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SQUID DAMAGE MONITORING FOR AUSTENITIC STAINLESS STEEL

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ABSTRACT

In-situ SQUID output monitoring tests for smooth and cracked specimens of austenitc stainless steel under monotonic and cyclic loading were performed. Under monotonic loading for smooth specimens SQUID output changed with increase of load, and it was divided into two stages. The changes in SQUID output in the first stage were reversible, and they recovered after unloading. While the changes in SQUID output in the second stage were irreversible, and there existed residual magnetization after unloading. The changes in SQUID output in the first stage were caused by the magneto-elastic effect, and the changes in SQUID output in the second stage were caused by martensitic transformation. Then it was found that the changes in SQUID output were correspondent with deformation behavior of austenitic stainless steel under monotonic loading. During fatigue crack growth, the changes in SQUID output amplitude were related to stress intensity factor range, and it increased with increase of stress intensity factor range. Then it was found that there was a possibility that fatigue crack growth rate was predicted by the changes in SQUID output amplitude during fatigue crack growth.

KEYWORDS

SQUID, Austenitic Stainless Steel, In-situ Damage Monitoring, Monotonic Loading, Cyclic Loading, Fatigue Crack Growth, Magneto-elastic Effect, Martensitic Transformation

INTRODUCTION

In order to ensure the integrity of structures, it is necessary to perform in-situ damage monitoring. However, there have been few researches[1-3] to perform in-situ damage monitoring by magnetic characterization. In addition, in these researches only ferromagnetic materials were investigated because of the limitation of sensitivity for their magnetic sensors. SQUID(Superconducting Quantum Interference Device) is an ultrahigh sensitive magnetic sensor and has become useful for non-destructive damage evaluation[4-6]. Then if SQUID is used as a magnetic sensor for in-situ damage monitoring, there is a possibility that in-situ damage monitoring for various kinds of materials including non-magnetic materials can be performed.

In this study in-situ damage monitoring tests were performed using a developed in-situ SQUID damage monitoring system[5]. The effects of monotonic and cyclic loading for austenitic stainless steel on magnetic characteristics were investigated with smooth and cracked specimens. The changes in SQUID output in magnetic characteristics were discussed related to the development of monotonic and cyclic deformation.

MATERIALS AND EXPERIMENTAL PROCEDURE

The material investigated in this study was austenitic stainless steel SUS304(C0.04, Si0.46, Mn0.86, P0.028, S0.003, Ni8.17, Cr18.17 wt%). Smooth specimens, which dimensions were 140×20×2mm, were used for tensile tests. And center notched plate tension specimens, which dimensions were 140×20×2mm and which initial notch dimensions were 7.5×0.3mm, were used for fatigue crack growth tests. In the case of fatigue crack growth tests fatigue pre-cracks were introduced with the final maximum stress intensity factor of 63.5MPam $^{1/2}$.

The changes in magnetization under monotonic and cyclic loading were examined by a developed in-situ SQUID damage monitoring system[5]. The system consisted of a SQUID sensor, a SQUID controller, a cryostat, and an electrohydraulic nonmagnetic materials testing machine. The DC・SQUID sensor, which operated at liquid helium temperature, was used with a 1-dimensional axial differential pickup coil to remove environmental magnetic noise around the system. In the electrohydraulic nonmagnetic materials testing machine only non-magnetic structural materials were used within 1m around the SQUID sensor. The distance between the bottom of the cryostat and the specimen was 1mm.

Tensile tests were performed at a crosshead speed of 0.5mm/min. Fatigue crack growth tests were performed at a stress ratio R=0.1 at a frequency of 10Hz. The crack length was measured by a traveling microscope and a scanning laser microscope on the specimen surface. All the tests were performed at room temperature and no magnetic field was imposed during in-situ SQUID output monitoring.

EXPERIMENTAL RESULTS AND DISCUSSION

Changes in SQUID Output under Monotonic Loading for Smooth Specimens

Typical relationships between SQUID output, load and displacement for smooth specimen of austenitic stainless steel under monotonic loading are shown in Figure 1(a). Although austenitic stainless steel was originally non-magnetic, SQUID output clearly changed with increase of displacement. It was found that a knee point appeared in the relationship between SQUID output and displacement and the changes in SQUID output were divided into two stages. In the first stage before the knee point SQUID output decreased with increase of displacement. In the second stage after the knee point SQUID output changed to increase with increase of displacement. And the inclination between SQUID output and displacement at the second stage was larger than that at the first stage.

Another relationships between SQUID output, load and displacement for smooth specimen of austenitic stainless steel under monotonic loading are shown in Figure 1(b). SQUID output changed with increase of displacement and the changes in SQUID output are also divided into two stages. However, the polarity of SQUID output was not the same as is shown in Figure 1(a), in the second stage after the knee point SQUID output decreased again with increase of displacement.

Because specimens were not magnetized before the tests, and no magnetic field imposed during in-situ damage monitoring, the polarity of SQUID output depended on the initial magnetization in each specimen. Then by using the absolute value of SQUID output the changes in SQUID output under monotonic loading are essentially expressed as shown in Figure 2.

Changes in SQUID Output under Monotonic Loading and Unloading for Smooth Specimens

In order to clarify the magnetic characteristics under monotonic loading, the changes in SQUID output under monotonic loading and unloading in each stage of the tensile tests were measured. Relationships between SQUID output, load and displacement for smooth specimen of austenitic stainless steel under monotonic loading and unloading in each stage of tensile test are shown in Figure 3. As shown in Figure 3①, in the first stage the relationship between load and displacement was linear and there existed almost no hysteresis in the load-displacement curve. In this case SQUID output increased again during unloading and there existed almost no hysteresis in the SQUID output-displacement curve. Then the changes in SQUID output in the first stage were found to be reversible. It was previously reported by Atherton et al.[1-3] that in ferromagnetic steels magnetization changed under stress conditions and it increased or decreased under monotonic loading, and by unloading magnetization completely recovers because of magneto-elastic effect in low magnetic field. Austenitic stainless steel is classified as a non-magnetic material. However, by using an ultrahigh sensitive magnetic sensor of SQUID, it was found that the effect of stress on magnetization was able to be measured.

While as shown in Figure 3③, where the relationship between load and displacement became nonlinear, there existed hysteresis in the load-displacement curve. And in this case there existed residual magnetization after unloading and hysteresis in the SQUID output-displacement curve was clearly observed . Then the changes in SQUID output in the second stage were found to be irreversible. It is well-known that SUS304 has a meta-stable austenitic phase and it easily changes to α'-martensite, which is a ferromagnetic phase, with increase of strain because of strain induced martensitic transformation. Then it was found that the hysteresis in the SQUID output –displacement curve was resulted from strain induced martensitic transformation of α'-martensite.

Changes in SQUID Output during Fatigue Crack Growth

Fatigue crack growth resistance for austenitic stainless steel is shown in Figure 4. It was found that fatigue crack growth rate was expressed by the power law. Relationships between SQUID output, load and displacement for austenitic stainless steel during a cyclic loading at a stress intensity factor range ΔK of $21.5 MPam^{1/2}$ are shown in Figure 5. During a cyclic loading there existed almost no hysteresis in the load-displacement curve. And in the SQUID output-load curve there also existed almost no hysteresis. Then it was found that fatigue crack growth behavior could not related to the hysteresis of SQUID output-load curve.

Changes in SQUID output amplitude between maximum and minimum loading for austenitic stainless steel during fatigue crack growth is shown in Figure 6. It was found that changes in SQUID output amplitude were related to the stress intensity factor range uniquely and it increased during fatigue crack growth. This was because the sizes of martensitic transformation region increased with increase of stress intensity factor range. Then there was a possibility that the fatigue crack growth rate could be predicted by the changes in SQUID output amplitude.

CONCLUSIONS

1. In the measurement of in-situ SQUID output monitoring for smooth specimens of austenitc stainless steel under monotonic loading, it was found that SQUID output changed with increase of displacement, and the changes in SQUID output were divided into two stages.
2. By the measurement of in-situ SQUID output monitoring under monotonic loading and unloading, it was found that the changes in SQUID output in the first stage were caused by the magneto-elastic effect. While the changes in SQUID output in the second stage were caused by martensitic transformation of α'-maretensite.
3. In the measurement of in-situ SQUID output monitoring during fatigue crack growth, the changes in SQUID output amplitude were related to the stress intensity factor range and they increased with increase of stress intensity factor range. Then it was found that there was a possibility that the fatigue crack growth rate was predicted by the changes in SQUID output amplitude during fatigue crack growth.

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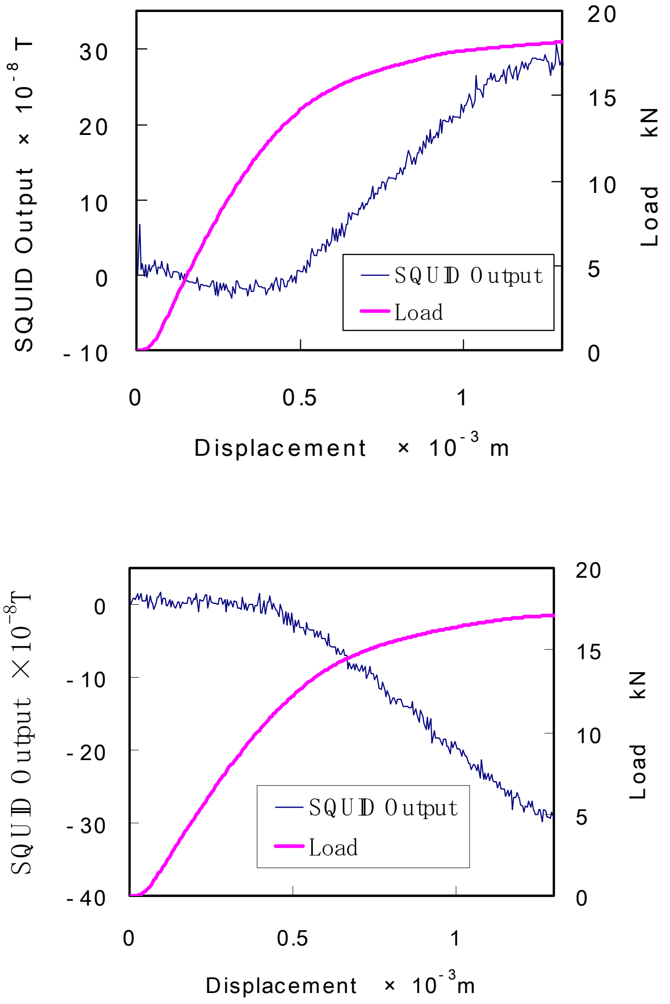

(a)

(b)

Figure 1: Relationships between SQUID output, load and displacement for smooth specimen of austenitic stainless steel under monotonic loading

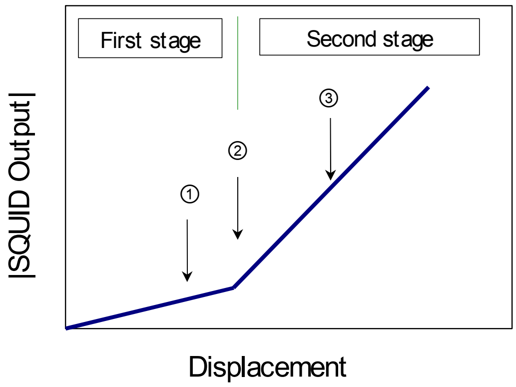

Figure 2: Schematic representation of changes in SQUID output under monotonic loading

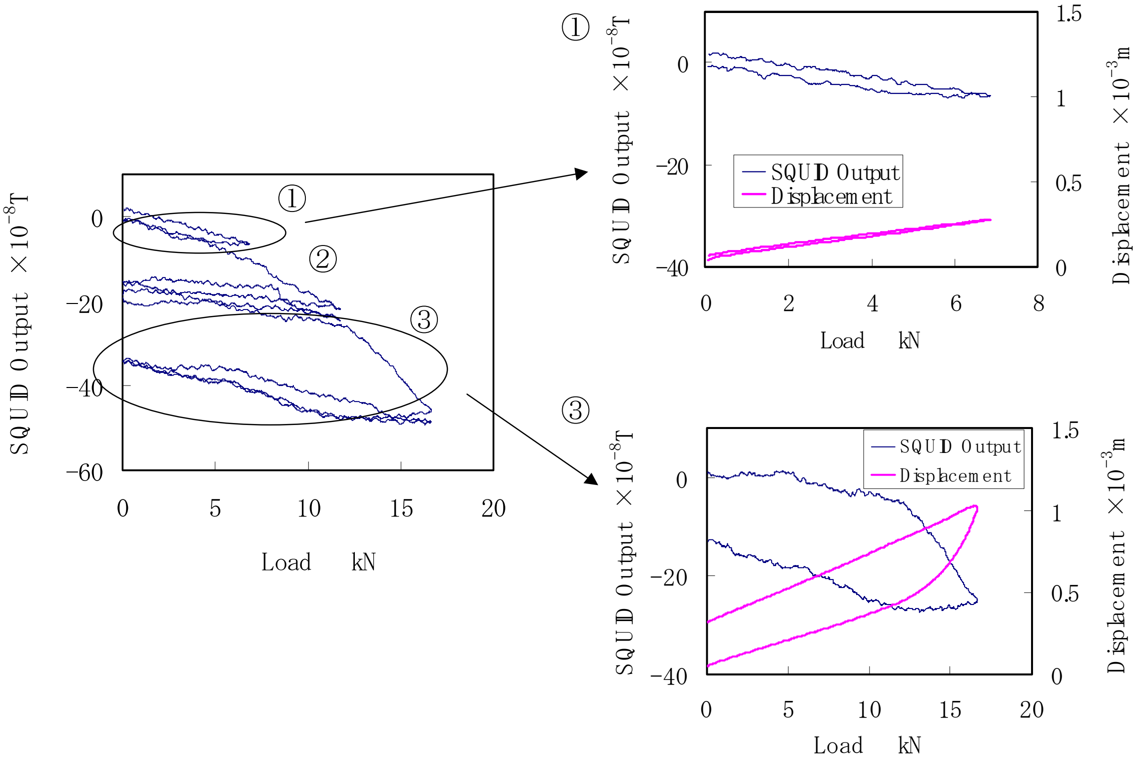

Figure.3: Relationships between SQUID output, load and displacement for smooth specimen of austenitic stainless steel under monotonic loading and unloading in each stage of tensile test

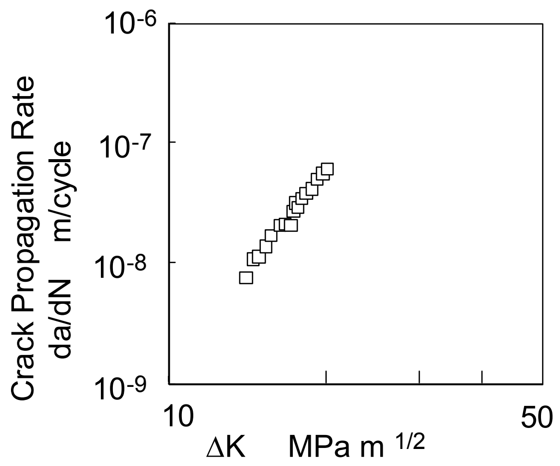

Figure 4: Fatigue crack growth resistance for austenitic stainless steel

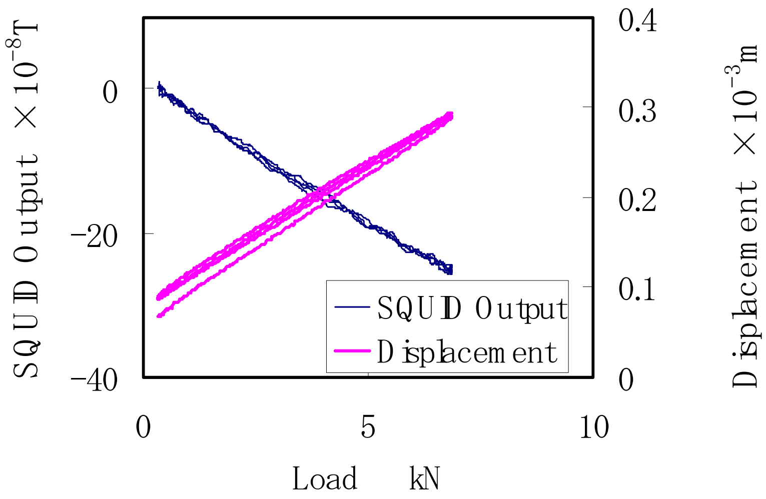

Figure 5: Relationships between SQUID output, displacement and load for austenitic stainless steel during a cyclic loading at a stress intensity factor range of $21.5 MPam^{1/2}$

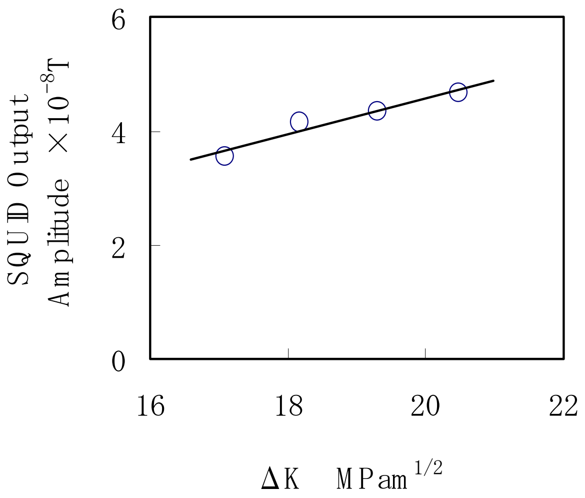

Figure 6:Changes in SQUID output amplitude for austenitic stainless steel during fatigue crack growth