The Effect of Prestrain on Fatigue Property of Precipitation Strengthening Stainless Steel SUH660

H. Wu[1,a], S. Hamada[2,b] and H. Noguchi[2,c]

[1] Department of Mechanical Engineering, Graduate School of Engineering, Kyushu University,

744 Moto-oka Nishi-ku, Fukuoka, 819-0395, Japan

[2] Department of Mechanical Engineering, Faculty of Engineering, Kyushu University,

744 Moto-oka Nishi-ku, Fukuoka, 819-0395, Japan

[a] wuhao@mech.kyushu-u.ac.jp, [b] hamada@mech.kyushu-u.ac.jp, [c] nogu@mech.kyushu-u.ac.jp

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Abstract. In precipitation-strengthened steel, precipitation particles are considered to be cut by the prestrain treatment and affect the fatigue property of the steel. In this study, fatigue tests on prestrained specimens were performed to investigate the effect of the prestrain and precipitate cutting on the crack initiation and propagation characteristics of precipitation-hardened stainless steel (SUH660). Plain specimens were used to observe the process of crack initiation and propagation. The fatigue life was divided into the crack initiation life and the crack propagation life. The results of the fatigue test showed that the crack initiation life of a prestrained specimen was longer than that of a nonstrained specimen. The observed crack propagation mode was mainly Mode II. The measured crack propagation life of the prestrained specimen was shorter than that of the non-strained specimen, which was the opposite of the results observed for carbon steel. It was assumed that this was because Mode II crack propagated more easily and faster in the prestrained specimen, where the precipitates were cut, than in the non-strained specimen. Therefore, the relationship between the fatigue life of the prestrained specimen and the non-strained specimen is considered to be dependent on the stress level. When the crack propagation life governed the fatigue life, the fatigue life of the prestrained specimen was shorter than that of the non-strained specimen. However, when the crack initiation life governed the fatigue life, the fatigue life of the prestrained specimen would be longer than that of the non-strained specimen.

Introduction

Austenitic precipitation-hardened heat-resistant stainless steel (SUH660) is a candidate material for equipment exposed to high-pressure hydrogen, such as a pressure vessel, because of its excellent hydrogen embrittlement resistance [1]. Although SUH660 stainless steel has high strength and can be developed for extreme environments, the effect of prestrain on the fatigue strength characteristic has not been investigated.

It is well known that, for common steel such as carbon steel, the fatigue life [2,3] and fatigue limit [2,3,4] increase with an increase in the hardness imposed by a prestrain. However, for aluminum alloys, which are precipitation-hardened materials, such as the 6xxx and 7xxx series, the fatigue life is reduced by an increase in the prestrain level [5,6], which is considered to be related to precipitate cutting [6]. Therefore, in SUH660 stainless steel, which is an iron-based precipitation-hardened alloy, the increase in hardness and precipitate cutting by prestrain treatment would affect the fatigue strength characteristics. In this research, the crack initiation and propagation behavior were examined to determine the effect of prestrain on the fatigue property of the precipitation-hardened stainless steel (SUH660).

Experimental Methods

In this research, prestrained and non-strained specimens of SUH660 stainless steel were used. Table 1 lists the chemical composition of SUH660 stainless steel. It should be noted that SUH660 stainless steel was solution treated (ST) for 1 h at 980 °C, air cooled, aged (A) for 16 h at 720 °C, and the air cooled. The prestrained specimen was then compressed by cold rolling to achieve a cross-sectional reduction rate of approximately 10%. The surfaces of the test specimens were buff-polished after machining and electro-polished at 50 °C to remove the damaged surface layer (10–20 μm).

Tensile tests and fatigue tests were performed in this study. For the tensile test, an AUTO GRAPH AG-5000 (Shimadzu Corporation) was used. For the fatigue tests, on Ono-type rotating-bending fatigue test machine was used in air at room temperature at a testing frequency of 55 Hz, and the microscopic fatigue crack behaviors were observed using the replica method. Figure 1 shows the shapes and dimensions of the tensile test specimen and fatigue test specimen.

Table 1. Chemical composition of SUH660 steel (wt. %)

C	Si	P	S	Ni	Cr	Mo	Ti	V	Al	Fe	N	B
0.041	0.11	0.003	0.0017	25.4	15.19	1.43	2.23	0.30	0.21	Bal.	0.0012	0.0033

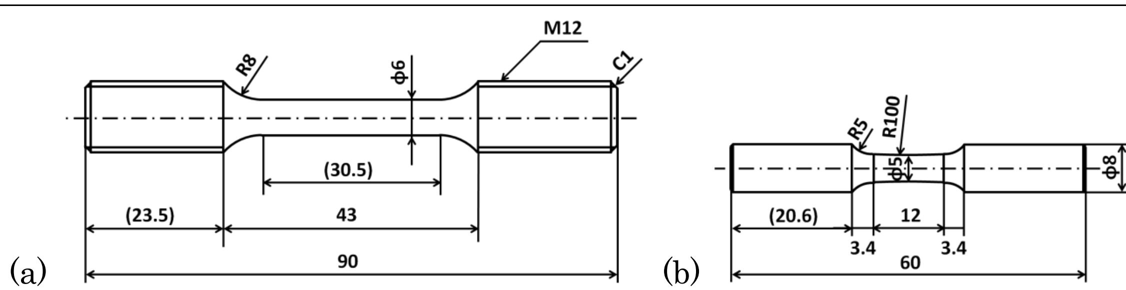
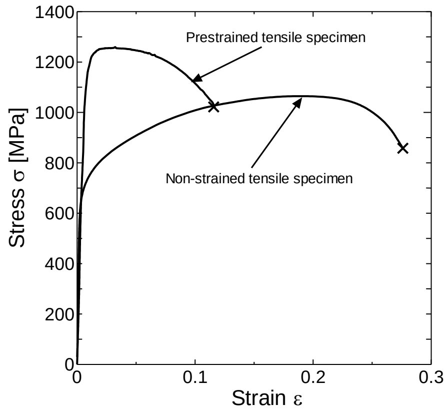


Fig. 1. Shapes and dimensions of specimens (unit: mm): (a) Tensile test specimen; (b) Fatigue test specimen.



(a)

(b)

Fig. 2. Tensile test results for SUH660 stainless steel: (a) Stress-strain curve; (b) Fractured non-strained tensile specimen.

Table 2. Tensile test results for SUH660 stainless steel

Type	Tensile strength (σ_B)	0.2% proof stress ($\sigma_{0.2}$)	Elongation (δ)
Non-strained tensile specimen	1065 MPa	664 MPa	27.6%
Prestrained tensile specimen	1259 MPa	1200 MPa	11.7%

Results and Discussions

Effect of Prestrain on Crack Propagation Life. Figure 2 and Table 2 show the tensile test results for SUH660 steel. The tensile strength and 0.2% proof stress of the prestrained specimen were higher than those of the non-strained specimen. The fractured tensile non-strained specimen shown in Fig. 2(b) has a cup-and-cone fracture, and SUH660 steel shows a ductile fracture, as shown by carbon steel. According to the material behavior for a ductile fracture, slips occur when the tensile stress approaches the yield strength, which affects the maximum tensile strength. For a fatigue fracture, slips affect the crack propagation and fatigue strength. Although a tensile fracture is different from a fatigue fracture, the tensile strength and fatigue strength are considered to be affected by the slip. Thus, for SUH660 steel, it is suggested that the fatigue strength at 1/4 cycle of the prestrained specimen, which had a higher tensile strength, was higher than that of the non-strained specimen.

Figure 3 shows the fatigue test results for SUH660 steel. In contrast to carbon steel, where the fatigue life increases with an increase in hardness imposed by a prestrain [2,3], at the same fatigue stress level amplitude, the prestrained specimen of SUH660 steel, which had a higher tensile strength than the non-strained specimen, had a shorter fatigue life than the non-strained specimen. To determine the reason for this difference in the fatigue life, we investigated the fatigue life by dividing it into the crack initiation life and crack propagation life. Figure 4 shows the crack propagation curves of SUH660 steel at σ_a = 260 MPa and 400 MPa. Below σ_a = 400 MPa, the crack

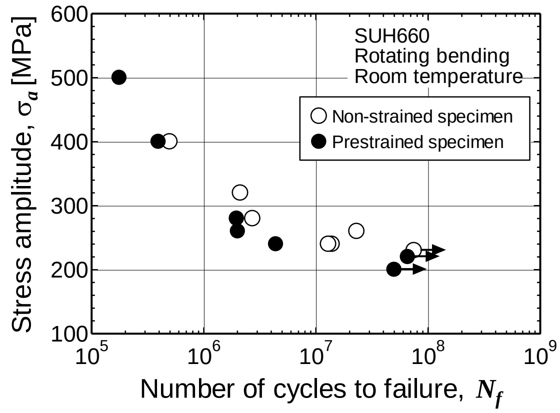


Fig. 3. Fatigue strength of SUH660 stainless steel.

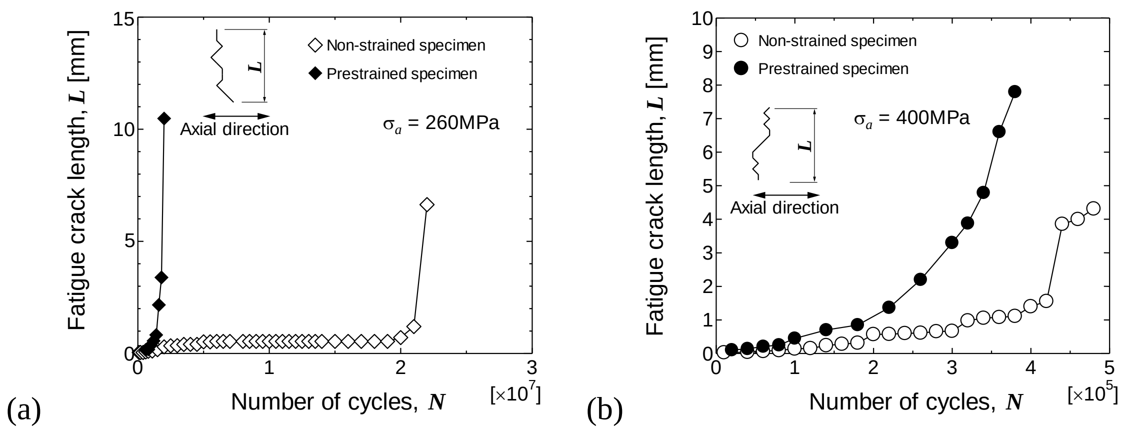


Fig. 4. Crack propagation curves of the prestrained and non-strained SUH660 specimens: (a) σ_a = 260 MPa; (b) σ_a = 400 MPa.

initiation life accounted for only a small part of the fatigue life, and the crack propagation life governed the fatigue life. Figure 4(a) shows the fatigue crack propagation curves at σ_a = 260 MPa. The fatigue crack propagated monotonously in the prestrained specimen, while in the non-strained specimen, the fatigue crack stopped propagating and then began to propagate again. Wu et al. [7] reported that, for SUH660 steel, a non-propagating crack coalesced with a new crack that was initiated near the non-propagating crack tip and then propagated again below the fatigue strength at 10^7 cycles. The non-strained specimen had a higher fatigue strength at 10^7 cycles than the prestrained specimen. According to the crack propagation curves at σ_a = 400 MPa shown in Fig. 4(b), the fatigue crack propagated faster in the prestrained specimen than in the non-strained specimen. Figure 5 shows crack photographs of the prestrained and non-strained specimens at σ_a = 400 MPa. In the case of SUH660 steel, the fatigue cracks in the prestrained and non-strained specimens were easily propagated by mixed Mode or Mode II. Figure 6 shows the crack growth rate diagram. When the fatigue crack length exceeded 100 μm, the Mode II crack growth rate of the prestrained specimen was approximately 10 times faster than that of the non-strained specimen, which was similar to aluminum alloy 6061-T6 [6]. Ikematsu et al. [6] reported that, for 6061-T6,

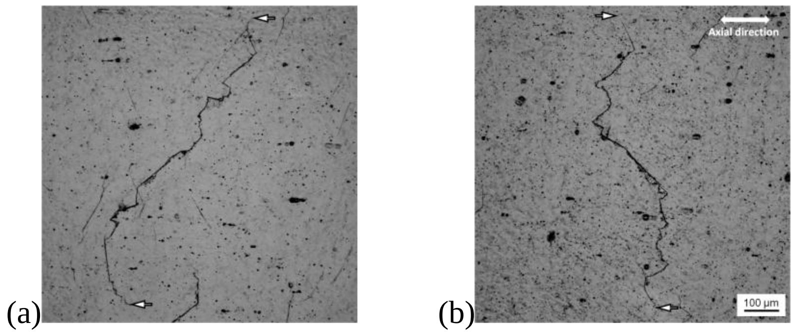


Fig. 5. Crack photographs of SUH660 specimens (arrows indicate crack tips) (σ_a = 400 MPa): (a) Non-strained specimen ($N = 3 \times 10^5$ cycles); (b) Prestrained specimen ($N = 1.8 \times 10^5$ cycles).

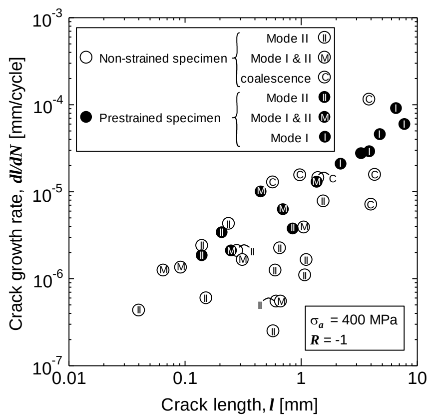


Fig. 6. Crack growth rate of SUH660 steel (σ_a = 400 MPa).

which is a precipitation-hardened aluminum alloy, precipitates are considered to be cut by a prestrain, which causes the easily occurrence of slips in a slip band. Prestrainis thought to have a limited effect on the Mode I crack growth rate on an average, because Mode I cracks propagate across slip bands and are only slightly affected by slip bands in general. Prestrain is thought to accelerate Mode II crack propagation, because Mode II cracks propagate along slip bands, and the resistance to Mode II crack propagation is low parallel to a slip band. Therefore, for SUH660 stainless steel, precipitates in the prestrained specimen are considered to be cut by the prestrain as in the case of 6061-T6, which accelerates Mode II crack propagation and reduces the crack propagation life.

Bayley et al. [8] reported that dislocation induced back stress and stress field were found around the dislocation. The back stress effect on the dislocation source is considered to decrease with an increase in the distance from the area of a dislocation pile-up along the slip plane. In the case of the non-strained specimen, many precipitates exist near the fatigue crack tip, and the dislocations pile up at the precipitate when the dislocations occur from the dislocation source of the fatigue crack tip. In the case of the prestrained specimen, because the precipitates were cut by prestrain, the dislocations piled up at the grain boundary when they occurred at the dislocation source of the fatigue crack tip. Then, because of the work hardening caused by the prestrain, the back stress had an effect on the dislocation source of the fatigue crack tip before the occurrence of the dislocation, and caused more resistance to slip than in case of the non-strained specimen. However, because the distance between the fatigue crack tip and the precipitates was shorter than that between the fatigue crack tip and the grain boundary, for the non-strained specimen, the back stress effect on the fatigue crack tip is considered to have increased quickly and exceeded the prestrained specimen while the dislocations piled up. Then, although work hardening caused by the prestrain inhibited slip occurrence, the prestrained specimen had a lower resistance to slip than the non-strained specimen when cracks were propagating, which accelerated the crack propagation and reduced the crack propagation life. Therefore, the fatigue crack growth rate was considered to be more affected by precipitate cutting than by work hardening, which was why the crack propagation life of the non-strained specimen was longer than that of the prestrained specimen for SUH660 steel.

Effect of Prestrain on Crack Initiation Life. From the crack propagation curves shown in Fig. 4, it is observed that the crack initiates later in the prestrained specimen than in the non-strained specimen, either at σ_a = 400 MPa or 260 MPa. The crack initiation life is considered to be influenced by the prestrain. When cyclic fatigue stress was applied to the specimen, slip first occurred on the softest slip plane of the softest grain and caused work hardening. It then occurred on the next softest slip plane until all of the soft slip planes were work-hardened, after which slip occurred on the softest slip plane again. Thus, slip concentration occurred in the softest grain and caused fatigue crack initiation. Meanwhile, a comparison of the slip motions in the forward and reverse directions showed that the cyclic fatigue stress caused slip concentration, whereas slip motion in a direction along the prestrain could not cause slip concentration. Thus, for either the non-strained specimen or prestrained specimen, fatigue cracks are considered to be initiated only under a cyclic fatigue stress. Therefore, in the fatigue test, because of the work hardening caused by the prestrain, the prestrained specimen had a higher resistance to slip than the nonstrained specimen, which inhibited the occurrence of slip and increased the crack initiation life.

Figure 7 shows the crack distribution on the SUH660 specimen surface at σ_a = 400 MPa. More cracks were observed on the non-strained specimen surface than on the prestrained specimen surface. Wu et al. [9] reported that intrinsic hardness variability was obtained on a non-strained SUH660 specimen, and cracks were easily initiated in the low hardness zone. For the non-strained specimen with intrinsic hardness variability, slips easily occurred and concentrated in the soft grains of the low hardness zone. In the prestrain process, the low hardness zone yielded first, after which the high hardness zone yielded as the stress increased. In addition to the increase in the resistance to slip occurrence by work hardening, the intrinsic hardness variability was thought to reduce after the prestrain treatment. Thusn, in constrast to the non-strained specimen, in which numerous slips occurred in soft grains and a slip concentration occurred easily, for the prestrained specimen, slips were considered to occur in harder grains than the non-strained specimen, which made slip concentration difficult in the soft grains of the low hardness zone and increased crack initiation life.

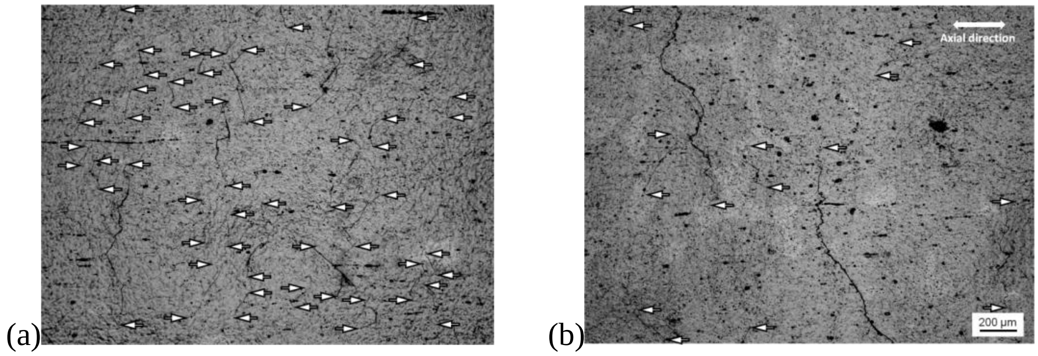


Fig. 7. Crack distribution on specimen surface of SUH660 steel (arrows indicate crack tips) (σ_a = 400 MPa, $N = 3.6 \times 10^5$ cycles): (a) Non-strained specimen; (b) Prestrained specimen.

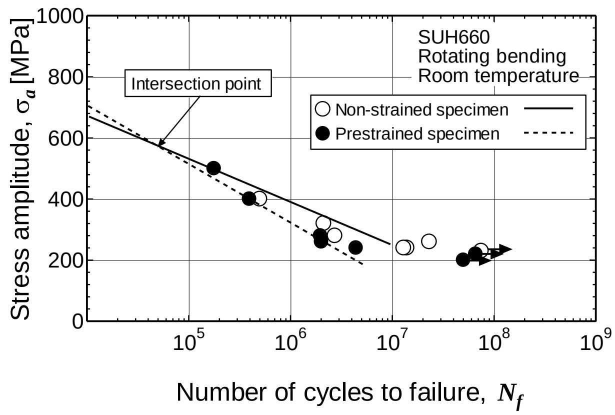


Fig. 8. *S*-*N* diagram of SUH660 steel with intersection point.

Therefore, for SUH660 steel, the prestrained specimen had a longer crack initiation life than the non-strained specimen.

Effect of Prestrain on Fatigue Life. The prestrained specimen had a longer crack initiation life than the non-strained specimen but had a shorter crack propagation life than the non-strained specimen. The prestrained specimen had a higher fatigue strength at 1/4 cycle but a shorter fatigue life below σ_a = 400MPa than the non-strained specimen. Therefore, in case of SUH660 steel, the fatigue life relationship between the prestrained and non-strained specimens is considered to be dependent on the stress level; in other words, there is an intersection point for the two finite life regimes of the prestrained and non-strained specimens in the S-N diagram. Figure 8 shows the S-N diagram of SUH660 steel with this intersection point. Hereafter, in this study, a low cycle fatigue life stress level amplitude indicates a stress level above the intersection point, and a high cycle fatigue life stress level amplitude indicates a stress level amplitude below the intersection point. At the high cycle fatigue life stress level amplitude, the crack propagation life governed the fatigue life, and although the fatigue crack of the prestrained specimen was initiated later than that in case of the non-strained specimen, the crack propagation life of the prestrained specimen was shorter than that of the non-strained specimen. Then the fatigue life of the prestrained specimen is shorter than the non-strained specimen. However, at the low cycle fatigue life stress level amplitude, the fatigue life was considered to be governed by the crack initiation life, and the fatigue life of the prestrained specimen would be longer than that of the non-strained specimen, because the crack initiation life of the prestrained specimen was longer than that of the non-strained specimen.

Conclusions

To investigate the effect of prestrain and precipitate cutting on the fatigue strength characteristics of an SUH660 plain specimen, tensile tests and fatigue tests were performed. The conclusions are described below.

(1) We divided the fatigue life into the crack initiation life and crack propagation life. In case of SUH660 steel, the crack propagation life of the prestrained specimen was shorter than that of the non-strained specimen because of the acceleration of the Mode II crack propagation, which is considered to be caused by precipitate cutting. The crack initiation life of the prestrained specimen was longer than that of the non-strained specimen because of the prestrain, which was considered to make the slip concentration difficult.

(2) In the case of SUH660 steel, the fatigue life relationship between the prestrained and the non-strained specimens was considered to be dependent on the stress level. In the high cycle fatigue life stress level amplitude, the crack propagation life governed the fatigue life, and the fatigue life of the prestrained specimen was shorter than that of the non-strained specimen. However, in the low cycle fatigue life stress level amplitude, the crack initiation life governed the fatigue life, and the fatigue life of the prestrained specimen was longer than that of the non-strained specimen.

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