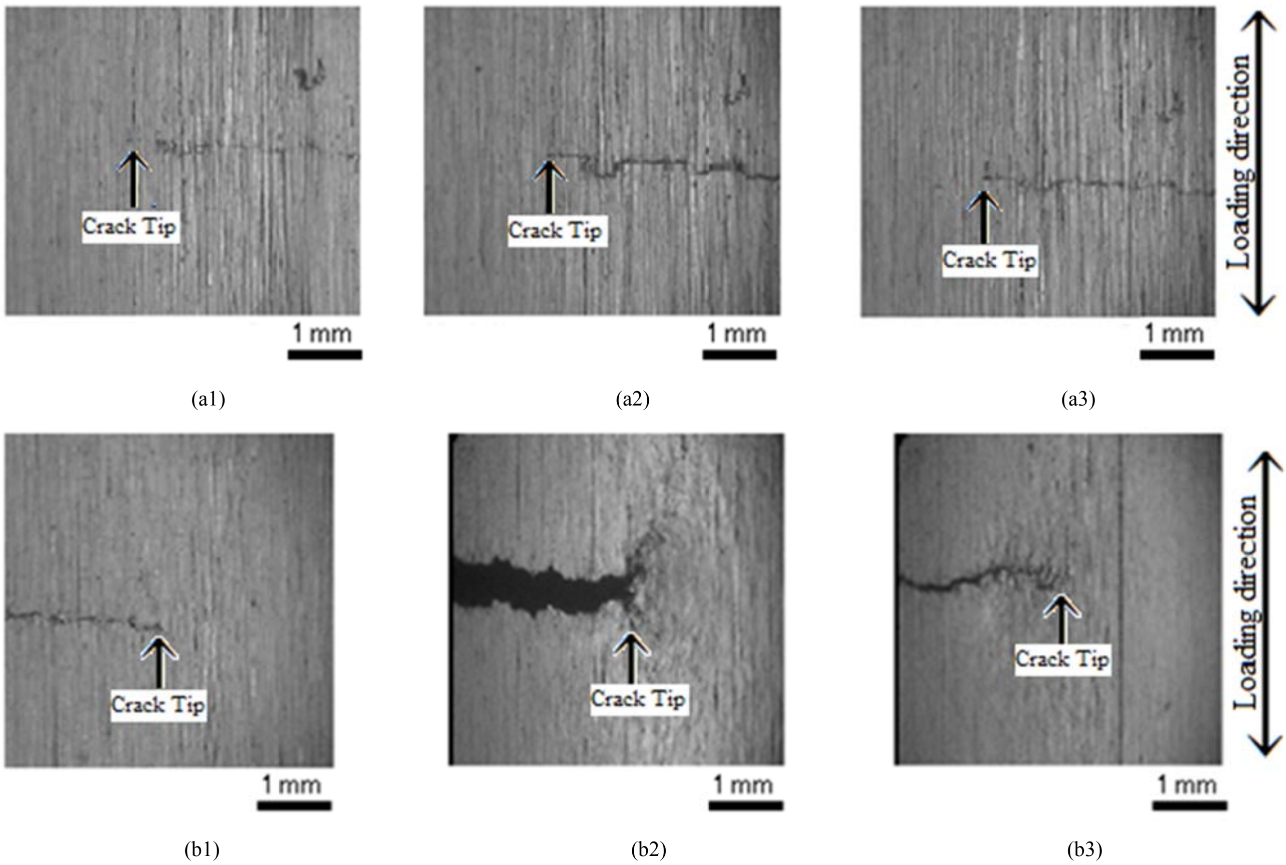

Fig. 10 Comparison of crack opening behavior after applying unexpected load: (a) In the case of σ_{ou} = -113MPa and 113MPa, (a1) Before application of overload and underload (N=313500, a=3.05mm), (a2) Just overloading (N=313760, a=3.10mm), (a3) After application of overload and underload (N= 314760, a= 3.12mm), (b) In the case of σ_{ou} = -185MPa and 185MPa, (b1) Before application of overload and underload (N=85229, a=2.35mm), (b2) Just overloading N=269000, a=3.10mm), (b3) After application of overload and underload (N= 272609, a= 3.20mm)

V. CONCLUSIONS

The method for detecting the application of an unexpected load leads to the acceleration of fatigue crack growth. The main results obtained are as follows:

(1) In the present study, an application of overload and/or underload was performed during fatigue crack growth test with constant stress amplitude. The acceleration of fatigue crack growth occurred when the residual tensile stress created in front of the crack tips and the crack opening and closing stresses reached a lower level.

(2) The shapes of stress – strain loops were changed when the crack growth rate was changed due to applying an unexpected load. This phenomenon was related to the crack closure behavior.

(3) The crack opening and closing stresses could be easily measured by using the relationship between the stress and the strain function which was proposed by Kikukawa et al. [12].

(4) Monitoring for the detection of an application of a dangerous load can continuously be performed by using the waveform of the stress and the strain function. Those waveforms changed when the crack growth rate varied due to the application of dangerous load.

ACKNOWLEDGEMENTS

This work was performed as a part of a Project of Okinawa innovation system building business of science and technology, which was supported by the Okinawa Science and Technology Promotion Center. Also this work was supported in part by the Collaborative Research Program of the Research Institute for Applied Mechanics, Kyushu University.

REFERENCES

[1] W. Elber, "The Significance of Fatigue Crack Closure," ASTM STP 486. ASTM International, West Conshohocken, pp. 230-242, PA, 1971.

[2] A. J. McEvily, "Current aspects of fatigue," *Metal Science*, vol. 11(1077), pp. 274-284, 1977.

[3] A. J. McEvily and Z. Yang, "The nature of the two opening levels following an overload in fatigue crack growth," *Metallurgical Transactions*, vol. 21A, pp. 2717-2727, 1990.

DOI: 10.5963/AMSA0601002

[4] H. Bao and A.J. McEvily, “The effect of overload on the rate of crack propagation under plane strain conditions,” *Metallurgical and Materials Transactions*, vol. 26A, pp. 1725-1733, 1995.

[5] D. H. Chen and H. Nisitani, “Analytical and experimental study of crack closure behavior based on an S shaped unloaded curve,” ASTM STP 982, Mechanics of Fatigue crack Closure, pp. 475-488, 1988.

[6] C. M. Ward-Close, A.F. Blom, and O. R. Richie, “Mechanism associated with transient fatigue crack growth under variable-amplitude loading: an experimental and numerical study,” *Engineering Fracture Mechanics*, vol. 32, pp. 613-618, 1989.

[7] C. Makabe, A. Purnowidodo, and A. J. McEvily, “Effects of surface deformation and crack closure on fatigue crack propagation after overloading and underloading,” *International Journal of Fatigue,* vol. 26, pp. 1341-1348, 2004.

[8] C. Makabe, A. Purnowidodo, T. Miyazaki, and A. J. McEvily, “Deceleration and acceleration of crack propagation after an overload under negative baseline stress ratio,” *Journal of Testing and Evaluation*, vol. 33, pp. 181-187, 2005.

[9] C. Makabe and H. Kaneshiro, “A method of detecting the fatigue crack initiation and growth in a holed specimen based on crack tip opening and closing,” *Engineering Fracture Mechanics*, vol. 41, pp. 395-403, 1992.

[10] C. Makabe, H. Kaneshiro, S. Nishida, and C. Urashima, “Detection of 1 mm fatigue crack initiation using strain waveform,” *Journal of Engineering Materials and Technology, ASME*, vol. 116, pp. 483-487, 1994.

[11] C. Makabe, A. Purnowidodo, T. Sueyoshi, and T. Utsunomiya, “Detecting overload from strain information during fatigue crack propagation under negative stress ratio,” *Testing and Evaluation*, vol. 32, pp. 56-61, 2004.

[12] M. Kikukawa, M. Jono, K. Takaka, and M. Takatani, “Measurement of fatigue crack propagation and crack closure at low stress intensity level by unloading elastic compliance method,” *Journal of the Society of Materials Science Japan*, vol. 25, pp. 899-903, 1976.

[13] S. Nishida, *Failure Analysis in Engineering Applications*, Butterworth Heinemann Ltd., pp. 1-5, 1992.

[14] A. J. McEvily, *Metal Failures Mechanisms, Analysis, Prevention*, Wiley Interscience Publication, pp. 1-20, 2002.

[15] C. Makabe, K. Naka, and Y. Katsushima, “Example of arresting crack growth in welded parts,” *Industrial Engineering & Management*, vol. 4, pp. 1-4, 2015.

DOI: 10.5963/AMSA0601002