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Fatigue crack healing by a controlled high density electric current field

A. Hosoi, T. Nagahama, Y. Ju*

Department of Mechanical Science and Engineering, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan

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ABSTRACT

A technique was developed to heal a fatigue crack in stainless steel by controlling a high-density electric current field. The high density electric current field was applied at the tip of the crack by using closely spaced electrodes. From the experimental results, it was observed the crack closure and the bridging between the surfaces of a crack were caused around the vicinity of the crack tip after a high density pulse current was applied to a specimen. It was shown that crack propagation was delayed temporarily in the healed specimen.

1. Introduction

Global warming and other environmental concerns continue increasing as industrialization rapidly grows. Reducing energy consumption to preserve the environment is a critical issue. Improving the long-term durability and reliability of structures helps to preserve the environment by reducing the resources and energy consumed during a structure's life cycle. Specifically, the main cause of failure accident is fatigue, thus, preventing fatigue fractures in structures is one way to save energy. Techniques that improve fatigue strength, such as high-frequency quenching, carburizing, nitriding and shot peening, have been developed. These techniques can prolong the fatigue life of materials by suppressing crack initiation at the material's surface. However, the advantages of these methods are not effective in materials with a pre-existing crack.

Various studies have investigated crack healing techniques and their mechanisms. Chen et al. [1] suggested a method that uses thermal reversibility to heal polymer materials. White et al. [2] investigated a microencapsulation method for similar materials. For ceramic materials, the method to heal a surface crack by oxidation was studied [3]. On the other hand, the technique to heal a crack in metallic materials has also been studied. Lumley [4] showed that creep resistance was enhanced and a fatigue crack was healed by dynamic precipitation in aluminum alloys. Kyono and Shinya [5] succeeded to control the growth of creep voids by promoting precipitation in the stainless steel added boron, nickel and titan instead of sulfur. However, these healing techniques are limited to particular materials and circumstances in which precipitation was caused. Wang et al. [6] also evaluated analytically the healing processes of defects in metallic materials by finite element modeling. However, the modeling assumed ideal conditions and did not compare to the actual phenomenon.

It is known that electric currents influence the material properties of metals. Karpenko et al. [7] demonstrated that the fatigue life of steel was prolonged by applying an electric current during fatigue loading, whereas Abdellatif [8] showed that the fatigue limit and fatigue life of mild steel were reduced by pre-application of an alternating current. Conrad and coauthors [9–13] investigated in detail the influence of a high density pulse current on materials, and showed that dislocation mobility was encouraged due to the action of drift electrons. Also, the following phenomena and their effects have been reported: the generation of Joule heating [14], the cause of compressive stress due to Joule heating [15–17], the induction of a Lorentz force [18], and the cause of an electron wind force due to the flow of the electric current [19]. In recent years, studies on crack healing in metallic materials have been conducted by utilizing the effects mentioned above. Yizhou et al. [20] was successful in healing a quenched crack in 1045 steel by applying a high density pulse current. They concluded that crack healing was caused by the temperature and transient thermal compressive stress during electropulsing. It was reported that microcracks formed during plastic deformation closed, and local recrystallization occurred due to the electropulsing treatment [21]. Suhong et al. [22] and Conrad et al. [11] showed that the persistent slip bands in fatigued copper vanished and homogenized locally by treated with high current

* Corresponding author. Tel.: +81 52 789 4672; fax: +81 52 789 3109.
E-mail address: ju@mech.nagoya-u.ac.jp (Y. Ju).

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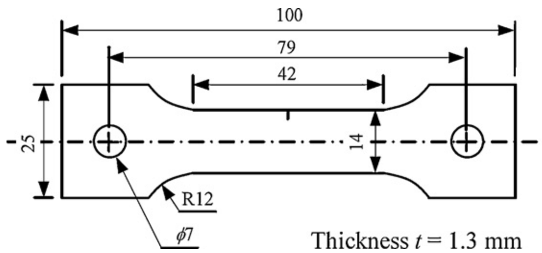

Fig. 1. Schematic of the specimen.

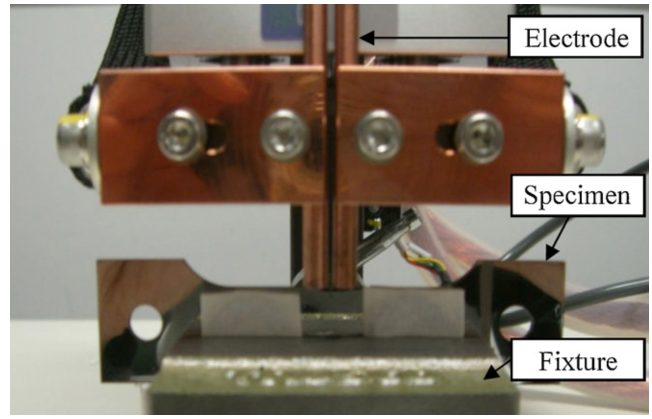

Fig. 2. Specimen and electrodes used for applying electric current.

pulsing. Moreover, Lin et al. [23] showed that the propagation of thermal fatigue crack in cast hot working die steel delayed due to the refinement of the grains around the crack tip by pulse current stimulation.

However, the essential healing of fatigue cracks in metallic materials by high density pulse currents has not been achieved. Moreover, the healing effect from high density pulse currents on the fatigue crack has not been evaluated quantitatively. In this paper, a technique to heal a fatigue crack by controlling high density electric current fields was demonstrated, and the healing effect was evaluated quantitatively with the Paris law.

2. Experiments

2.1. Specimen

Austenite stainless steel SUS316NG was used in this study. The chemical compositions and the mechanical properties of it are shown in Tables 1 and 2, respectively. Dumbbell-shaped specimen was used (see Fig. 1), and a notch was created at the center of the one edge of the specimen. The length and the root radius of the notch were 2 mm and 0.18 mm, respectively. The specimen was treated with a stress relief annealing treatment to remove residual stresses that were caused by the machining process. The heat treatment process was as follows. The specimens were heated to 1173 K for 4 h, and then were kept the temperature of 1173 K for 10 min. Afterwards, the specimens were cooled slowly to room temperature in a furnace. After the heat treatment, the surface was polished with emery papers of the grain number from #180 to #2000, and was finished up into a mirror plane by buffing with alumina powder of 0.05 μm grain diameter in order to observe a fatigue crack.

2.2. Experimental procedure

After a fatigue crack with an arbitrary length was introduced into the specimen, a high density pulse current was applied to the specimen. The crack state on the specimen's surface was observed by an optical microscope (OM) and a scanning electron microscope (SEM) before and after an electrical stimulation. There is no additional treatment being carried out after the electrical stimulation. After observing the crack, the fatigue test was again carried out with the same specimen. The crack length under cyclic loading was measured by in situ observations with an OM. The change in the crack growth behavior due to the electrical stimulation was evaluated quantitatively with the Paris law.

2.3. Conditions of the fatigue test and electrical stimulation

Tensile fatigue tests were conducted at room temperature in an atmosphere under load control conditions with a hydraulic driven testing machine. All of the tests were run at a stress ratio of $R = 0.05$, a maximum stress of $\sigma_{\max} = 150$ MPa and a frequency of $f = 10$ Hz. The details of the fatigue test conditions are shown in Table 3. The two specimens which were treated with current healing process were named "Specimen A" and "Specimen B". For comparison, the specimen which was examined with a similar fatigue test without applying electric current was named "Specimen C". It was used to confirm the influence on crack propagation which may be induced by removing the specimen from the testing machine and resetting it again. The pre-crack length in Specimens A, B and C was 5.51, 4.07 and 4.17 mm, respectively.

The electric current was supplied by a transistor power source in the range of 0.5–10 kA. It was applied into the specimen through two electrodes with the pulse duration in the range of 0.5–10 ms. Chromium copper electrodes with 5 mm diameter were used. The two electrodes were connected to the side of the specimen and straddling the notch as shown in Fig. 2. The distance between the two electrodes was 1.3 mm. The conditions of the electrical stimulation for specimens A and B are shown in Table 4. When an instantaneous pulse current was applied, only the crack area can be electrically stimulated without influencing the rest of the specimen.

Table 1
Chemical composition of the SUS316NG stainless steel (wt.%).

C	Si	Mn	P	S	Cu	Ni	Cr	Mo	N	C + N
0.016	0.43	1.54	0.028	0.0006	0.26	11.94	17.13	2.15	0.1	0.12

Table 2
Mechanical properties of SUS316NG.

Yield stress [MPa]	Tensile strength [MPa]	Young's modulus [GPa]	Poisson's ratio	Elongation [%]	Reduction of area [%]
253	581	197	0.295	49	84

Table 3
Fatigue test conditions for specimens A, B and C.

	Specimen A	Specimen B	Specimen C
Maximum stress, σ_{max} [MPa]	150	150	150
Stress ratio, R	0.05	0.05	0.05
Frequency, f [Hz]	10	10	10
Number of cycles for pre-crack introduction, N [cycle]	6.5×10^4	7.4×10^4	7.9×10^4
Crack length before current application, a [mm]	5.51	4.07	4.17
Stress intensity factor range, ΔK [MPa·mm$^{1/2}$]	38.6	26.4	26.9

3. Experimental results

3.1. Observation of the fatigue crack

Figs. 3–6 are the SEM photographs, which show changes in the condition of the fatigue crack before and after the application of the electric current. Fig. 3 shows a picture of Specimen A. It was observed that the crack closed due to the electrical stimulation. Fig. 4 is a close-up picture of Specimen A at the crack tip. The crack healed around the vicinity of the crack tip after applying the electric current. Also, microparticles were observed around the crack tip on the specimen's surface after the electrical stimulation.

Fig. 5 shows a picture of Specimen B, while Fig. 6 is an enlarged picture of the area, which is approximately 300 μm away from the crack tip in Specimen B. Formation of the bridges between the crack surfaces around the vicinity of the crack tip was observed.

Table 4
Electric current applied in specimens A and B.

	Specimen A	Specimen B
Application current [A]	5560	970
Pulse duration [ms]	0.5	0.5

3.2. Evaluation of the crack growth behavior

The crack growth behavior was evaluated quantitatively with the Paris law to observe the electrical stimulation's effect on crack growth. Fig. 7 shows the test result of Specimen C by removing it from the testing machine and resetting it again after setting it to the current inducing system without applying electric current. The open symbols show the behavior of the crack growth before removing the specimen from a testing machine, and the solid symbols show the behavior of the crack growth after setting the specimen to the current applying system without applying electric current.

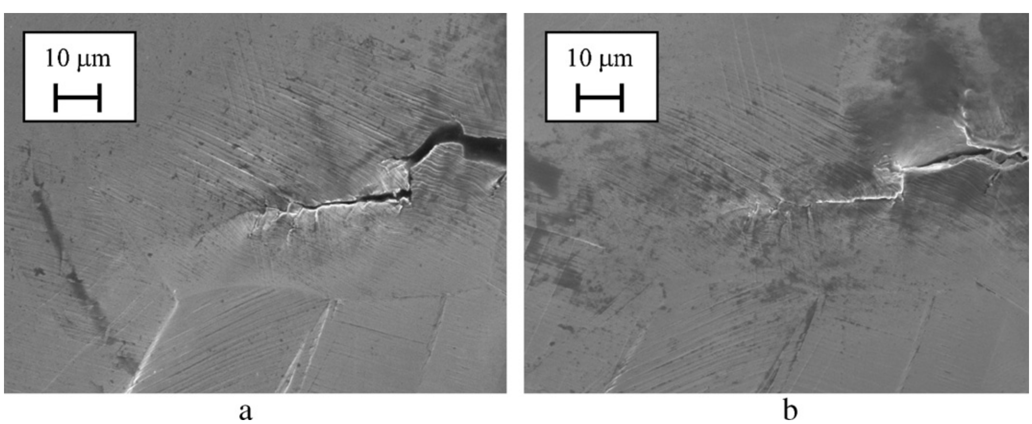

Fig. 3. Images of the fatigue cracks in specimen A: (a) before and (b) after the application of the electric current.

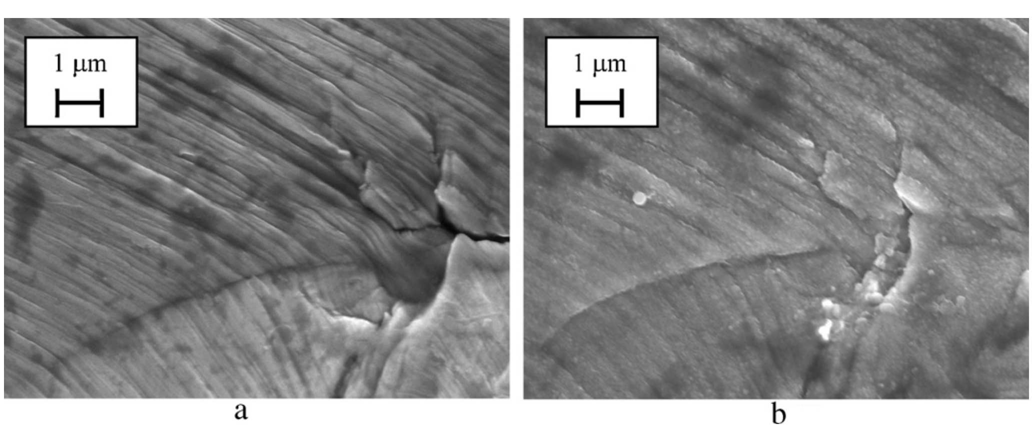

Fig. 4. Magnified images of the crack tip in Fig. 3: (a) before and (b) after the application of the electric current.

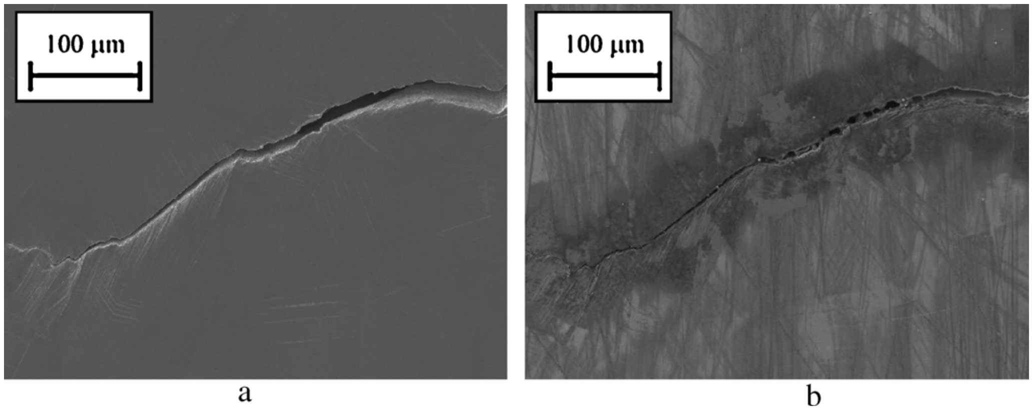

Fig. 5. Images of the fatigue cracks in specimen B: (a) before and (b) after the application of the electric current.

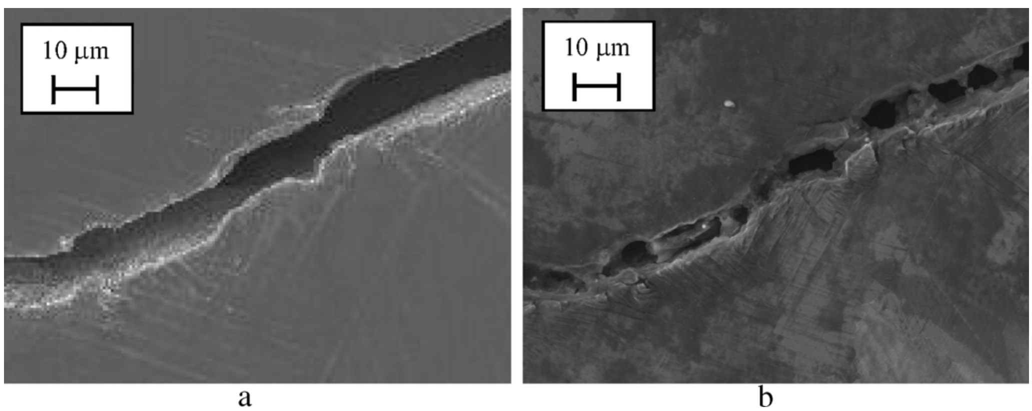

Fig. 6. Magnified images of the bridging in Fig. 5: (a) before and (b) after the application of the electric current.

It was found that there is no effect on crack propagation by removing a specimen from the testing machine and resetting it again. Fig. 8 shows the crack growth behavior of Specimen B before and after the application of the electric current. The solid line indicates the results obtained from Fig. 7. The open and solid symbols in Specimen B show the behavior of the crack growth before and after the application of the electric current, respectively. It was observed that the crack growth rate decreased from 7.65×10^{-5} to 2.40×10^{-5} mm/cycle just after the electrical stimulation. However, the crack growth rate returned to the standard crack growth rate after several thousand loading cycles were applied to the specimen.

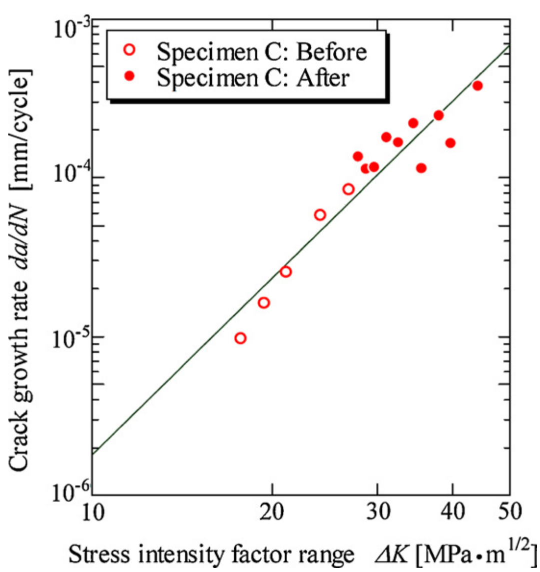

Fig. 7. Fatigue crack growth rate as a function of the stress intensity factor range before removing Specimen C from the testing machine and after resetting it again.

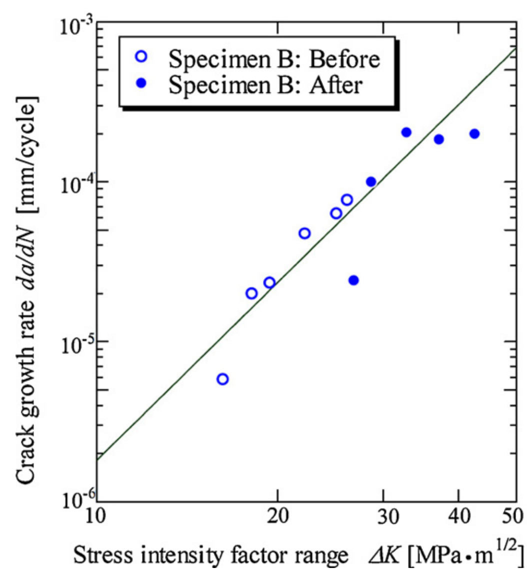

Fig. 8. Fatigue crack growth rate as a function of the stress intensity factor range before and after the application of the electric current.

4. Discussion

4.1. Closure and healing of a crack

One hypothesis to explain the crack closure and healing that are shown in Figs. 3 and 4 is Joule heating generated by the high density electric current field at the crack tip. When an electric current is applied across a crack, it flows along the crack because of the electrical resistance on the crack's surface. Therefore, a 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 because the high electric current is applied in just a few hundred microseconds. In contrast, the area outside of the crack tip, where the high density electric field is not applied, remains intact. Because the heated area was constrained by the surrounding unheated area, the thermal compressive stress was caused. When the compressive stress exceeds the yield point, it is thought that the crack will then close. Moreover, part of the crack will melt and heal when the material's melting point is reached. It is necessary to apply the appropriate electric current to close and heal a crack. When too high of a current flow is applied, an open hole forms around the vicinity of the crack tip, when too low of a current flow is applied, the crack remains unchanged. In addition, it is thought that the bridges were formed due to the discharge caused by the high density electric current.

4.2. Change in the crack growth rate due to the electrical stimulation

The crack propagation rate decreased as shown in Fig. 8 in this study. It is considered that crack closure, bridging between the crack surfaces, annealing at the crack tip and blunting due to the local melting at the crack tip have an influence on the fatigue crack growth by the application of electric current. The crack closure reduces the driving force for the crack propagation because of the decrease of the crack opening displacement. The bridging between the crack surfaces also makes the crack opening suppressive. These results are in agreement with those of Ritchie's studies [24,25]. It is shown that the contact shielding through wedging and bridging reduces driving force of fatigue crack growth. On the other hand, the residual stress at the crack tip also has an influence of the crack growth resistance. It is thought that the tensile residual stress may once occur at the vicinity of the crack tip when the compressive thermal stress applied at the crack tip exceeds the yield points and closes the crack. The tensile residual stress has the effect to promote the fatigue crack growth. However, it is reported that the annealing by heating can release the residual stress around the crack tip [26]. Therefore, it is thought that the tensile residual stress at the crack tip was finally released by the local annealing effect. In addition, since the blunting at the crack tip cannot be confirmed by the SEM observation, it is thought that the effect of the blunting is not a main factor on the crack growth retardation in this study.

5. Conclusion

A technique to heal cracks by controlling a high density electric current field was studied. The closure of the crack and the formation of bridges between the crack surfaces were achieved by applying a high density electric current field at the crack tip. Moreover, by the Paris law, it was observed that the crack growth rate decreased just after applying the electric current. The results indicate that this technique has the potential to heal a fatigue crack.

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