Healing of Fatigue Crack Treated with Surface-Activated Pre-Coating Method by Controlling High-Density Electric Current

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Abstract A technique to heal a fatigue crack for a stainless steel by controlling a high-density electric current field was studied. The high-density electric current was applied at the crack tip using electrodes. A surface-activated pre-coating technique was used in order to improve adhesion of the crack surface. The crack on the specimen surface was observed by scanning electron microscope (SEM) before and after the application of the high-density electric current to examine the effect of the fatigue crack healing. The experimental results showed that the fatigue crack was closed and the crack growth rate of a healed specimen was decreased by the electrical stimulation.

Keywords Crack Healing, Fatigue, Crack Closure, Electric Current, Stainless Steel

1. Introduction

Fatigue is the main reason of failure accidents in metallic structures. To improve long term durability and reliability of structures, various methods are studied. The techniques to improve the fatigue strength, such as high-frequency quenching, carburizing, nitriding and shot peening, had been developed. They can prolong the fatigue life of materials by suppressing the crack initiation on the material surface. However, the advantages of these methods are limited for the materials where a crack had been existed. If damage of materials can be healed, it is possible to improve the reliability and durability of the industrial materials remarkably. Recently, some researchers have studied crack healing techniques in polymer materials and ceramic materials [1-3]. However, a technique to heal essentially a fatigue crack detected in metallic materials has not been established.

The studies to improve the mechanical properties of metallic materials have been conducted by the application of the electric current for a few decades. Karpenko et al. [4] showed that the fatigue life of a steel was prolonged by the application of the electric current during fatigue loadings. Golovin et al. [5] studied the effect of the high-density pulse current on the crack propagation of a silicon iron during the dynamic tensile loading. They showed that the crack propagation halted when the high-density pulse current was applied just before the crack initiation. Conrad and coauthors [6-10] investigated the influence of high-density pulse current on materials in detail. They showed that the action of drift electrons influenced the dislocation mobility. As other effects, the following phenomena are known, such as the generation of Joule heating [11], the cause of the compressive stress due to Joule heating [12-14], the induction of Lorentz force [15], the cause of the electron wind force due to the flow of the electric current [16].

Although some studies to improve the mechanical and material properties by applying the electric current in metallic materials have been conducted, a method for the essential healing of a fatigue crack has not been established yet. Therefore, the authors developed the technique to heal a fatigue crack in a stainless steel by controlling the high-density electric current field [17, 18]. In these researches, it is revealed that the crack was closed and the bridging by partial melting was formed between the crack surfaces. However, the adhesion between the crack surfaces is prevented due to the oxide layer on the crack surfaces. In this study we proposed to improve the adhesion of the crack surfaces by treating surface-activated pre-coating technique, which eliminates oxide layer and coats Ni on the crack surfaces. In addition, we evaluated quantitatively the healing effect of the fatigue crack treated with the surface-activated pre-coating method by controlling high-density electric current.

2. Experiments

2.1. Specimens

Austenite stainless steel SUS316 was used as the experimental material. The chemical compositions and the mechanical properties of SUS316 are shown in Tables 1 and 2, respectively. The dumbbell-shaped specimens were used, and the schematic is represented in Fig. 1. A notch was introduced at the center of the one-side edge in the specimens. The specimens were treated with stress relief annealing to remove the residual stress caused in machining process. The heat treatment process is as follows. The specimens are heated to 1173 K for 4 hours, and the temperature is kept at 1173 K for 10 minutes. After that, the specimens are cooled slowly to a room temperature in a furnace. The surfaces of the specimens were polished to a mirror plane by using a buffing machine to observe the surface condition.

2.2. Experimental conditions

2.2.1. Fatigue test conditions

The tensile fatigue tests were conducted to introduce a fatigue crack with the annealed specimen, and were carried out at the room temperature in the atmosphere under load control conditions with a hydraulic driven testing machine. All of the tests were conducted at a stress ratio of R=0.05 and a frequency of f=10 Hz. The details of the fatigue test conditions are shown in Table 3. The crack length under cyclic loading was measured by in-situ observation using a digital microscope. In this paper, the test conditions and results of two major examples were indicated. Each specimen is named Specimen A and B. For comparison, the specimen which is not applied electric current is named Standard specimen.

2.2.2. Surface-activated pre-coatings

The surface-activated pre-coating technique, which eliminates the oxide layer and coats Ni film for preventing reoxidation, was treated on the crack surfaces. The surface-activated pre-coating technique was composed of three stages as follows. The first stage is electrolytic cleaning, the second stage is HCl activating and the third stage is Ni striking. The schematic of surface-activated pre-coating technique is represented in Fig. 2. The specimen is washed by using pure water between every stage. In the stage of the electrolytic cleaning, the specimen is washed in alkali solution. The composition of the alkali solution is 30 g/L NaOH, Na_2Co_3 and Na_4SiO_3. The anode was connected to Al plate and the cathode was to the specimen. The electrolytic cleaning current density is 10 A/dm^2, a time of current duration is 60 seconds and the alkali solution is maintained at a temperature of 60 °C. In the stage of the HCl activating, the oxide layer on the specimen was eliminated in 37 % HCl solutions for 10 seconds. At the stage of Ni striking, the oxide layer on the specimen was eliminated and the Ni film was coated for preventing reoxidation. The composition of the Ni coating solution is 240 g/L $NiCl_2$ and 80 g/L 37%HCl. The anode was connected to Ni plate and the cathode was to the specimen in the coating solution. The current density is 10 A/dm^2 and a time of current duration are 60 seconds.

2.2.3 Conditions of electric current application

The electric current was applied to heal the fatigue crack. The application of electric current was carried out using a transistor type power source. The pulse current was applied through the electrodes striding across the notch as shown in Fig. 3. The chromium cupper electrodes of 5 mm in diameter were used. Two electrodes were connected straddling the notch of the specimen. The distance between two electrodes was 1.3 mm. The conditions of the application of the electric current are shown in Table 4. The pulse electric current was applied to the specimen once and more, and the crack state on the specimen surface was observed with a scanning electron microscope (SEM) before and after every application of the electric current.

Table 1. Chemical compositions of the stainless steel SUS316 (wt. %)

C	Si	Mn	P	S	Ni	Cr	Mo	Fe
0.05	0.26	1.3	0.028	0.03	10.1	17.09	2.01	Balance

Table 2. Mechanical properties of SUS316

Yield stress [MPa]	Tensile strength [MPa]	Young's modulus [GPa]	Poisson's ratio	Hardness HBW
300	573	193	0.3	161

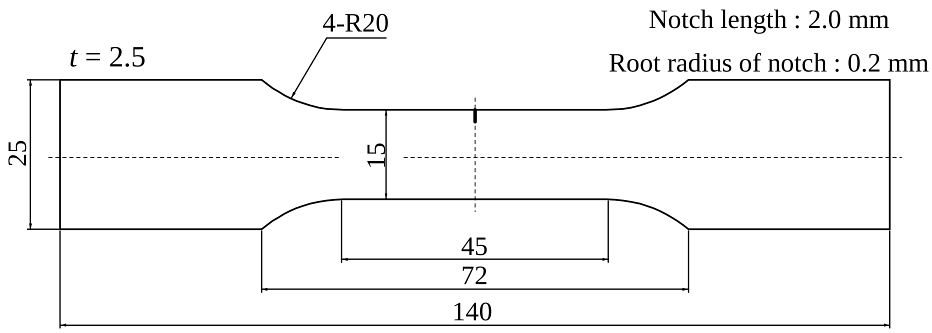


Figure 1. Schematic of specimen

Table 3. Fatigue test and crack conditions before current application

	Specimen A	Specimen B	Standard
The maximum gross stress σ_{max} [MPa]	180	150	150
Stress ratio R	0.05	0.05	0.05
Frequency f [Hz]	10	10	10
Pre-crack length a [mm]	1.55	1.08	-

Table 4. Conditions of the electric current

	Specimen A	Specimen B
Applied current [A]	4000	8000
Pulse duration [msec]	2.0	1.0
The Number of current application	12	1

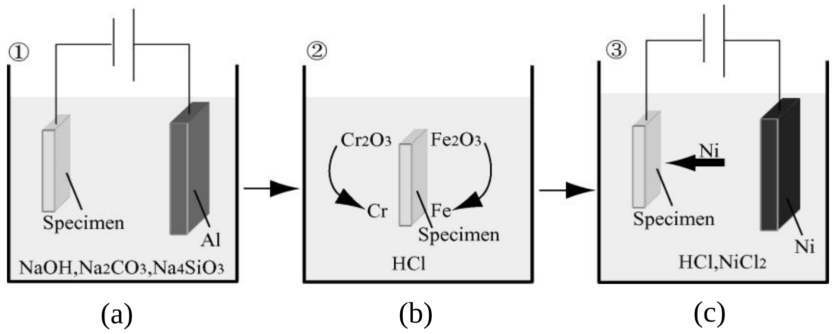


Figure 2. Schematic diagram of surface-activated pre-coating technique:
(a) Electrolytic cleaning, (b) HCl activating, (c) Ni striking

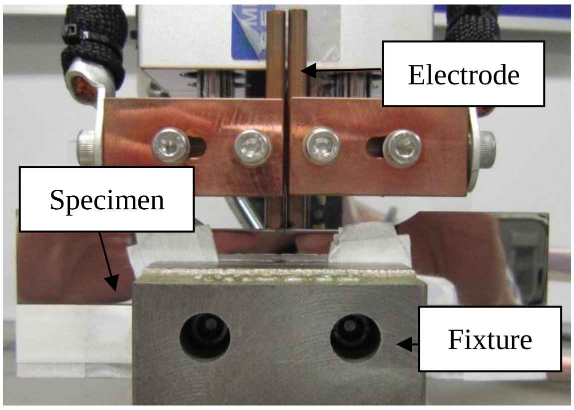


Figure 3. Applying electric current

3. Experimental results

3.1. Observation of fatigue crack

The elemental components were observed with an auger microprobe to confirm the effect of the surface-activated pre-coating technique. Figure 4 shows the relationship between atomic concentration of O, Cr, Fe and Ni and depth from the specimen surface after Ni striking. The Fe and Cr are the main element of the specimens, SUS316, and Ni is the element coated by the surface-activated pre-coating technique. It is observed that the oxide layer, O is almost eliminated at the surface of the specimen and Ni coating film is approximately 630 nm thick.

The crack state on the specimen surface was observed with SEM. Figure 5 shows the fatigue crack shape before the application of the electric current in Specimen A. The points to measure the change of the crack width were indicated. Figure 6 shows the change of the fatigue crack shape at each application of the electric current in Specimen A. It is observed that the crack was closed for almost every application of the electrical current. Figure 7 is an enlarged picture at the area near the point 3 which is approximately 900 μm away from the crack tip before the application and after the 12th application of the electric current in Specimen A. The adhesion between the crack surfaces was observed and it is observed that the application of electric current also has an effect on the area far from the crack tip. Figure 8 shows the change of crack width for every application of the electric current. Compared to before the application and after the twelfth application of the electric current, the crack width near the notch decreased from approximately 39 μm to 8.5 μm. After the twelfth application of the electric current, the whole crack was closed 75-97 % from original crack, and the whole crack width was less than 10 μm. The bonding of the crack surfaces was confirmed by cutting the specimen vertically to the direction of the crack propagation.

The elemental components at the inside of the crack were observed with the auger microprobe. Figure 9 shows the auger spectrum at the bridge formation inside of the crack after the application of the electric current. It is observed that the intensity of the spectral line is strong at the electron energy of Fe and Ni, and Fe and Ni are alloyed on the crack surface.

3.2. Evaluation of crack growth behavior

The behavior of the crack growth was evaluated quantitatively in order to research the effect of the crack healing. The crack closure was confirmed at the Specimen B in the same way like Specimen A. Figure 10 shows the crack growth rate as a function of the stress intensity factor range, Paris law, with Standard specimens without the application of the electric current. The fatigue test was conducted at σ_{max} = 150 MPa in the Specimen B after the application of the electric current. Figure 11 shows that before and after the application of the electric current in the Specimen B. The solid line indicates the approximate line of the results of Standard specimens without applying the electric current. The open and solid symbols B show the behavior of the crack growth in specimen B before and after the application of the electric current, respectively. It was observed that the crack growth rate decreased from 3.69×10^{-8} to 2.52×10^{-8} m/cycle just after the application of current compared to that of Standard specimens.

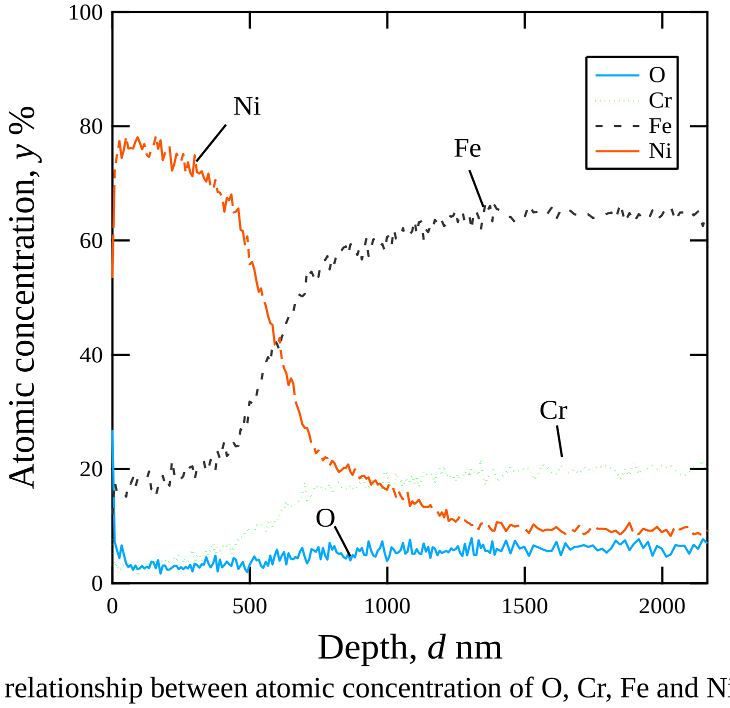


Figure 4. The relationship between atomic concentration of O, Cr, Fe and Ni and depth from the specimen surface after Ni striking

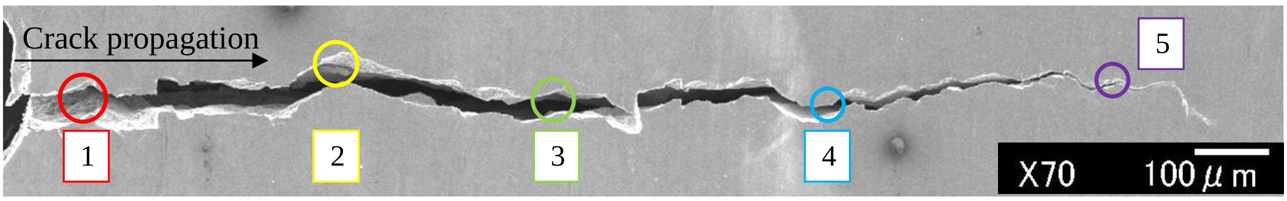
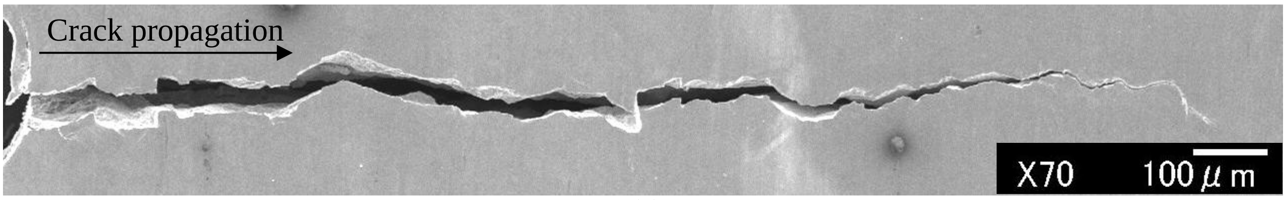
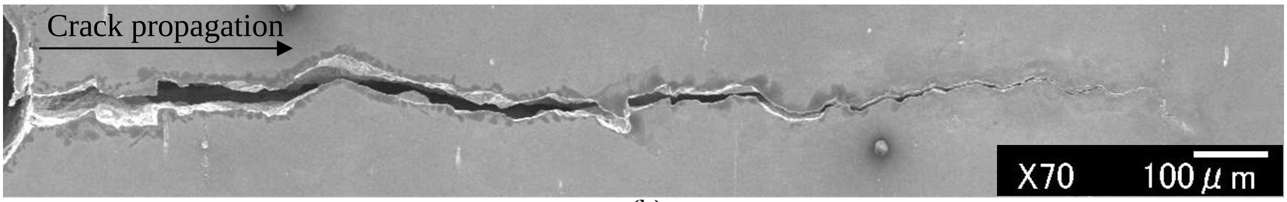


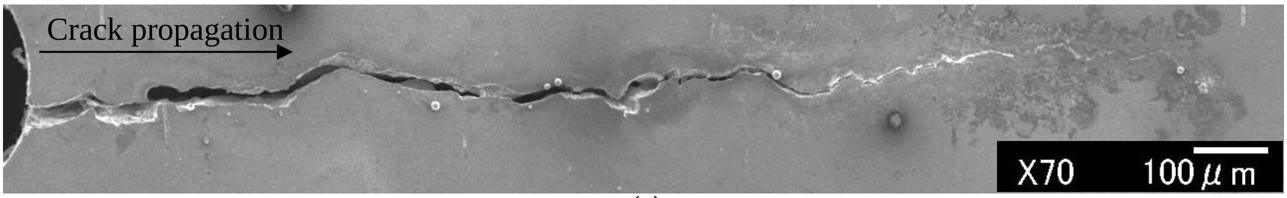
Figure 5. Image of fatigue crack before the application of the electric current and the measurement points of the crack width in Specimen A



(a)



(b)



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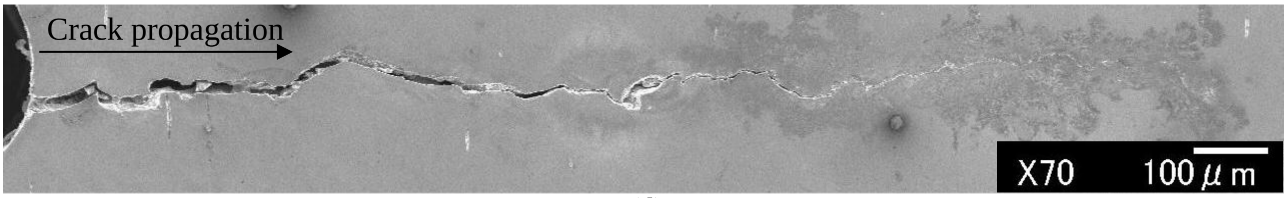

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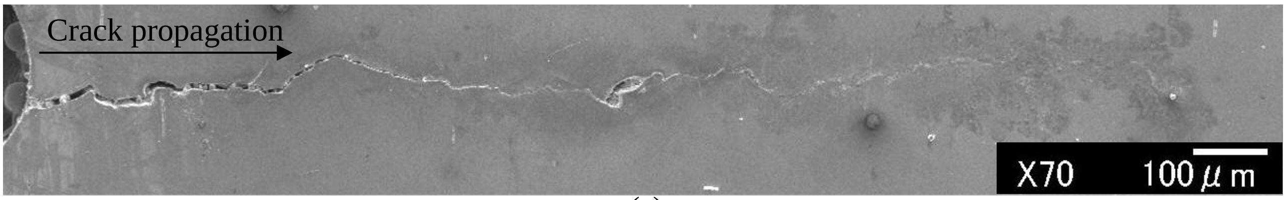
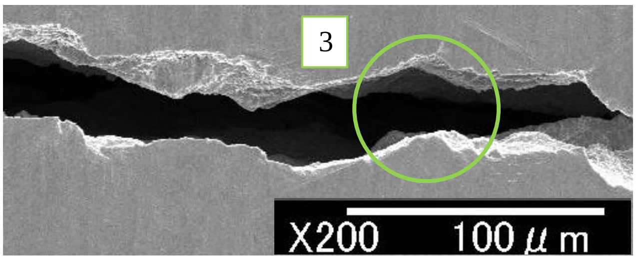
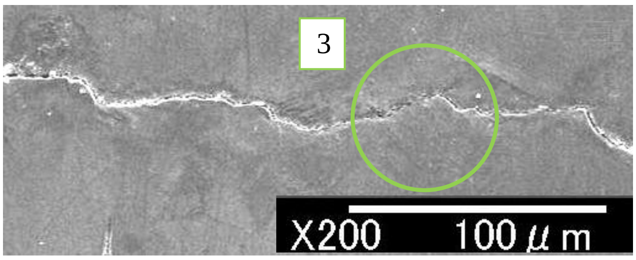


(e)

Figure 6. Images of fatigue crack in Specimen A: (a) before, (b) after first, (c) after forth, (d) after sixth and (e) after twelfth application of electric current



(a)



(b)

Figure 7. Magnified images of fatigue cracks in Fig. 5:
(a) before and (b) after the twelfth application of electric current

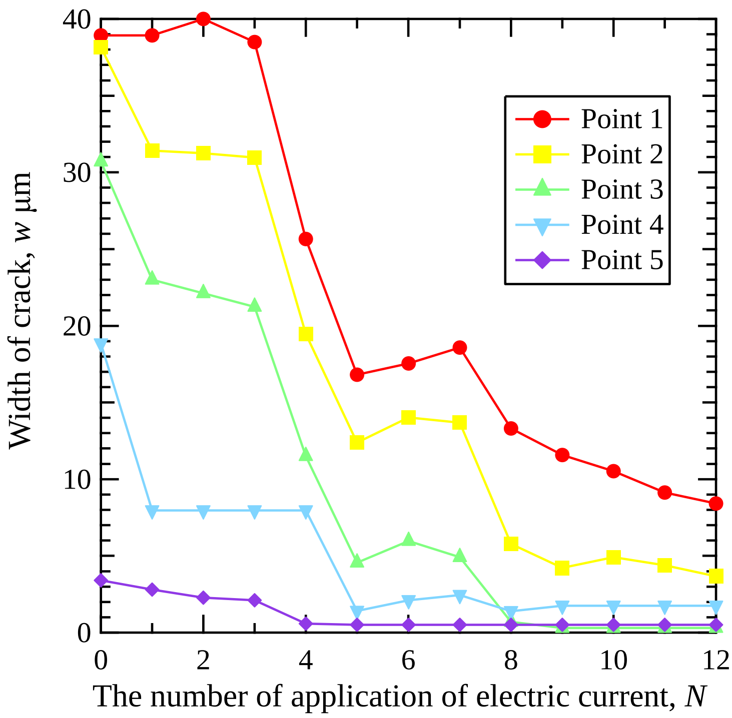


Figure 8. Change of crack width at the measure point in Fig. 5 for every application of the electric current in Specimen A

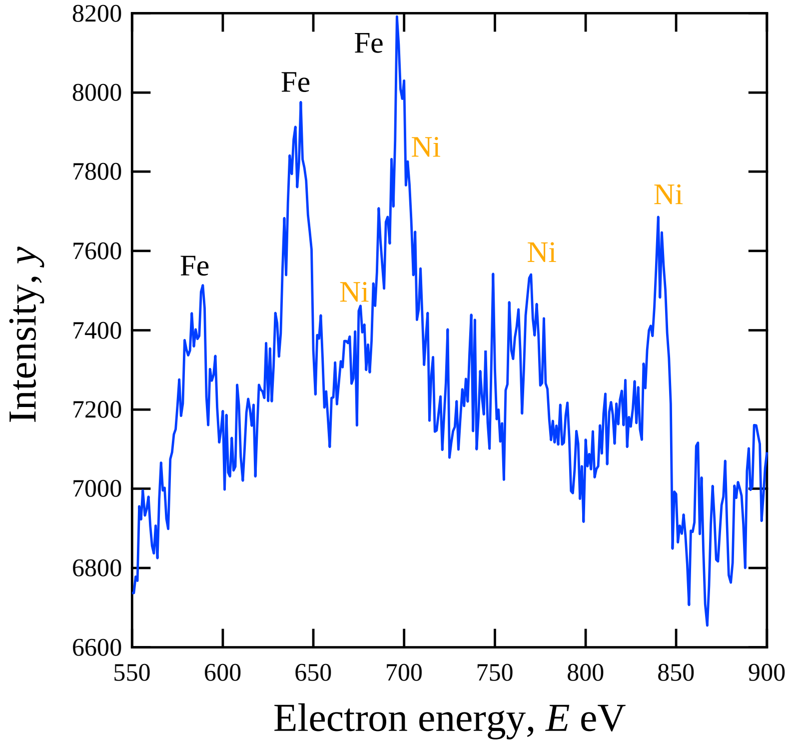


Figure 9. Auger spectrum at the inside of the crack after the application of the electric current

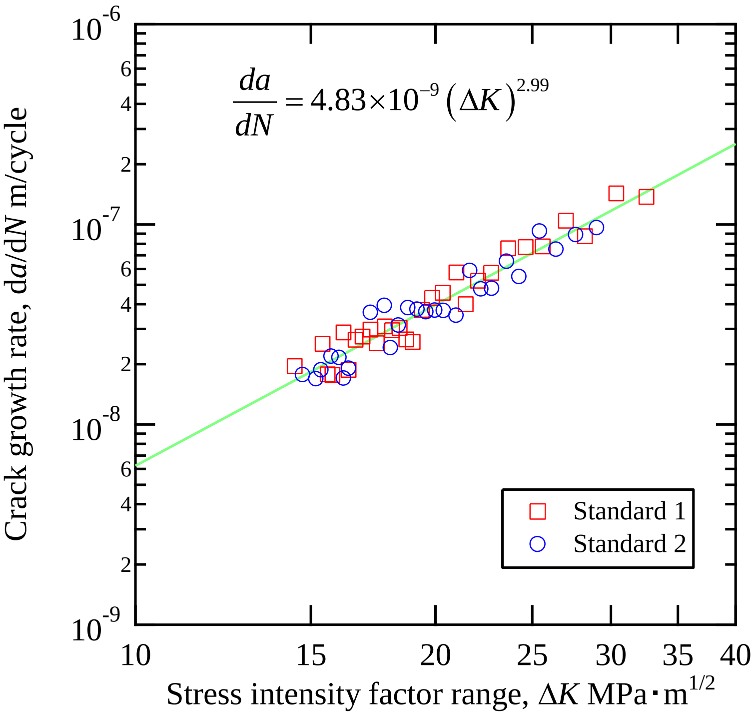


Figure 10. Fatigue crack growth rate as a function of stress intensity range with Standard specimens without the application of the electric current

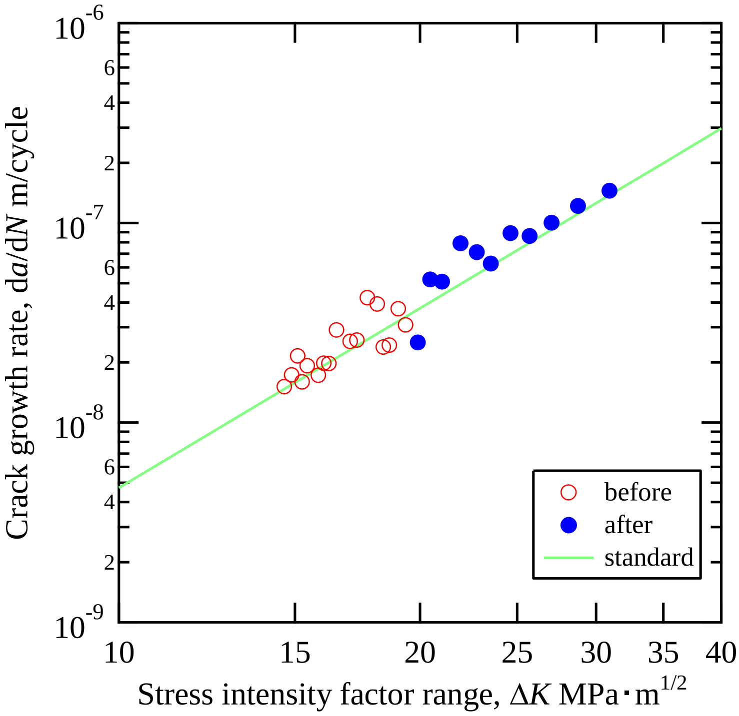


Figure 11. Fatigue crack growth rate as a function of the crack length before the application and after the application of the electric current in Specimen B

4. Discussions

One of the reasons that the crack was closed and healed as shown in Figs. 6 and 7 is thought to be thermal compressive stress due to Joule heating caused by the high-density electric current field formed at the clack tip. When the electric current is applied as crossing a crack, it flows along the crack because of the electric resistance on the crack surface. Therefore, the high-density electric current field is formed at the crack tip. The area at the tip and the vicinity of the crack is heated rapidly and expands due to Joule heating. On the other hand, the outside area of the crack tip where the high-density electric field is not caused remains intact. Therefore, the direction of expansion is restricted and the thermal compressive stress toward crack closure is caused due to the thermal expansion and it is thought that the crack is closed. Moreover, it is thought that the crack surfaces are easily bonded because the oxide layer preventing the bonding between each crack surfaces is eliminated by the surface-activated pre-coating technique, and the Ni film works as the well-adhesion inner layer. In addition, for every application of the electric current, the crack is closed, and the crack tip transfers to the direction to the notch. Therefore, the area of the current concentration continuously transfers to the direction of the notch and the whole crack was closed by the application of electric current.

On the other hand, the crack growth rate decreased temporarily as shown Fig. 11. The reason the crack growth was decreased is thought that the crack closure and bonding between the crack surfaces influenced on fatigue crack growth by applying electric current. The crack closure reduces the driving force for the crack propagation because of the decrease of the crack opening displacement. The bonding between the crack surfaces also makes the crack opening suppressive.

5. Conclusion

The technique to heal fatigue crack treated with surface-activated pre-coating method by controlling high-density electric current field was researched. The closure of the crack and the bonding between crack surfaces were realized by applying high density electric current. The crack was closed 75-97 % from original crack by improving adhesion between crack surfaces and applying the multiple electric current. Moreover, it was observed that the crack growth rate was decrease temporarily after the application of the electric current. As a result, it was indicated that the technique with the electrical stimulation has the potential to heal a fatigue crack.

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