FATIGUE BEHAVIOUR OF PRE-STRAINED TYPE 316 STAINLESS STEEL

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ABSTRACT

The present paper describes the fatigue behaviour of prestrained type 316 stainless steel. Two types of fatigue tests, conventional *S-N* test and increasing stress test, were performed under rotary bending using specimens subjected to 5 % and 15 % tensile prestrains. Fatigue strength increased with increasing prestrain, resulting in 7 % and 27 % increase of fatigue limit in the 5 % and 15 % prestrained specimens, respectively, relative to the unprestrained specimen. The increase of fatigue strength in the prestrained specimens was attributed to both crack initiation resistance and small crack growth resistance enhanced by prestraining. Under increasing stress tests, fatigue limit increased significantly in the unprestrained and 5 % prestrained specimens, but no increase was seen in the 15 % prestrained specimen. Remarkable increase in hardness of the failed specimens was recognized in the unprestrained and 5 % prestrained specimens, while only a slight increase in the 15 % prestrained specimen. It was indicated, therefore, that the coaxing effect was strongly related to the ability of work hardening during stress cycling.

Introduction

Various machine components are usually subjected to plastic deformation during processing or forming. If heat treatments such as full annealing or stress-relieved annealing are not applied after cold working, changes in the mechanical properties resulted from cold deformation are remained. Therefore, it is necessary to clarify the effect of prestraining on fatigue behaviour.

Austenitic stainless steel is widely used for machine components and structures, because it has a good combination of superior creep resistance and corrosion resistance, coupled with enhanced resistance to sensitization and associated intergranular cracking. In addition, it is well known that austenitic stainless steel has remarkable work hardening ability. Hence, prestrained materials would behave in different manner from unprestrained material or other materials. Therefore, it is particularly important to clarify the fatigue behaviour of prestrained austenitic stainless steels as a structural material. There have been many studies on the fatigue properties of austenitic stainless steels, but studies on the effect of prestraining on fatigue behaviour have been very limited [1-3].

In the present study, two types of fatigue tests, conventional *S-N* test and increasing stress test, have been performed under rotary bending using specimens subjected to 5 % and 15 % tensile prestrains in a type 316 austenitic stainless steel, and the effects of prestraining on fatigue behaviour were discussed.

Experimental details

Material and specimen

The material used is a 316 austenitic stainless steel of 14 mm diameter. The chemical composition (wt. %) is C: 0.04, Si: 0.23, Mn: 1.33, P: 0.03, S: 0.03, Ni: 10.0, Cr: 16.9, Mo: 2.01, Fe: bal. The material was solution-treated at 1353 K for 1 h. The mechanical properties are listed in Table 1. After solution treatment, tensile prestrains were given to the material, from which hourglass-shape fatigue specimens with a reduced section of 5 mm diameter shown in Figure 1 were machined and then mechanically polished by emery paper before experiment.

Figure 2 illustrates the stress-strain diagram of the material. Based on this diagram, two different tensile prestrains of 5 % and 15 % were selected, for which the corresponding stresses are 316 MPa and 422 MPa, respectively. Hereafter, the materials subjected to 5 % and 15 % are denoted as the 5 % prestrained specimen and the 15 % prestrained specimen, respectively, and the material not subjected to prestrain is referred to as the unprestrained specimen.

Table 1. Mechanical properties of material

0.2% proof stress $\sigma_{0.2}$ (MPa)	Tensile strength σ_B (MPa)	Breaking strength on final area σ_T (MPa)	Elongation δ (%)	Reduction of area ϕ (%)
211	560	1539	66	77

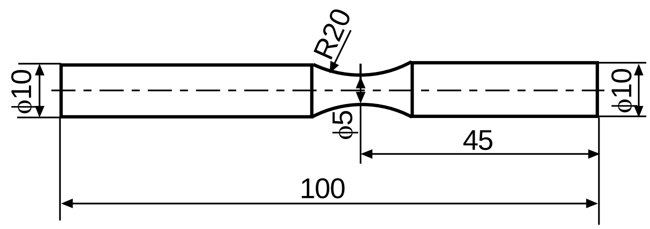

Figure 1. Configuration of fatigue specimen

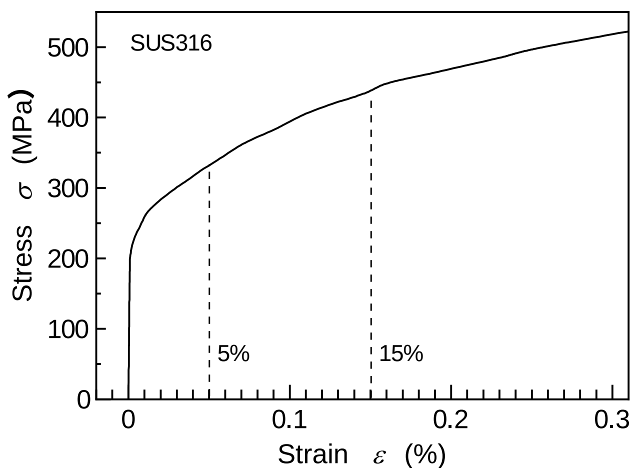

Figure 2. Stress-strain diagram

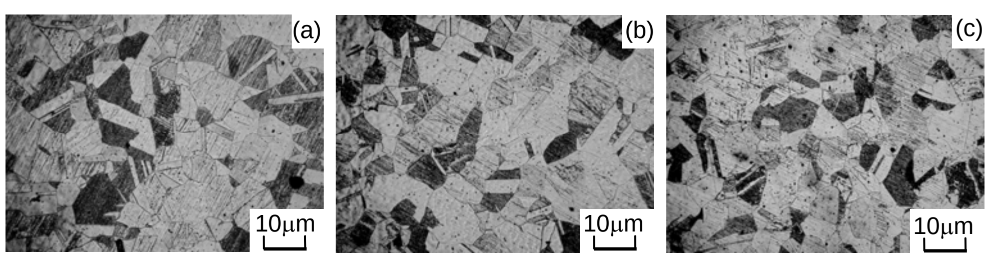

Figure 3. Microstructures: (a) unprestrained, (b) 5 % prestrained, (c) 15 % prestrained

Microstructures and hardness of prestrained specimens

The microstructures on the cross section in the unprestrained and prestrained specimens are represented in Figure 3. As can be seen in the figure, microstructure is not affected by prestraining. The average grain sizes are 69 μm, 70 μm and 70 μm for the unprestrained, 5 % prestrained and 15 % prestrained specimens, respectively. Vickers hardness was measured by micro Vickers hardness tester. It was found that hardness increased with increasing prestrain and the obtained hardness levels were *HV*137, *HV*177 and *HV*214 for the unprestrained, 5 % prestrained and 15 % prestrained specimens, respectively.

Procedures
Two types of fatigue tests, conventional *S-N* test and increasing stress test, were performed using cantilever-type rotary bending fatigue testing machine operating at a frequency of 52.5 Hz in laboratory air at ambient temperature. Crack initiation and small crack growth were monitored by replication technique. In increasing stress test, experiments were started at a stress 20 MPa below the fatigue limit, σ_w. When the specimen does not fail until 10^7 cycles, then the stress was increased by 20 MPa. This procedure was repeated until the specimen fails. After experiment, fracture surfaces were examined in detail using a scanning electron microscope (SEM).

Results and discussion

Effects of prestrain on fatigue behaviour

Fatigue strength
The *S-N* diagram is shown in Figure 4. As can be seen in the figure, fatigue strength increases with increasing prestrain. A slight increase in fatigue strength can be seen in the 5 % prestrained specimens, while a very large increase is attained in the 15 % prestrained specimens. The fatigue limits of the unprestrained, 5 % prestrained and 15 % prestrained specimens are 300 MPa, 320 MPa and 380 MPa, respectively.

Crack initiation
Figure 5 reveals typical examples of SEM micrographs of fracture surfaces near the crack initiation site. In all the specimens, it seems that the cracks were generated at the specimen surface due to cyclic slip deformation, because a stage I-like facet was seen at the crack initiation site.

Crack growth behaviour
Surface crack length, 2*c*, is represented in Figure 6(a) and (b) as a function of number of cycles, *N*, and cycle ratio, N/N_f,(N_f: fatigue life), respectively. As can be seen in Figure 6(a), the crack initiation lives for the prestrained specimens are longer than that for the unprestrained specimen. Therefore, it is concluded that the crack initiation resistance becomes higher due to prestraining. As can be seen in Figure 6(b), most of fatigue life in the prestrained specimens is occupied by small crack growth, as well as in the unprestrained specimen.

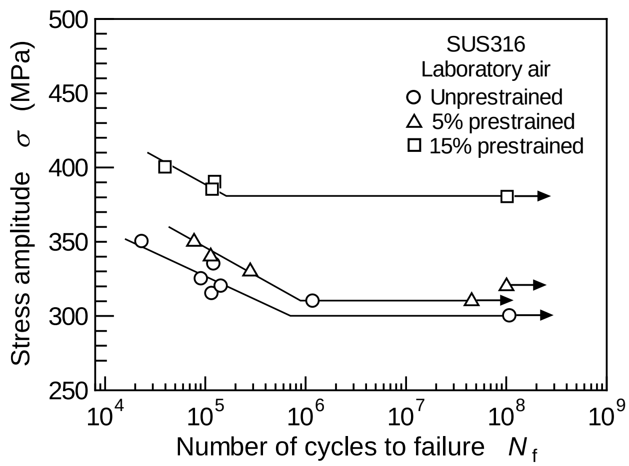

Figure 4. *S-N* diagram

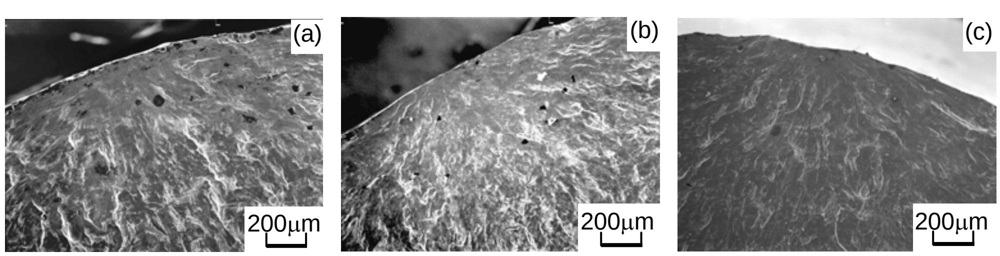

Figure 5. SEM micrographs of fracture surfaces near crack initiation site: (a) unprestrained (σ=335 MPa, N_f =1.2×10^5), (b) 5 % prestrained (σ=330 MPa, N_f =2.8×10^5), (c) 15 % prestrained (σ=400 MPa, N_f =4.0×10^4)

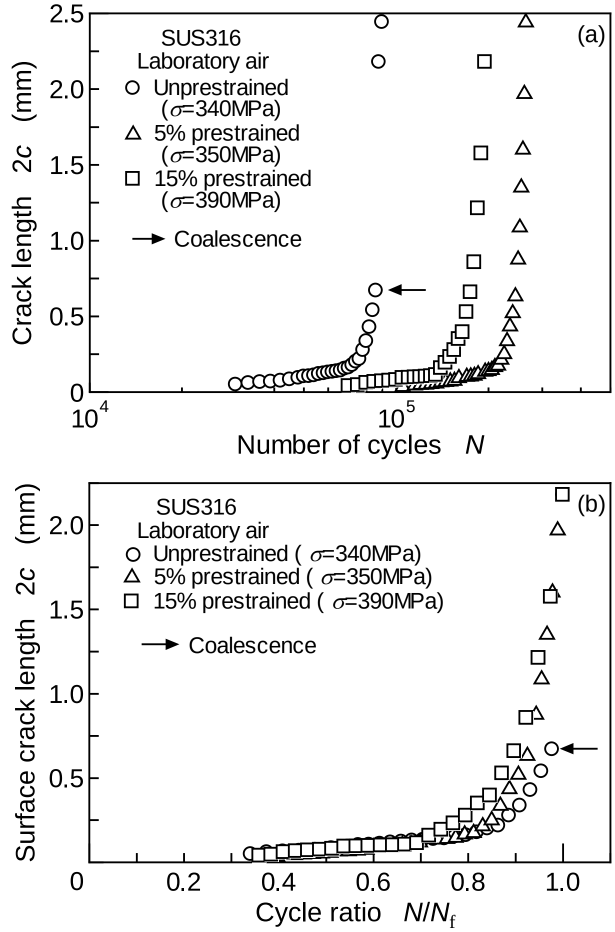

Figure 6. Surface crack length as a function of (a) number of cycles, (b) cycle ratio

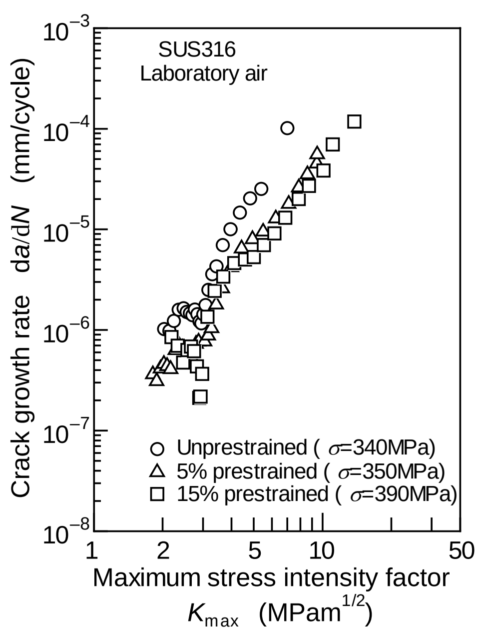

Figure 7. Relationship between crack growth rate and maximum stress intensity factor

Small crack growth

Figure 7 shows the relationship between crack growth rate, d*a*/d*N*, and maximum stress intensity factor, K_{max}. The crack growth rates of both prestrained specimens are almost the same and are lower than those of the unprestrained specimen, indicating that the crack growth resistance is enhanced by prestraining [1].

Relationship between fatigue limit and hardness

The relationship between Vickers hardness, *HV*, and fatigue limit, σ_w, is shown in Figure 8. It has been indicated that there is a correlation of σ_w=1.6*HV* for below *HV*400 in steels [4]. The fatigue limits of all the materials are slightly higher than estimated from σ_w=1.6*HV*, but it seems that the present data are roughly included within the scatter of the relationship.

Prestain dependence of coaxing effect

The results of increasing stress tests are shown in Figure 9. It has been indicated that austenitic stainless steels exhibited remarkable coaxing effect [5, 6]. As can be seen in the figure, the unprestrained specimen shows a marked increase in fatigue limit from 300 MPa to 380 MPa which corresponds to 27 % increase compared to the ordinary fatigue limit. Also in the 5 % prestrained specimen, the fatigue limit increases remarkably from 320 MPa to 400 MPa (25 % increase). On the contrary, it is worth noting that the 15 % prestrained specimen shows no increase in fatigue limit. Based on these results, it is believed that the coaxing effect becomes less remarkable with increasing prestrain.

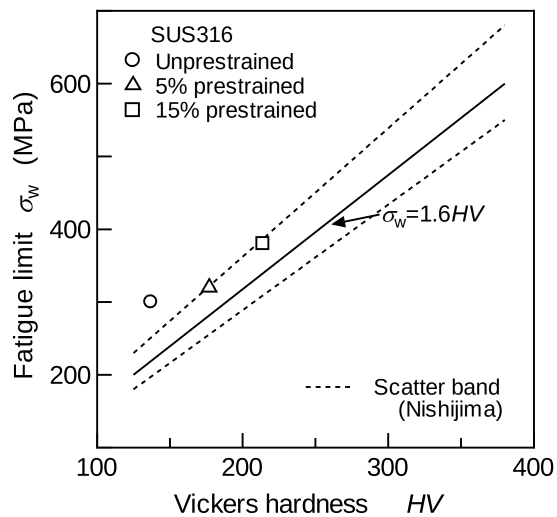

Figure 8. Relationship between Vickers hardness and fatigue limit

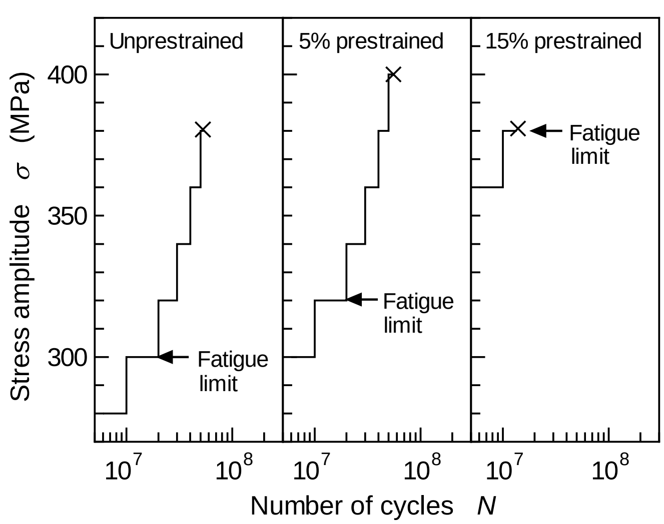

Figure 9. Increasing stress test results

After experiment, Vickers hardness of the failed specimens was measured. Consequently, a remarkable increase in hardness was observed in the unprestrained and 5 % prestrained specimens, while only a slight increase was seen in the 15 % prestrained specimen. Hardness was *HV*228 for the unprestrained specimen, *HV*282 for the 5 % prestrained specimen and *HV*237 for the 15 % prestrained specimen, resulting in 66 %, 59 % and 11 % increase, respectively, relative to the hardness before experiment. Therefore, this suggests that the coaxing effect is strongly related to the ability of work hardening during stress cycling, because the increased tendency in fatigue limit is consistent with that in hardness. In the 15 % prestrained specimen, work hardening is almost exhausted by large prestraining, thus little work hardening occurs during stress cycling, resulting in no coaxing effect.

As a final note, it has been indicated that the coaxing effect in austenitic stainless steels was attributed to the strain-induced martensitic transformation [5]. In the present study, however, it was confirmed that no martensitic transformation occurred after prestraining due to X-ray diffraction measurement.

Conclusions

(1) Fatigue strength increased with prestrain, resulting in 7 % and 27 % increase in fatigue limit for the 5 % and 15 % prestrained specimens, respectively, relative to the unprestrained specimen.
(2) Both crack initiation resistance and crack growth resistance were increased by prestraining.
(3) The coaxing effect became less remarkable with increasing prestrain. The increase in fatigue limit relative to the ordinary fatigue limit was 27 %, 25 % and 11 % for the unprestrained, 5 % and 15 % prestrained specimens, respectively.
(4) The coaxing effect was strongly related to the ability of work hardening during stress cycling.

Acknowledgements

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