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Journal of Materials Processing Technology 161 (2005) 66–74

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

Application of magnetic phenomena to analysis of stress corrosion cracking in welded part of stainless steel

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Abstract

Stress corrosion cracking (SCC) failures have been reported in many nuclear power plants for the past few years. It is desirable to be able to detect SCC cracks easily and nondestructively before or just after crack initiations for maintaining the integrity of the aged plants. In this study, a new magnetic nondestructive method to detect initial SCC cracks is proposed. The materials are Inconel 600 alloy and type 304 stainless steel which are representative structural materials in nuclear power plants. The change of magnetic flux density due to SCC was measured by flux gate sensors. Moreover, magnetic microstructures near SCC cracks were revealed by magnetic force microscopy observation. The obtained results show availability of the proposed method.

Keywords: Stress corrosion cracking; Magnetic nondestructive inspection method; Magnetic force microscope; Flux gate sensor; Martensitic transformation

1. Introduction

Today, 52 commercial nuclear power plants are operated in Japan. They provide one-third of electric power used by the country. Nuclear power is one of the most important electric sources. But, it has already passed more than 40 years since the full-scale commercial nuclear electric power generation started. Maintaining the integrity of the aged plants has become an essential issue to ensure constant stable operation and achieve higher plant operability.

As for reactor core internal structures, the considerable aged deterioration phenomena are fatigue, stress corrosion cracking (SCC), and irradiation assisted stress corrosion cracking. Among them, SCC failures have been reported in many plants for the past few years. It is desirable to be able to detect SCC cracks easily and nondestructively before or just after crack initiations for enhancement of safety of nuclear power plants and more rational lifetime prediction. Although some nondestructive inspection methods for initial SCC cracks have been proposed until now [1–3], it is difficult for any of those methods to come into practical use. Since they use pulse signals such as electrochemical noise and acoustic emission measured when SCC cracks initiate and propagate, they require full-time monitoring with many sensors.

In this study, a new magnetic nondestructive inspection method is proposed. A magnetic method is not used widely in practice, but the specific one is promising. Magnetic properties are closely related to material degradations such as dislocations and local changes of chemical composition. For example, it is shown that magnetic methods are available for evaluation of material sensitivity to SCC [4,5]. If there are relationships between SCC and magnetic properties, it is possible to detect initial SCC cracks by scanning of some magnetic sensors without full-time monitoring by using many sensors.

The materials used in this study are Inconel 600 alloy and type 304 stainless steel which are typical structural materials in nuclear power plants. The changes of magnetic flux densities of materials due to SCC crack initiations are measured

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doi:10.1016/j.jmatprotec.2004.07.017

Table 1
Chemical composition of Inconel 600 alloy studied

Element	wt.%
C	0.03
Mn	0.30
Fe	9.50
Si	0.32
Cu	0.16
Ni	73.28
Cr	16.41

by flux gate sensors. As for type 304 stainless steel, in situ measurements during accelerated SCC tests are performed. Moreover, magnetic microstructures near SCC cracks are revealed by magnetic force microscopy (MFM) observation. The availability of the proposed method is discussed via the obtained results.

2. Experimental procedures

2.1. Materials

A tube of Inconel 600 alloy and a plate of type 304 stainless steels were used. Their chemical compositions are listed in Tables 1 and 2, respectively.

The tube of Inconel 600 alloy was sensitized to SCC by heat treatment at 600 °C for 20 h. Then, an SCC crack was induced on the sample surface by tensile stress loading in the axis direction in 0.5% polythionic acid solution. The outline of the SCC crack was controlled by masking of the sample. The sample shape and a photograph of the SCC crack are shown in Fig. 1. A small piece for measurement of the distribution of magnetic flux density was cut out from the tube as shown in Fig. 2 because it was difficult to magnetize the tube uniformly in our present experimental system. The laser microscopy image of the SCC crack after mechanical polish is presented in Fig. 3. It can be confirmed that the crack runs along grain boundaries. In some grains near the SCC crack, slip lines are observed.

The plate of type 304 stainless steel was sensitized to SCC by heat treatment at 620 °C for 18 h. Specimens of 5 mm × 20 mm were cut from the original plate, and polished mechanically.

Table 2
Chemical composition of type 304 stainless steel studied

Element	wt.%
Fe	71.89
Ni	8.65
Cr	18.12
C	0.05
Si	0.43
Mn	0.83
P	0.027
S	0.002

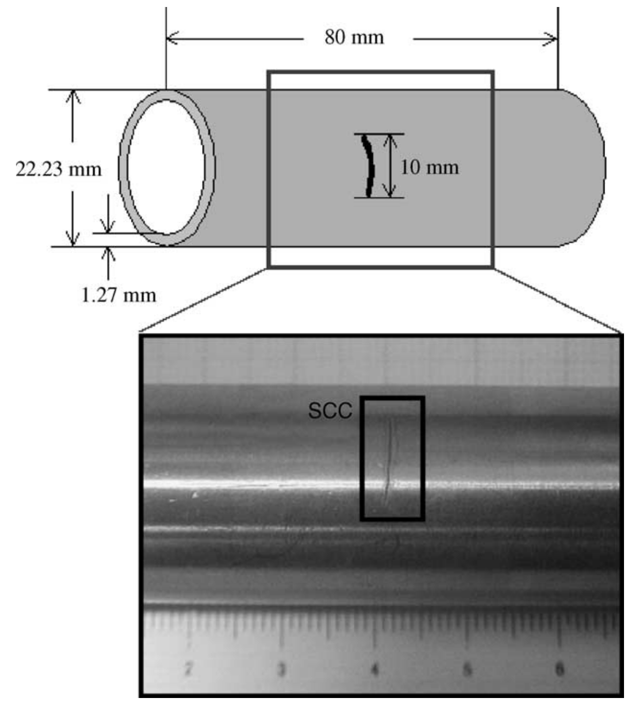

Fig. 1. A tube of Inconel 600 alloy with an SCC crack on the sample surface.

2.2. The relationship between SCC and magnetic property of Inconel 600 alloy

2.2.1. Measurement of magnetic flux density near the SCC crack

The magnetic flux density near the SCC crack was measured by using a thin film flux gate sensor (FG sensor) developed by Shimadzu Corporation. The magnetic flux density resolution of this sensor is estimated about 5×10^{-4}G [6], which is much smaller than those of a hall sensor and a giant magnetoresistance sensor. Although it is larger than that of a superconducting quantum interference device (SQUID), an FG sensor does not need any cooling systems which a SQUID needs and so it is possible to measure near sample surface (∼0.2 mm). Moreover, the size of the FG sensor is about 2 mm × 2 mm, which is smaller than that of a SQUID used generally. Therefore, the FG sensor has the higher spatial resolution than a SQUID. From these facts, we can say that the FG sensor is a powerful sensor to measure weak magnetic flux densities.

The measurement setup is shown in Fig. 4. In this system, not a sensor but a sample is moved to remove the effect of the environmental magnetic field depending on the sensor position. The measurement region and the measurement coordinates are shown in Fig. 2. The liftoff between the sensor and the sample surface was 0.5 mm. The sample was magnetized in the vertical direction before the measurement. A permanent magnet (∼0.4 T) was used to magnetize samples throughout this study.