Considering the Mechanisms Causing Reduction of Fretting Fatigue Strength by Hydrogen

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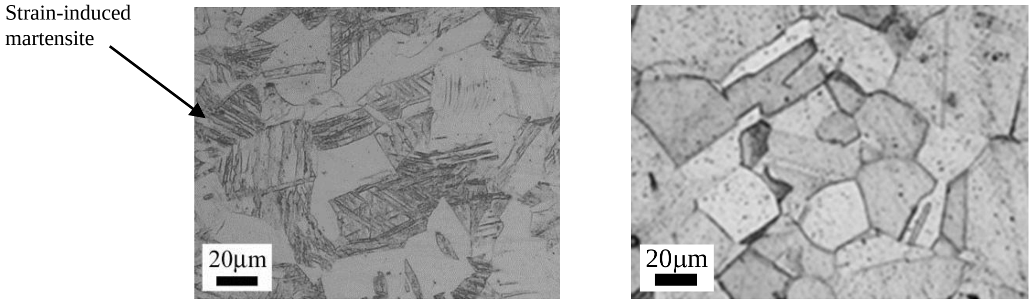
Abstract. The fretting fatigue test of austenitic stainless steels, JIS SUS304 and SUS316, was carried out in 0.12MPa hydrogen and air. The fretting fatigue strength of both materials was reduced by hydrogen. One of the possible causes was adhesion between the fretting surfaces which was predominant in hydrogen. The effect of specimen finishing on adhesion was also verified. For this purpose, two surface roughness were prepared with Ra = 0.420μm and 0.008μm. During the fretting fatigue test of these specimens in air, adhesion occurred in the smoother surface specimen but did not occur in the rougher surface specimen. As a result, the fretting fatigue strength decreased when adhesion occurred. Therefore, it can be considered that adhesion resulted in the reduction of the fretting fatigue strength in smoother specimens in air and in 0.12MPa hydrogen. Strain-induced martensite was found in the region of the adhered part, possibly due to the severe cyclic strain occurred locally at the adhered region.

Introduction

Fretting is one the most important issues in the design of mechanical components involving contact because fretting can cause a significant reduction in the fatigue strength of the contact part. In machines using hydrogen, the importance of fretting is even higher because hydrogen can influence both the fatigue and friction. The authors have reported a significant reduction in the fretting fatigue strength of several kinds of materials due to hydrogen [1-4]. The objectives of this study are: to evaluate the effect of hydrogen on the fretting fatigue strength of austenitic stainless steels and to understand the mechanism of the reduced fretting fatigue strength in hydrogen. The effect of surface finishing roughness on fretting fatigue strength is also verified.

Effect of Environmental Hydrogen on Fretting Fatigue Strength of SUS304

Test procedure. The test material was the austenitic stainless steel 304 type which is designated by the JIS as SUS304. The specimen and contact pad were made of 30% pre-strained SUS304 material. The pre-strain was applied to the material by uniaxial tension, and then the specimen was taken from the pre-strained material so that the specimen axis coincided with the tensile load axis. The Vickers hardness was HV311. The microstructure of the material is shown in Fig. 1(a). Strain-induced martensite was present.



(a) 30% pre-strained SUS304 (b) Solution heat-treated SUS316

Fig.1. Microstructure of test materials

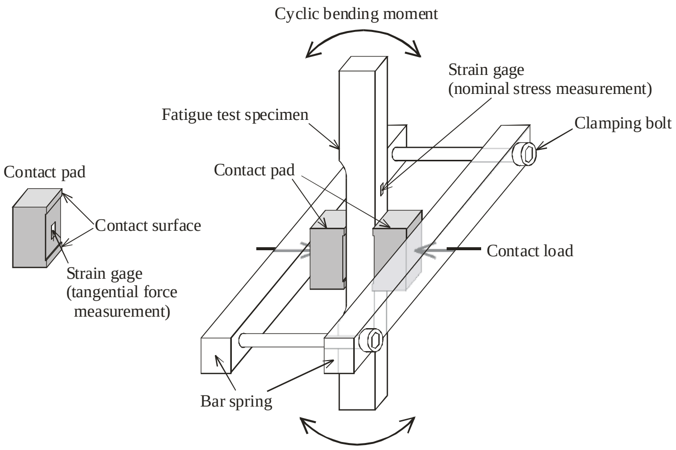
Fretting fatigue test. The fretting fatigue test set-up used in the experiment is shown in Fig. 2. Two contact pads were pressed onto the front and back side surfaces of the fatigue test specimen at a contact pressure of 100MPa. Fretting was induced at the contact part by applying a bending fatigue load. The reduction in the contact pressure during the fretting fatigue test due to fretting wear was within 5% of the initial value.

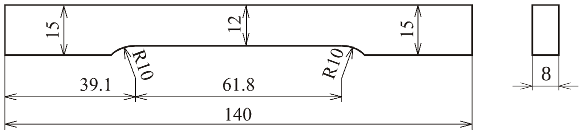
The fretting fatigue test was carried out with a stress ratio of $R = -1$ at a test frequency of $f = 18.7$Hz at ambient temperature. The test frequency may be one of the factors affecting the fretting fatigue properties in hydrogen similarly to fatigue [5, 6]. The effect of the test frequency on the fretting fatigue in hydrogen remains to be characterized.

The configurations of the specimen and contact pad are shown in Fig. 3. The contact surfaces of the specimen and the contact pad were finished by #400 emery paper in the direction of the fretting motion. A bridge-type contact pad was used to measure the tangential force acting on the contacting surfaces. As shown in Fig. 2, a strain gage was sticked to the center of the recessed part of the contact pad to measure the tangential force. The tangential force coefficient (ϕ) was defined as the ratio of the tangential force (F_t) to the contact force (F_c). The test environments were 0.12MPa hydrogen and air. The hydrogen purity was 99.9999%.

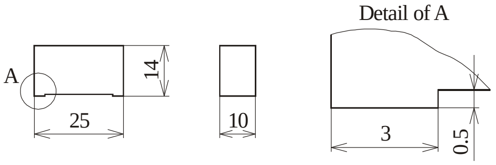
Effect of hydrogen on fretting fatigue strength of SUS304. The result of the fretting fatigue test is shown in Fig. 4. The fretting fatigue test was carried out to 3×10^7cycles if no failure occurred. The fretting fatigue failure definitely occurred around 10^7cycles in hydrogen, while no failure occurred at the same stress level in air. Thus, the reduction of the fretting fatigue limit in hydrogen was clearly observed. It can be considered that the reduction in fretting fatigue strength is associated with some specific mechanisms of fretting fatigue other than the mechanism that causes a reduction in the fatigue strength, since there are reports that the high-cycle fatigue strength of the same kind of austenitic stainless steel in hydrogen is not changed [7] or rather increased [8].

Tangential force. Figure 5 shows the relationship between the tangential force coefficient and stress amplitude. The tangential force value was higher in hydrogen than in air due to adhesion between the contacting surfaces. Thus, an increase in the tangential force causes a decrease in the fretting fatigue





(a) Specimen

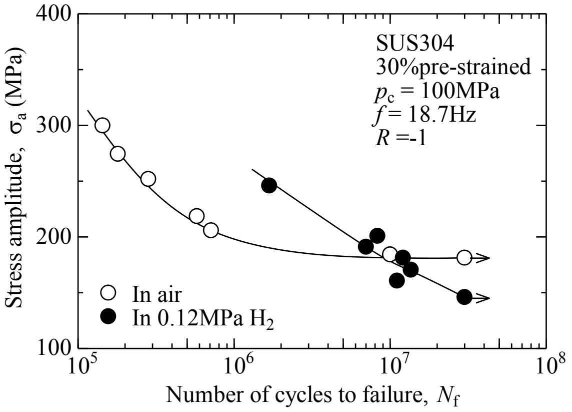


(b) Contact pad

Fig.2. Fretting fatigue test set-up.

Fig.3. Configurations of specimen and contact pad (dimensions are in mm).

strength [9]. These findings could explain the reduction of fretting fatigue strength in hydrogen. However, the development of adhesion between the fretted surfaces depends on the presence and the access of oxygen to the fretting surfaces. If oxygen is suppressed, such as in inert environments, the adhesion is more pronounced [10]. The fretting wear mechanism changes from an oxidation dominant process to an adhesion dominant process, such as in a vacuum [11] and nitrogen gas [12]. In air, the formation of oxidized fretting wear particles and oxidation of the fretted surface prevented the adhesion. Therefore, it can be considered that the absence of oxygen is the major reason for the increase in the tangential force in low-pressure hydrogen and the formation of adhered zones.



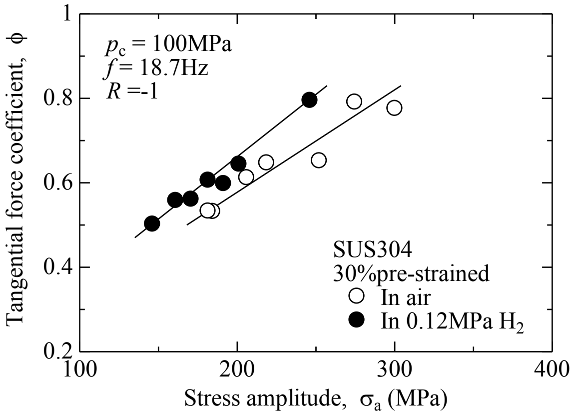


Fig.4. Effect of hydrogen on fretting fatigue strength of 30% pre-strained SUS304.

Fig.5. Tangential force coefficient in fretting fatigue test in hydrogen.

Adhesion between fretting surfaces in hydrogen and formation of small cracks. Figure 6 shows the longitudinal cross-section of the specimen and contact pad after the fretting fatigue test in hydrogen, which was observed without disassembling the specimen and pad. If the specimen and pad were simply pressed together, a straight line should appear on the cross-section as the boundary between the specimen and contact pad. However, at positions A, B and C, the interface between the specimen and pad shows a zigzag path. This is evidence for adhesion. The details of the formation mechanism and the role of the small cracks have been discussed in ref. [4]. The zigzag path is formed by the crosswise overlap of small cracks which emanated at the ends of the adhered spot.

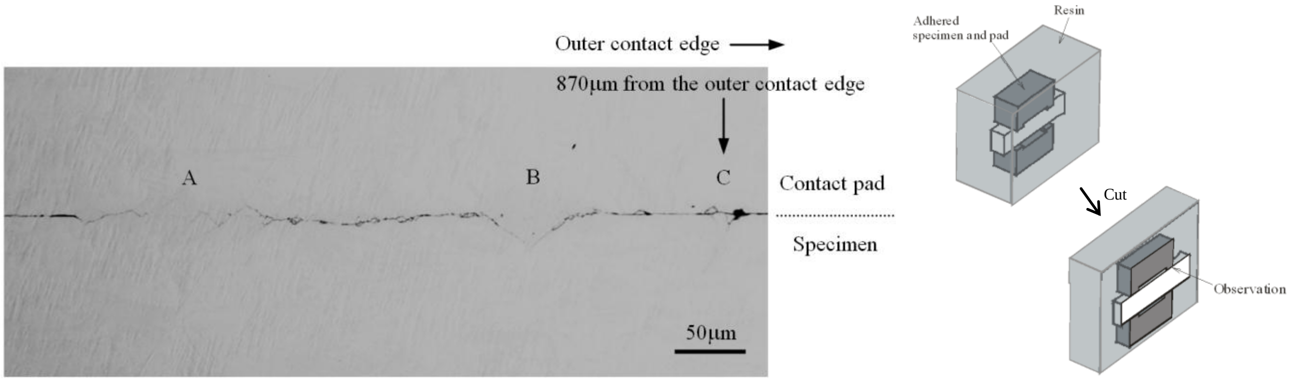


Fig.6. Longitudinal cross-section of the specimen and contact pad after the fretting fatigue test in hydrogen (σ_a = 200MPa, $N = 5.0 \times 10^5$).

These small cracks, which act as a starter of major crack that causes failure of the specimen, resulted in the reduction of the fretting fatigue strength in hydrogen.

Effect of Hydrogen on Fretting Fatigue Strength of SUS316 and the Role of Adhesion to Reduce Fretting Fatigue Strength in Hydrogen

Test procedure and material. For the fretting of SUS304 in a vacuum, the mechanism for the initiation of a small fretting crack has been investigated from the view point of stress concentration at the contact edge [13]. This study was intended to understand the association of adhesion to reduce the fretting fatigue strength in hydrogen. For this purpose, a fretting fatigue test using two types of specimens of which the roughness of the contact surface was different was carried out in air. As for the objective of this experiment, if the fretting fatigue strengths under the two test conditions when adhesion occurs and no adhesion occurs in the same environment are compared, the role of adhesion to reduce fretting fatigue strength can be clarified independent of the effect of hydrogen.

The material used in this experiment was SUS316. The material received a solution heat treatment. The configuration of the specimen, the fretting fatigue test method and the environment are the same used in the SUS304 experiment. The surface roughness of the contact surface of the specimen and contact pad was the same. Two types of surface finishing have been employed: Ra = 0.420μm and 0.008μm, respectively.

Effect of hydrogen on fretting fatigue strength of SUS316. The result of the fretting fatigue test of the rougher surface specimen is shown in Fig. 7. ○ and ● indicate the S-N data in air and in hydrogen, respectively. The fretting fatigue strength of SUS316 is significantly reduced in hydrogen. The high-cycle fatigue strength on SUS316 of the smooth specimen is less affected by hydrogen [14]. However, the crack growth rate of SUS316 using the specimen containing a small artificial hole was accelerated by hydrogen [15]. Therefore, it can be considered that one of the key roles of fretting that causes a reduction in the fatigue strength in hydrogen is nucleation of small fatigue cracks acting as a starter of the growth of major crack which led to specimen failure. This is consistent with the observation shown in Fig. 6. Initiation of a fretting fatigue crack in air is the early stage of the fretting fatigue life [16, 17]. This is also shown in hydrogen [18].

Consideration on the role of adhesion. Figure 8 shows the S-N data for the specimen having the surface roughness of Ra = 0.008μm. The fretting fatigue strength in hydrogen（▲）was equivalent to that in air（△）. The effect of hydrogen on the fretting fatigue strength of this material is different

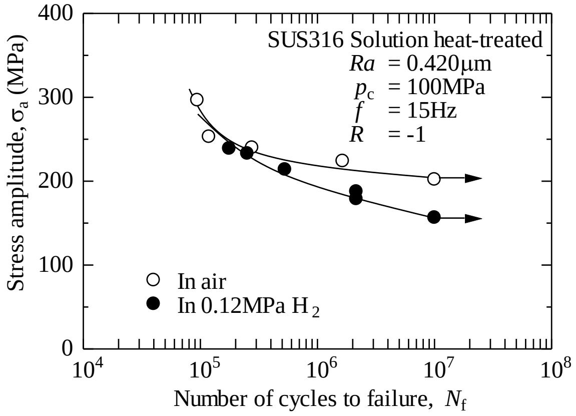


Fig.7. *S*-*N* diagram for SUS316 with *Ra* = 0.420μm.

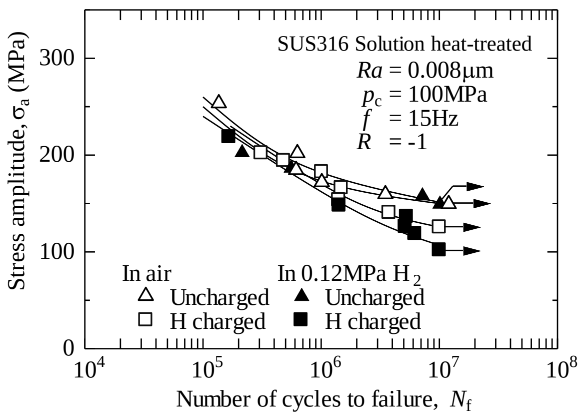


Fig.8. *S*-*N* diagram for SUS316 with *Ra* = 0.008μm

from that of the rougher surface specimen. On the other hand, the fretting fatigue strength of the smoother surface specimen in air （△） was significantly lower than that of the rougher surface specimen in air （○） and it was almost the same for that of the rougher surface specimen in hydrogen （●） .

As shown in Fig. 9, the adhesion between the fretting surfaces and the small cracks which emanated from the adhered parts were observed in the smoother surface specimen after the fretting fatigue test in air. Figures 10 and 11 show the fretted surfaces of the SUS316. The morphology of the fretting damage of the smoother surface specimen in air was similar to that in hydrogen. The amount of oxidized fretting wear particles was very low in the smoother surface specimen even when the test was done in air. The results of the fretting fatigue test and the observations indicate that adhesion occurred in air when the contact surface has an extremely low surface roughness and it played a dominant role in causing the fretting fatigue failure. The reduction in the fretting fatigue strength of SUS316 in low-pressure hydrogen was mainly caused by the change in the fretting wear process.

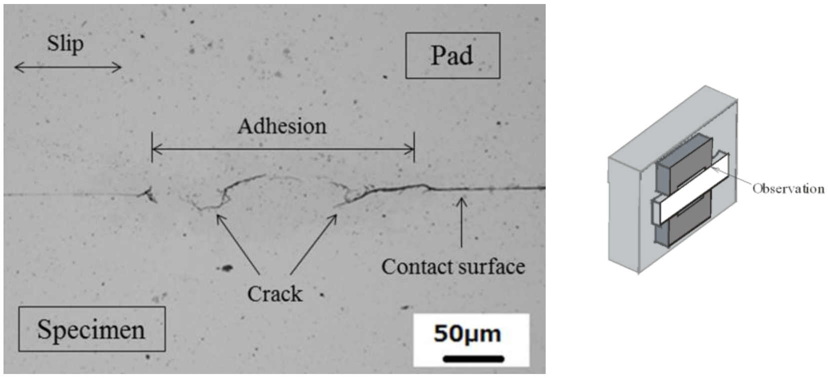
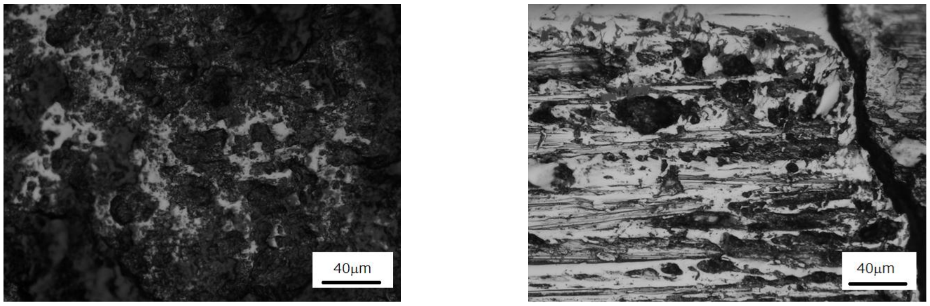
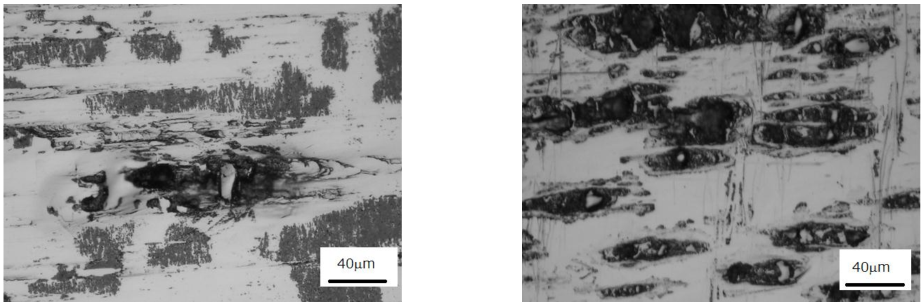


Fig.9. Adhesion between fretting surfaces and small cracks in SUS316 produced during the fretting fatigue test in air (σ_a = 182MPa, $N_f = 10^6$)



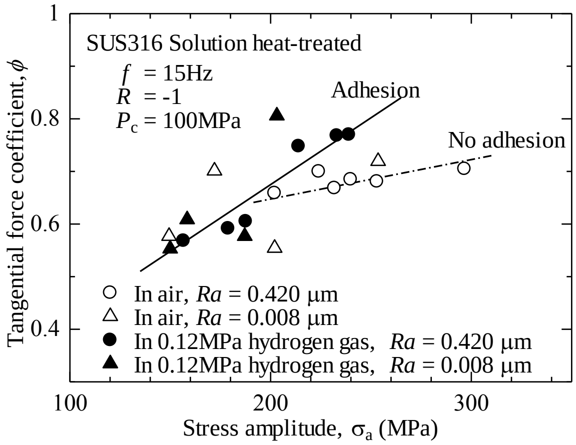
(a) In air, σ_a = 294MPa, $N_f = 9.4\times10^4$ (b) In hydrogen, σ_a = 240MPa, $N_f = 1.8\times10^5$

Fig.10. Fretted surface of the *Ra*=0.420μm specimen.



(a) In air, σ_a = 172MPa, $N_f = 1.0\times10^6$ (b) In hydrogen, σ_a = 150MPa, $N = 1.0\times10^7$.

Fig.11. Fretted surface of the *Ra*=0.008μm specimen.



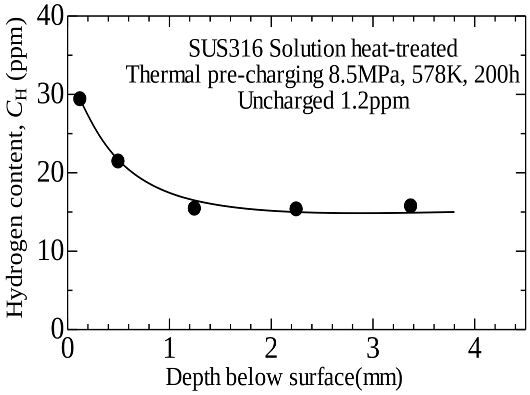


Fig.12. Comparison of tangential force coefficient between adhesion and no adhesion.

Fig.13. Distribution of hydrogen content below surface in hydrogen pre-charged material.

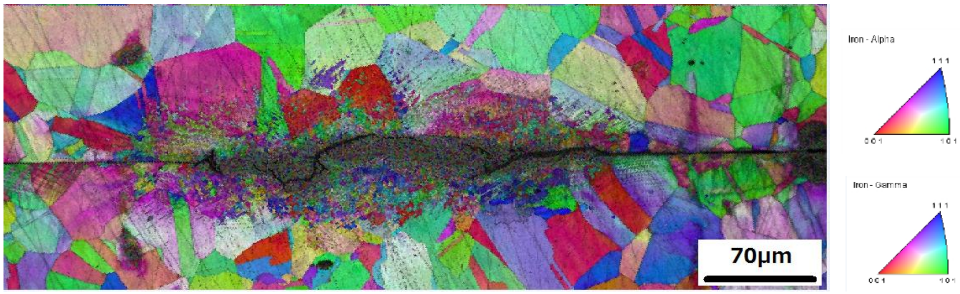
Figure 12 shows the tangential force coefficient in the fretting fatigue test of both specimens. The rougher surface specimen tested in air, which showed the higher fretting fatigue strength, showed a lower value.

Effect of internal hydrogen on fretting fatigue strength of SUS316. In order to enhance the understanding of the effect of hydrogen on the fretting fatigue strength, the experiment using the hydrogen pre-charged specimen was carried out. Thermal pre-charging in 8.5MPa hydrogen at 573K for 200h was applied to both the specimen and contact pad. The distribution of the hydrogen content in the material is shown in Fig.13. The surface roughness of the specimen and contact pad was *Ra* = 0.008μm. The result of the fretting fatigue test is shown in Fig. 8. The fretting fatigue strength was significantly reduced by hydrogen pre-charging.

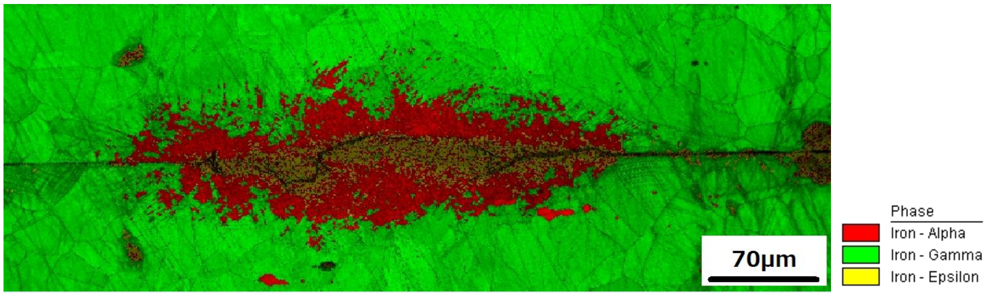
Transformation of microstructure due to fretting. Figure 14 shows the result of the EBSD observation of the adhered part which is shown in Fig. 9. In the crystallographic orientation map, the image of the adhered part is different from that of the position away from the contacting surfaces. α-iron, which is considered to be strain-induced martensite, was detected at the adhered part. On the other hand, there is no significant difference at the position where no adhesion occurred. The diffusivity of hydrogen is significantly greater in the martensitic phase than in the austenitic phase [19]. As a result, the transformed martensite in the austenitic stainless steel can act as a low resistance diffusion pathway for hydrogen diffusion [20].

The presence of strain-induced martensite may indicate that the material in the adhered part underwent severe cyclic plastic strain. Plastic deformation enhances the transportation of hydrogen [21]. There are reports that the reduction of the low-cycle fatigue life of austenitic stainless steels due to hydrogen is significant [7, 22]. Furthermore, in austenitic stainless steels, the fatigue strength of a work-hardened material is sensitive to hydrogen embrittlement, while that of solution heat-treated material is only slightly affected by hydrogen [14, 23]. Therefore, it can be presumed that adhesion caused by fretting enhances the effect of hydrogen.

During fretting, the temperature of the material in the fretted region increases [24]. The temperature increase may have an influence on the diffusion of hydrogen. However, it can be considered that the temperature increase in this experiment is not significant because the transformation from austenite to martensite becomes less effective with an increase in the temperature [25]. The association of hydrogen that enhanced the localized plastic deformation with the plastic deformation at the adhered part remains to be examined.



(a) Crystallographic orientation map



(b) Phase map.

Fig.14. EBSD observation of adhered part between fretting surfaces (The same position as Fig. 9).

Summary

The effect of hydrogen on the fretting fatigue strength of SUS304 and SUS316 and the mechanisms that cause reduction of the fretting fatigue strength were investigated.

(1) The fretting fatigue strength of both materials was reduced by hydrogen.
(2) The cause of the reduced fretting fatigue strength in low-pressure hydrogen was adhesion between the fretting surfaces and the formation of small cracks.
(3) Strain-induced martensite was formed at the adhered part between the fretted surfaces.

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