FATIGUE DAMAGE ANALYSIS OF AUSTENITIC STAINLESS STEEL BY MAGNETIC FORCE MICROSCOPE

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A new damage analysis technique by magnetic force microscope with image processing analysis was developed. This technique has an advantage to analyze volume fraction of martensitic transformed phase with high resolution. Fatigue damage of martensitic transformed phase for austenitic stainless steel SUS316L in cryogenic and high-magnetic cryogenic environments was analyzed by this method. It was found that martensitic transformed phase near fatigue crack edge was composed of fully transformed zone and partially transformed zone, and transformation induced crack closure in cryogenic environments and high-magnetic cryogenic environments was controlled by the size of fully transformed zone. And fatigue crack growth characteristics in cryogenic and in high magnetic cryogenic environments were explained by transformation induced crack closure, which was caused by fully transformed zone.

INTRODUCTION

Recently many superconducting devices have been developed, and it becomes important to clarify fatigue crack growth characteristics of cryogenic structural materials to ensure long term structural durability. We (Suzuki et al (1)-(3)) investigated fatigue crack growth characteristics of cryogenic structural materials, and found that fatigue crack growth resistance for austenitic stainless steel SUS316L increased in cryogenic and high-magnetic cryogenic environments because of martensitic transformation induced crack closure. Then it is necessary to examine the microstructure of martensitic transformed phase around fatigue crack to clarify the fatigue crack growth mechanism in cryogenic and high-magnetic cryogenic environments.

Magnetic force microscope (MFM) is one of the scanning probe microscopes and it has recently been applied to observe magnetic image of magnetic recording materials (Martin et al (4), Rugar et al (5)). In this study a new technique to analyze martensitic transformed phase by magnetic force microscope was presented. Fatigue damage of martensitic transformed phase for austenitic stainless steel SUS316L was analyzed by this method, and fatigue crack growth characteristics in cryogenic and high-magnetic cryogenic environments were discussed.

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MATERIALS AND EXPERIMENTAL PROCEDURE

Materials and Specimen

The material used in this study is austenitic stainless steel SUS316L(C0.019, Si0.70, Mn 1.31, P 0.034, S 0.006, Ni 12.18, Cr 17.81, Mo 2.13, N 0.032Wt%). The 1CT specimen(thickness 10mm) was used for the 293K and 77K fatigue tests and the 0.4CT specimen(thickness 4mm) was used for 4K fatigue tests.

Fatigue Tests and MFM Observation

Fatigue crack growth tests were performed at 293K, 77K, and 4K at a stress ratio R=0.05 with a frequency f=10Hz by using the developed high-magnetic cryogenic material testing system. And at 4K fatigue crack growth tests were also performed in high-magnetic field (6T). The magnetic field direction was identical with the loading direction. The details of the developed testing system and other testing conditions are shown in reference (3).

After the fatigue tests, the specimen was cut at the center of thickness by a cutting saw and polished by diamond pastes. Magnetic force microscope (MFM) observation was conducted on the polished specimen surface near fatigue crack edge by using multi-type commercial scanning probe microscope. After the MFM observation, image processing analysis was performed with a personal computer.

EXPERIMENTAL RESULTS AND DISCUSSION

Example of Fatigue Damage Analysis

A MFM image of a cryogenic fatigue damage of martensitic transformed zone for SUS316L is shown in Figure 1. Because martensitic transformed phase (α` martensite) is high-magnetic and austenitic phase is non-magnetic, the martensitic transformed phase is clearly distinguished from austenitic phase with high contrast.

Image processing analysis of binarization operation was performed with the MFM image of Figure 1. The MFM image after binarization operation is shown in Figure 2. The region in Figure 1 was completely divided into two groups of martensitic transformed phase and austenitic phase. Then it is possible to calculate the volume fraction of martensitic transformed phase in any region in Figure 2 with high resolution. And this method has also an advantage that morphology of martensitic transformed phase is found without etching.

Fatigue Damage of Matensitic Transformed Phase in Cryogenic Environments

MFM images of fatigue damage of martensitic transformed phase around fatigue crack edge in each test temperature are shown in Figure 3(a)-(c). In all images martensitic transformed phases are observed near fatigue crack edge. And it is found that there exist two kinds of martensitic transformed zone around fatigue crack edge. In the vicinity of the fatigue crack edge, martensitic transformed phase is produced uniformly in each grain, and around this region martensitic transformed phase is produced selectively in a specific grains or in specific regions in a grain.

Changes of magnetic force of martensitic transformed phase near fatigue crack edge in Figure 3(b) is shown in Figure 4. It is also found that there exists a high-magnetic region near fatigue crack edge, and that the high-magnetic region is divided into two groups apparently.

Then in this study, the region which martensitic transformed phase is produced in each grain in the vicinity of fatigue crack edge is called "fully transformed zone", and the region which martensitic transformed phases are produced selectively in specific regions is called "partially transformed zone". And the size of martensitic transformed zone R_o, which contains fully transformed zone and partially transformed zone, is defined as the region where the magnetic force is larger than 20% of the maximum magnetic force. The size of fully transformed zone R_f is defined as the region where the magnetic force is larger than 50% of the maximum magnetic force.

Influence of Test Temperature on Size of Martensitic Transformed Zone

Influence of test temperature on the size of martensitic transformed zone R_o is shown in Figure 5. In all K_{max} values, the sizes of martensitic transformed zone R_o at cryogenic temperature (77K, 4K) are much larger than those at 293K. And the sizes of martensitic transformed zone at 77K are larger than those at 4K.

Influence of test temperature on the size of fully transformed zone R_f is shown in Figure 6. It is found that the sizes of fully transformed zone R_f at cryogenic temperature (4K, 77K) are much larger than those at 293K in all K_{max} values. On the other hand the sizes of fully transformed zone at 77K are almost equal to those at 4K in all K_{max} values.

Influence of Size of Martensitic Transformed Zone on Fatigue Crack Closure

Previously we (Suzuki et al(3)) reported fatigue crack growth resistance at cryogenic temperature, and the fatigue crack growth resistance at 4K and 77K was larger than that at 293K because of martensitic transformation induced crack closure.

Influence of test temperature on K_{open}/K_{max} is shown in Figure 7. It is found that the values of K_{open}/K_{max} at cryogenic temperature (77K, 4K) are larger than those at 293K. And the values of K_{open}/K_{max} at 77K are almost equal to those at 4K. The relationship between K_{open}/K_{max} and K_{max} in Figure 7 agree well with the relationship between the size of fully transformed zone R_f and K_{max} in Figure 6 rather than the relationship between the size of martensitic transformed zone R_o and K_{max} in Figure 5. Then it is found that fatigue crack closure is mainly controlled by the size of fully transformed zone. And it is concluded that the increase of fatigue crack growth resistance at cryogenic environments is explained by martensitic transformation induced crack closure, which is caused by fully transformed zone.

Fatigue Damage of Matensitic Transformed Phase in High-magnetic Cryogenic Environments

MFM image of fatigue damage of martensitic transformed phase in high-magnetic cryogenic environments is shown at Figure 3(d). And the sizes of fully transformed zone in high-magnetic cryogenic environments are also shown in Figure 6. It is found that the sizes of fully transformed zone of high-magnetic cryogenic environments(4K, 6T) are almost equal to those at non-magnetic cryogenic field(4K, 0T).

Previously we (Suzuki et al (3)) reported that the values of K_{open}/K_{max} at high-magnetic cryogenic environments were also a little larger or almost equal to those at non-magnetic cryogenic environments. Then in the case of high-magnetic cryogenic environments, it is also found that fatigue crack closure is controlled by the size of fully transformed zone.

CONCLUSION

(1) A new technique to analyze fatigue damage of martensitic transformed phase by magnetic force microscopy with image processing was presented. This technique was successfully applied to perform quantitative analysis of volume fraction of martensitic transformed phase with high resolution.

(2) By analyzing fatigue damage of martensitic transformed phase, it was found that there exist two kinds of martensitic transformed zone near fatigue crack edge, fully transformed zone and partially transformed zone, at each test temperature. And the size of fully transformation zone R_f at 77K was almost equal to that at 4K, and it was much larger than that at 293K. By analyzing fatigue damage of martensitic transformed phase in high-magnetic cryogenic environments, it was found that the size of fully transformed zone was almost equal to that in non-magnetic cryogenic environment.

(3) The fatigue crack growth characteristics in cryogenic and high-magnetic cryogenic environments were explained by martensitic transformation induced crack closure, which was caused by fully transformed zone.

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Figure 1 MFM image of cryogenic fatigue damage of martensitic transformed phase for SUS316L(4K, K_{max}=61.1MPam$^{1/2}$)

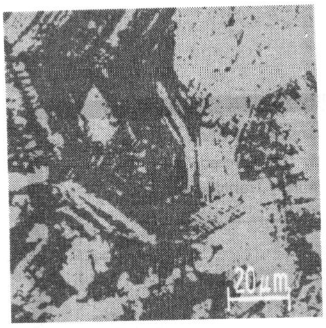
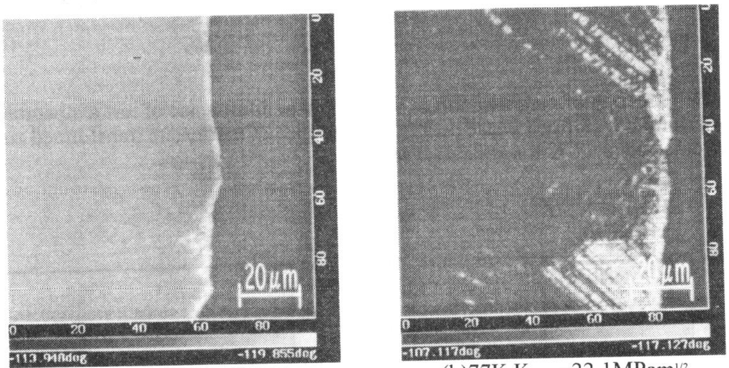
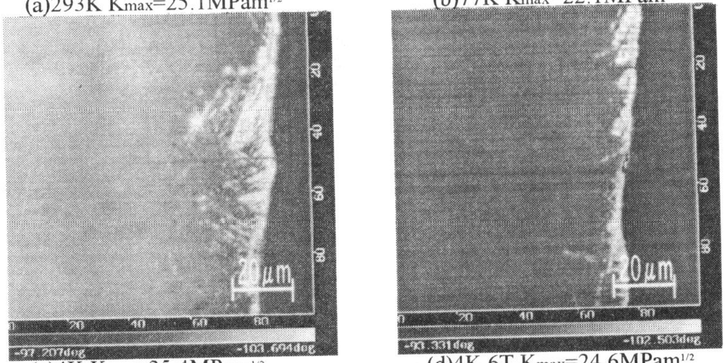


Figure 2 MFM image of cryogenic fatigue damage after image processing analysis (4K, K_{max}=61.1MPam$^{1/2}$)



(a)293K K_{max}=25.1MPam$^{1/2}$ (b)77K K_{max}=22.1MPam$^{1/2}$



(c)4K K_{max}=25.4MPam$^{1/2}$ (d)4K 6T K_{max}=24.6MPam$^{1/2}$

Figure 3 MFM images of fatigue damage of martensitic transformed phase around fatigue crack edge in each test temperature and in high-magnetic field

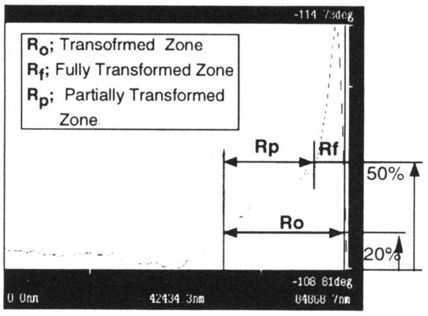


Figure 4 Changes of magnetic force of martensitic transformed phase near fatigue crack edge (77K K_{max}=22.1MPam$^{1/2}$)

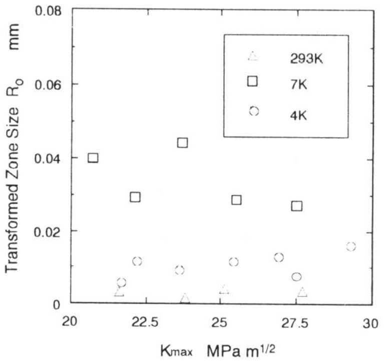


Figure 5 Influence of test temperature on size of martensitc transformed zone R_o

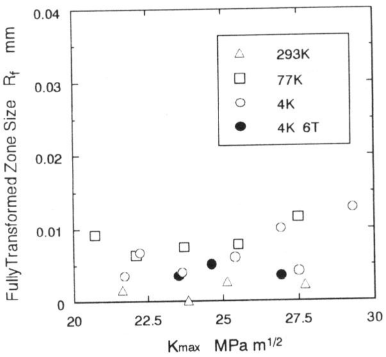


Figure 6 Influence of test temperature and high- magnetic field on size of fully transformed zone R_f

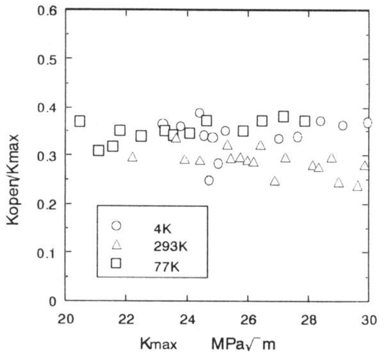


Figure 7 Influence of test temperature on K_{open}/K_{max} values