Fretting fatigue properties under the effect of hydrogen and the mechanisms that cause the reduction in fretting fatigue strength

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Abstract Fretting fatigue, which is a composite phenomenon of metal fatigue and friction, is one of the major factors in the design of mechanical components as it significantly reduces fatigue strength. Since hydrogen can influence both fatigue and friction, fretting fatigue is one of the important concerns in designing hydrogen equipment. The authors carried out the fretting fatigue tests on austenitic stainless steels in order to characterize the effect of hydrogen and to explain the mechanism responsible for hydrogen embrittlement. In this study, the significant reduction in fretting fatigue strength due to hydrogen is shown including other factors influencing the fretting fatigue strength such as surface roughness, hydrogen content and the addition of oxygen. The cause of the reduction in the fretting fatigue strength in hydrogen is local adhesion between the contacting surfaces and subsequent formation of many small cracks. Furthermore, hydrogen enhances crack initiation under fretting fatigue conditions. Transformation of the microstructure from austenite to martensite is another possible reason. A hydrogen charge also reduces the fretting fatigue strength. The cause is the reduction in the crack growth threshold, ΔK_{th}, due to hydrogen.

Keywords Hydrogen, Fretting, Fatigue, Austenitic stainless steels, Adhesion

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1. Introduction

Hydrogen embrittlement is a classic problem, but recent studies on hydrogen embrittlement have clarified that there are many technical challenges to achieving a balance between reducing the cost of hydrogen equipment and ensuring their safety. In this study, fretting fatigue in hydrogen is the focus, since fretting fatigue is one of the major factors in the design of mechanical components due to the significant reduction in fatigue strength. It has been reported that fretting can cause a reduction in fatigue strength by half to one-thirtieth of that of a smooth specimen [1]. Fretting fatigue occurs at the position where metal fatigue and fretting occur simultaneously. Fretting is the cyclic relative slip motion involving wear between the contacting surfaces of components mechanically fastened. In hydrogen equipment, fretting fatigue is definitely an important issue, since hydrogen can have an influence on both fatigue and friction phenomena. A significant reduction in the fretting fatigue strength due to hydrogen and the mechanisms causing the reduction are described. Several factors influencing the fretting fatigue properties in hydrogen are also investigated.

2. Procedures

2.1 Fretting fatigue test method

Figure 1 shows the fretting fatigue test method under tension and compression loading. In addition, a bending fretting fatigue test was also carried out. Detailed configurations of the specimen and contact pad are shown in refs. [2, 3]. In either case, two contact pads were pressed onto the front and back side surfaces of the fatigue test specimen. When a fatigue load is applied to the specimen, fretting is induced between the contacting surfaces due to the difference in the deformation between the specimen and contact pad. The shape of the contact pad is the so-called bridge type in which there are two contact parts. As shown in Fig. 1, a strain gage was cemented at the midpoint of the contact parts to measure the friction force.

The nominal contact pressure was 100MPa. The tangential force coefficient, ϕ, was defined as the ratio of the friction force and the contact force. The fretting fatigue test was carried out with a stress ratio, R, of -1 at a loading frequency, f, of 20Hz. The test environment was hydrogen and laboratory air. The hydrogen pressure was 0.2MPa. The test temperature was room temperature. The fretting fatigue test in this study was terminated at 10^7 cycles if no specimen failure occurred.

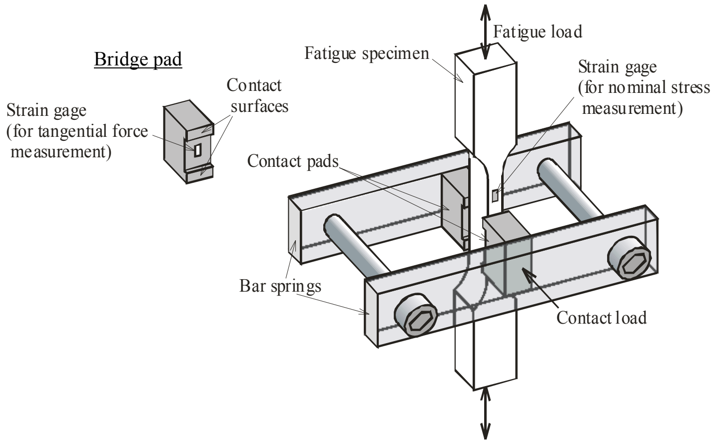


Figure 1. Fretting fatigue test method

2.2. Material

The test materials were three kinds of austenitic stainless steels, JIS SUS304, SUS316 and SUS316L. The chemical compositions of the materials are listed in Table 1. A solution heat treatment was done to the materials by quenching following heating at 1303K for 3.9ks.

Since fretting is a surface phenomenon, hydrogen diffusion into the material is one of the important issues. Therefore, hydrogen pre-charged materials were used in a part of the fretting fatigue test. The method of hydrogen pre-charging was thermal hydrogen charging.

Table 1. Chemical composition

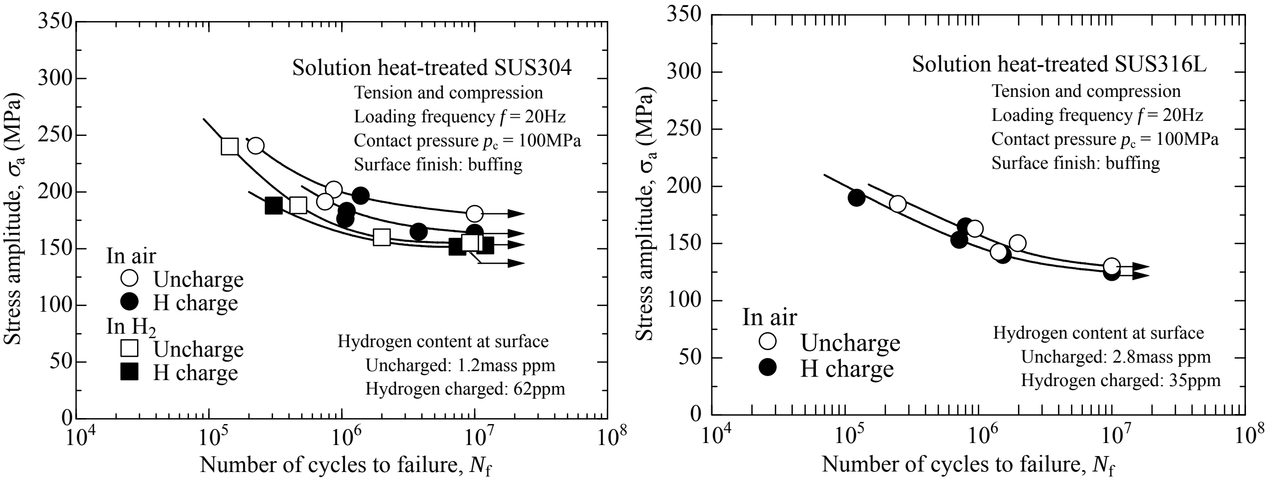
Material	C	Si	Mn	P	S	Ni	Cr	Mo	Fe
SUS 304	0.06	0.51	0.92	0.033	0.004	8.08	18.8	-	Bal.
SUS 316	0.05	0.49	1.31	0.030	0.027	10.22	17.0	2.04	Bal.
SUS 316L	0.012	0.19	1.64	0.031	0.012	12.19	16.6	2.22	Bal.

3. Effect of hydrogen on fretting fatigue strength

3.1. *S-N* curves

Figure 2 shows the fretting fatigue *S-N* diagrams. For the SUS304, the fretting fatigue strength of the uncharged material was significantly lower in the hydrogen than in air (□ and ○). The effect of hydrogen pre-charging is also shown in Fig. 2. The details of the hydrogen pre-charging are found in ref. [1]. In air, the fretting fatigue strength was significantly reduced by the hydrogen pre-charging (● and ○). The fretting fatigue strength of SUS304 is reduced by not only gaseous hydrogen, but also internal hydrogen. When the fretting fatigue test of the hydrogen-charged material was done in hydrogen, the reduction in the fretting fatigue strength was very significant (■). The gaseous hydrogen and internal hydrogen synergistically works in decreasing the fretting fatigue strength. The mechanisms will be discussed in the latter part of this paper.

Figure 2 also shows the fretting fatigue strength of SUS316L. A failure of the hydrogen-charged specimen occurred at the fretting fatigue limit of the uncharged material. There was a trend that the finite life of the hydrogen-charged material was shorter than that of the uncharged material. Although the amount of the reduction in the fretting fatigue was small compared to SUS304, hydrogen reduced the fretting fatigue strength of the SUS316L. Since this material is recognized as a hydrogen compatible material [4, 5], the result which shows the reduction in fatigue strength is important for the design of hydrogen equipment. The hydrogen embrittlement during the fatigue of SUS316L was also reported by Murakami et al [6].



(a) Solution heat-treated SUS304 (b) Solution heat-treated SUS316L

Figure 2. Effect of hydrogen on fretting fatigue strength

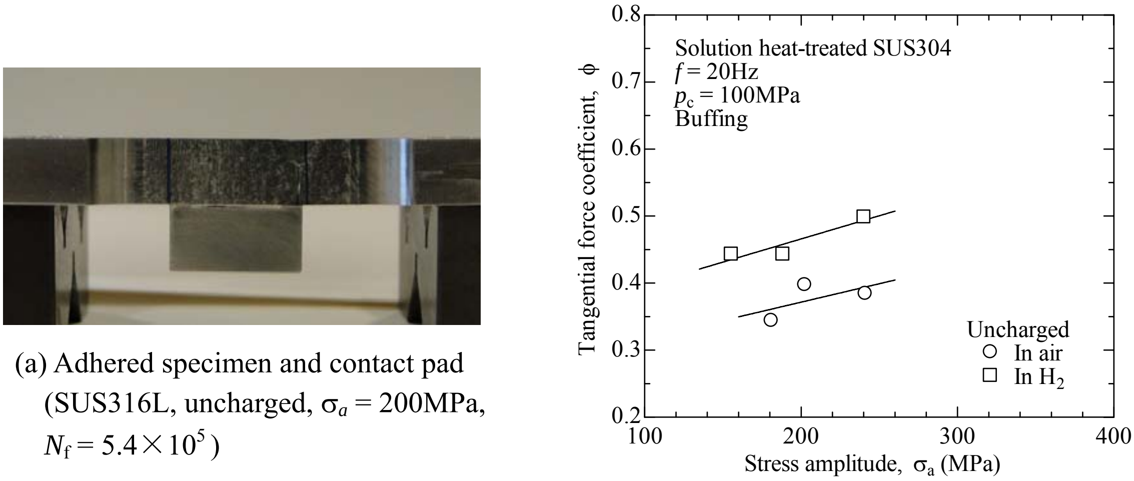
3.2. Mechanism that causes the reduction in fretting fatigue strength due to hydrogen

3.2.1. Local adhesion between contacting surfaces

Figure 3 shows the characteristic phenomenon that occurs during fretting fatigue in hydrogen. The specimen and contact pad adhered to each other during the fretting fatigue in hydrogen. During the fretting in air, oxidized fretting wear particles separate the specimen and pad. In air, the fretting damage is produced by an oxidation dominant process. On the other hand, during the fretting in non-oxidative environments, such as a vacuum [7] or nitrogen [8], the fretting damage mechanism changes to an adhesion dominant process. In hydrogen, a similar mechanism may occur.

Figure 3 also shows the tangential force coefficient in each environment. An increase in the tangential force in hydrogen is clearly shown. The adhesion between the contacting surfaces is the cause of the increased tangential force in hydrogen. The stress conditions on the fretted surface are determined by the fatigue stress, contact stress and tangential stress due to friction [9]. The tangential force is a dominant factor of the fretting fatigue strength [10]. The increase in the tangential force in hydrogen causes an increase in the mechanical stresses on the contact surface. Consequently, the increase in the tangential force due to adhesion is one of the possible reasons for the reduced fretting fatigue strength in hydrogen.

Figure 4 shows the section along the specimen axis of the adhered specimen and contact pad during the fretting fatigue test in hydrogen. There were many small cracks at the interface between the specimen and pad. The small cracks propagated in two directions at which the small cracks made angles of approximately 45 or 135 degrees to the contact surface. During the fretting fatigue in air, small oblique cracks and multiple small cracks are the typical characteristics [11]. However, the angle of the oblique small cracks is constant [12]. Furthermore, the small cracks observed in this experiment propagated into both the specimen and the contact pad. Fretting fatigue cracks are



(a) Adhered specimen and contact pad (SUS316L, uncharged, σ_a = 200MPa, $N_f = 5.4 \times 10^5$)

(b) Increase in tangential force coefficient

Figure 3. Adhesion between contacting surfaces during fretting fatigue test in hydrogen

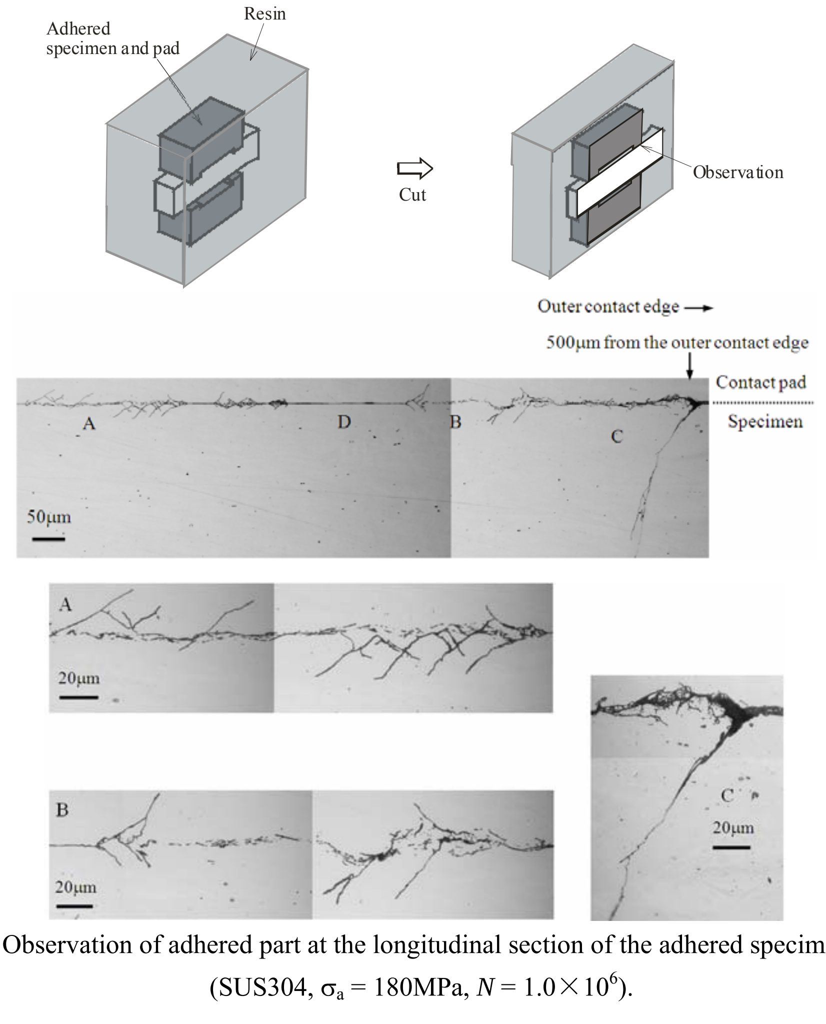
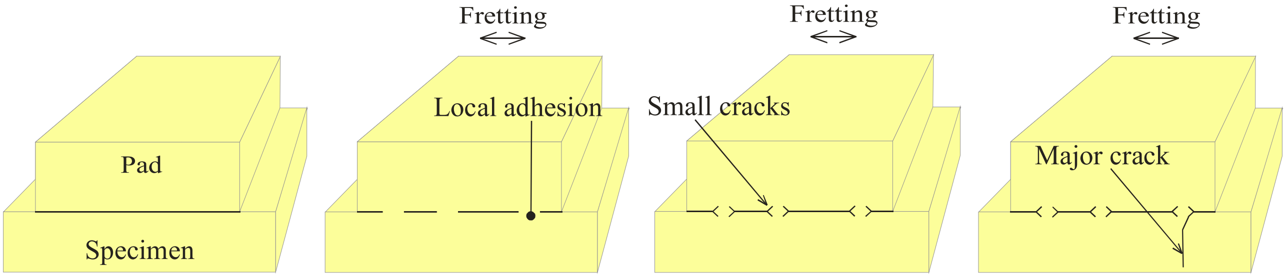


Figure 4. Observation of adhered part at the longitudinal section of the adhered specimen and pad (SUS304, σ_a = 180MPa, $N = 1.0 \times 10^6$).

typically found in a specimen because no fatigue stress is applied to the contact pad. The morphology of the small fretting fatigue cracks in hydrogen was unique compared to that observed in air.

If a contact pad is simply placed on the specimen without fretting, the boundary of the specimen and pad should be a straight line. However, at positions A, B and C, the interface was not continuous and winding. These are microscopic evidence of adhesion. At position D where a straight line was observed, there was no fretting fatigue cracks. Therefore, the formation of the small cracks is related to the local adhesion.

There was a major crack leading to specimen failure at position C. The major crack started to grow from one of the small cracks that emanated from the adhered spot. Therefore, the adhesion and the subsequent formation of many small cracks are one of the root causes of the reduced fretting fatigue strength in hydrogen. Based on this observation, a model to describe the fretting fatigue failure in hydrogen is shown in Fig. 5.



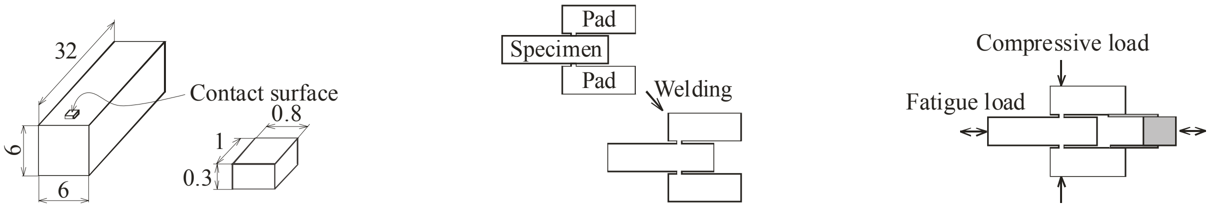
(a) Before test (b) Local adhesion (c) Crack initiation (d) Specimen failure

Figure 5. Model to cause fretting fatigue failure in hydrogen

3.2.2. *Effect of hydrogen on fretting fatigue crack initiation*

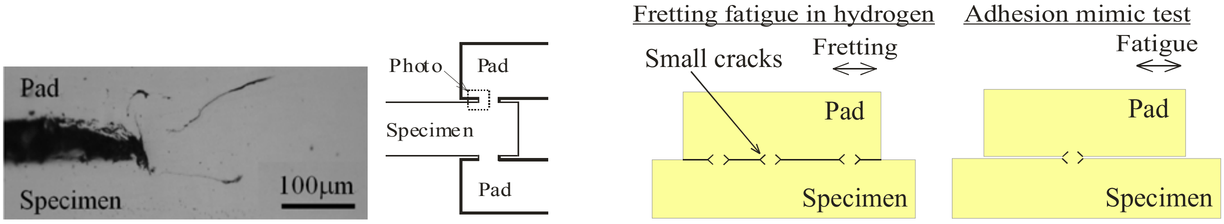
Figure 6 shows the test method used to investigate the effect of hydrogen on the initiation of a fretting fatigue crack. The specimen and contact pads were welded using a spot welding machine to mimic adhesion during fretting fatigue in hydrogen. A compressive load, which corresponds to the contact load in the fretting fatigue test, was applied. The fatigue test was interrupted at 10^5 cycles and identification of a small crack was then carried out. The details of the experiment are described in ref. [13].

Figure 7 shows an example of the fatigue crack in the adhesion mimic test. About 100 μm-deep cracks were found. The morphology of the cracks is similar to that observed in the fretting fatigue test in hydrogen as shown in the figure.



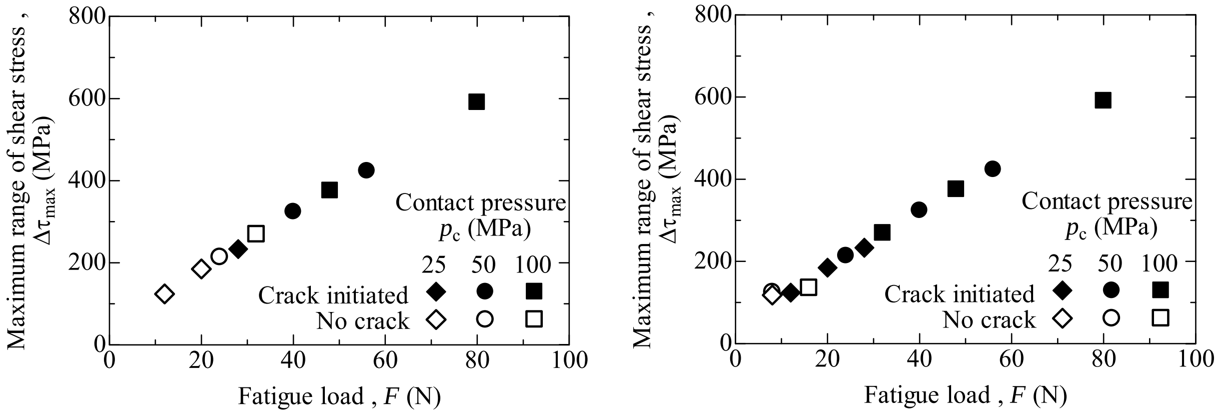
(a) Contact pad (b) Welding of specimen and pad (c) fatigue test method

Figure 6. Adhesion mimic fatigue test (dimensions are in mm)



(a) Small crack in adhesion mimic test (b) Morphology of small crack

Figure 7. Observation of small cracks



(a) In air (b) In hydrogen

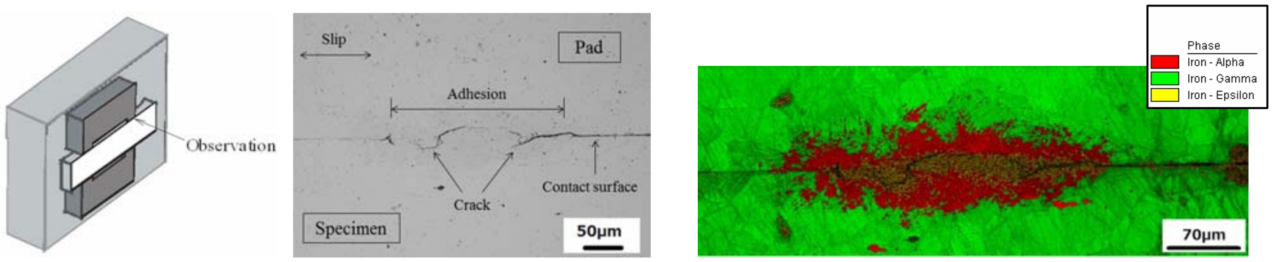
Figure 8. Effect of hydrogen on crack initiation under adhesion condition

The result of the local adhesion mimic fatigue test is shown in Fig. 8. The maximum range of shear stress was obtained by an elastic-plastic finite element (FE) analysis [13]. The crack initiation occurred in a significantly lower maximum shear stress range in hydrogen than in air. It was confirmed that hydrogen assisted the crack initiation in this experiment. This is one of the mechanisms other than stress concentration due to local adhesion that causes a reduction in the fretting fatigue strength in hydrogen.

The maximum shear stress range was greater than the proof strength of the material. Since the regions with a higher strain attract more hydrogen [14] and mobile dislocations transport hydrogen [15], it is presumed that the local adhesion activates the hydrogen embrittlement. As further evidence, the authors confirmed the facilitating of crack initiation due to hydrogen in a low-cycle fatigue of austenitic stainless steel [16]. Furthermore, fretting wear removes the oxidized surface which may prevent the diffusion of hydrogen into the material. There is a possibility that such a higher stress causes a microstructure change from austenite to martensite. The microstructure change during the fretting fatigue will be described in the next section.

3.2.3. Microstructure change

Figure 9 shows the result of the electron backscatter diffraction (EBSD) observations of the adhered part. Alpha-prime, which is considered to be strain-induced martensite, was detected at the adhered part. Martensite is vulnerable to hydrogen. Besides this, the diffusivity of hydrogen is significantly greater in the martensitic phase than in the austenitic phase [17]. As a result, the transformed martensite in the austenitic stainless steel can act as a low resistance diffusion pathway for hydrogen diffusion [18]. The transformation of the microstructure is one of the important mechanisms that cause a reduction in the fretting fatigue strength in hydrogen.

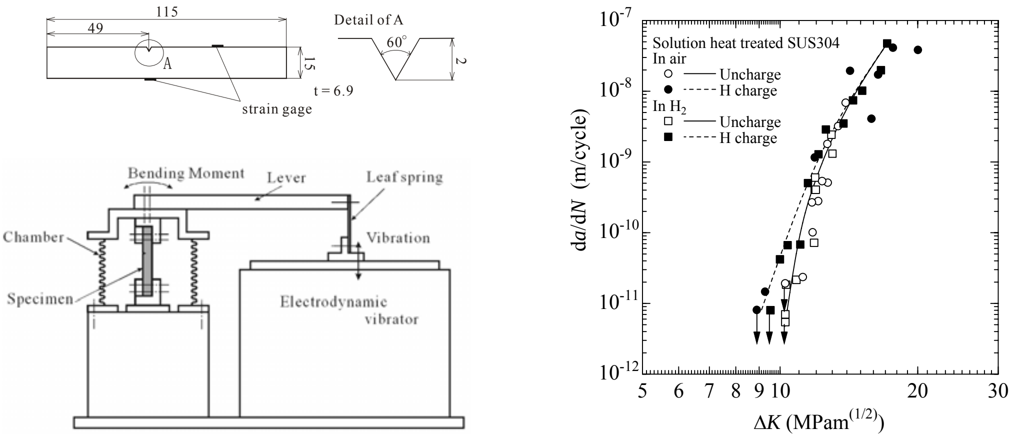


(a) SEM image (b) Phase map obtained by EBSD

Figure 9. Microstructure change due to local adhesion between fretting surfaces
(SUS316, σ_a = 182MPa, $N_f = 10^6$)

3.2.4. Reduction in fatigue threshold by absorbed hydrogen

Figure 10 shows the result of the crack growth test. The details of the test method are found in ref. [19]. In the hydrogen-charged specimen, the reduction in the threshold stress intensity factor, ΔK_{th}, is clearly shown. The reduction in ΔK_{th} is one of the causes of the reduced fretting fatigue strength by a hydrogen charge. The fretting fatigue limit of both the hydrogen-charged and uncharged materials can be quantitatively evaluated by the model based on the ΔK_{th} [19].



(a) Specimen and test method (b) Crack growth curves

Figure 10. Effect of hydrogen on crack growth threshold of SUS304

4. Effect of work-hardening

Work-hardening is a fundamental method of increasing the strength of austenitic stainless steels. Strengthened austenitic stainless steels are frequently used for high-pressure components. A 40% plastic strain was applied to the solution heat-treated materials by the tensile test at room temperature. The mechanical properties of the work-hardened austenitic stainless steels are shown in Table 2.

Figure 11 shows the result of the fretting fatigue test of the work-hardened SUS304. When the fretting fatigue strength of the uncharged material in air was compared between the solution heat-treated material (Fig. 2) and work-hardened material, it was found that the work-hardening improved the fretting fatigue strength (○ in each graph). However, the reduced fretting fatigue strength due to hydrogen was almost equivalent between the solution heat-treated material and the work-hardened material. The effect of the work-hardening was suppressed by the hydrogen. This indicates that special consideration is required in the design of hydrogen equipment made of work-hardened austenitic stainless steels.

5. Effect of surface roughness

For mechanical components requiring a gas tightness, surface roughness is one of the design factors. Figure 12 shows the fretting fatigue *S*-*N* curves of SUS316 in which the specimens have two

Table 2. Mechanical properties and Vickers hardness

Material	Conditions	Proof strength $\sigma_{0.2}$ (MPa)	UTS σ_B (MPa)	Elongation δ (%)	Vickers hardness HV
SUS304	Solution heat-treated	294	667	60	242
	40% pre-strained	955	1027	26	358

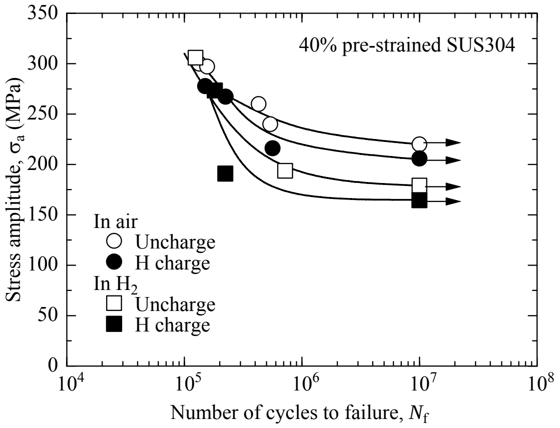


Figure 11. Effects of work-hardening and hydrogen on fretting fatigue strength of SUS304.

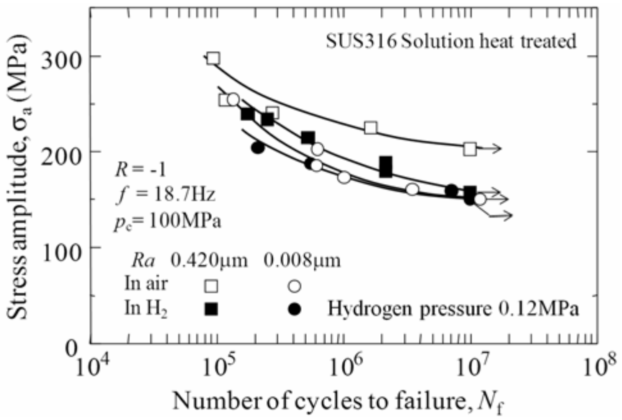
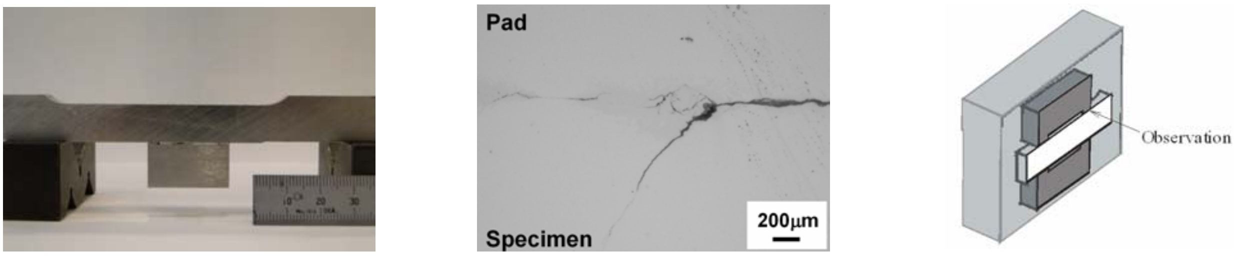


Figure 12. Effects of surface roughness and hydrogen on fretting fatigue strength of SUS316.

different contact surface roughnesses. The smoother surface specimen showed a considerably lower fretting fatigue strength than the rougher surface one (○ and □). The effect of hydrogen was significant in the rougher surface specimen (□ and ■), but not so in the smoother surface specimen (○ and ●).

These results can be interpreted by the crack nucleation mechanism. Figure 13 shows the major crack in the smoother surface specimen used for the fretting fatigue test in air. The major crack started to grow from the locally adhered spot similar to that observed in hydrogen. That is, when the contact surface has an extremely low surface roughness, adhesion occurred even in air and the adhesion played a dominant role in causing the fretting fatigue failure.



(a) Adhered specimen and pad

(b) Major crack emanated from adhered spot

Figure 13. Fretting fatigue test of smooth contact surface specimen in air

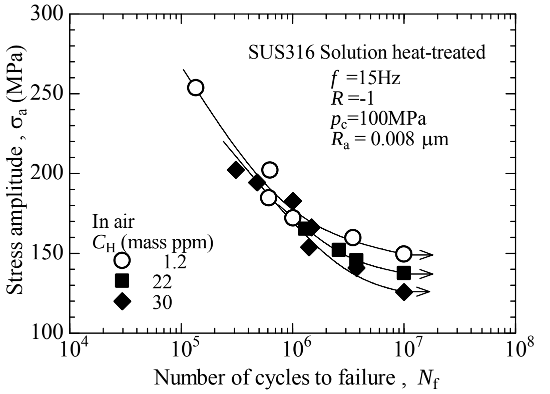
6. Effect of hydrogen content

Figure 14 shows the fretting fatigue strength of the SUS316 for specimens having different hydrogen contents. The hydrogen content in the material was increased by the thermal hydrogen charging at 573K for 200h. The fretting fatigue strength of the SUS316 decreased with an increase in the hydrogen content.

7. Effect of hydrogen-containing oxygen as minor impurity

The purity of hydrogen used in hydrogen equipment is one of the most important concerns in terms of the performance of hydrogen equipment and the cost of hydrogen. Figure 15 shows the effect of oxygen addition on the fretting fatigue strength of the SUS304 in hydrogen. The oxygen content was 100vol ppm. The fretting fatigue strength in the oxygen-hydrogen mixture was between that in the pure hydrogen and in air.

One of the causes of the increase in the fretting fatigue strength in the oxygen-hydrogen mixture is the reduction of the tangential force between the contacting surfaces due to generation of oxidized fretting wear particles. Another cause is the increase in the crack initiation limit. Based on the adhesion mimic test (section 3.2.2), the critical maximum shear stress range to crack initiation in the hydrogen-oxygen mixture was between that in hydrogen and air [20].



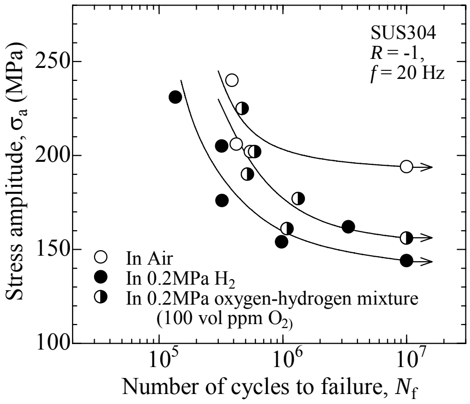


Figure 14. Effect of hydrogen content on fretting fatigue strength of SUS316

Figure 15. Effect of addition of oxygen on fretting fatigue strength of SUS304 in hydrogen

8. Conclusions

Fretting fatigue is one of the major concerns in various engineering fields such as railway, energy, aviation, automobile, etc., because fretting fatigue strength is significantly lower than the fatigue strength of a smooth specimen. This study showed the additional reduction in fretting fatigue strength due to hydrogen. The major results can be summarized as:

- ***S-N* curves:** the fretting fatigue strength of SUS304 and SUS316L is reduced by gaseous hydrogen. When the fretting fatigue test of the hydrogen-charged material, such as SUS304 was done in hydrogen, the reduction in the fretting fatigue strength was more affected due to the synergistic effect of gaseous hydrogen and internal hydrogen;
- **Mechanisms that cause the reduction in fretting fatigue strength in gaseous hydrogen:** The first mechanism is explained by the action of hydrogen as the cause for local adhesion between contacting surfaces in fretting-fatigue samples of both SUS304 and SUS316L. The second one is the microstructure change to martensite in the local adhesion part. Both mechanisms will act together in lowering the fretting fatigue strength of these stainless steels in contact with gaseous hydrogen;
- **Reduction in fatigue threshold by absorbed hydrogen:** The reduction in ΔK_{th} is one of the causes of the reduced fretting fatigue strength by a hydrogen;
- **Effect of surface roughness:** The effect of hydrogen was significant in the rougher surface specimen, but not so in the smoother surface specimen. Rough surfaces present more stress concentrators to attract hydrogen;
- **Effect of hydrogen content:** The fretting fatigue strength of the SUS316 decreased with an increase in the hydrogen content;
- **Effect of hydrogen-containing oxygen as minor impurity:** The oxygen content of 100vol ppm in gaseous hydrogen had a beneficial effect by improving fretting fatigue strength of SUS304. Even at this low impurity level, oxygen causes the reduction of the tangential force between the contacting surfaces due to generation of oxidized fretting wear particles, and the increase in the crack initiation limit.

Despite all these findings, additional work is needed to better explore the mitigating effects of oxidizing impurities in hydrogen environments.

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