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Effect of compression Residual Stress on Fatigue Properties of Stainless Cast Steel

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Abstract

In this study, in order to clarify the fatigue properties under compressive mean stresses statement and to establish the accurate evaluation method of fatigue properties of materials with compressive residual stress at surface applied by surface treatments, tension-compression fatigue tests were carried out under various kinds of compressive mean stresses by using ASTM CA6NM stainless cast steel with two kinds of modes, the load control mode and the strain control mode, respectively.

In the case of tension-compression fatigue tests under the load control mode, the higher the compressive mean stress value, the higher the fatigue limit because the setting stress level was loaded simply if the compressive mean stress value beyond the compressive yield limit.

In the case of tension-compression fatigue tests under the strain control mode, specimens yielded greatly at the first cycle of the fatigue tests, then the mean stress didn't change to the tensile side with increasing the loading cycles and continued to load at the same stress level. As the results, the fatigue life decreased remarkably and specimens fractured early in comparison with a case of fatigue tests under the load control mode because shakedown behavior was occurred.

Keywords: fatigue properties; compressive residual stress; shakedown behavior

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1. Introduction

In recent years the security issue of nuclear power generation station is becoming more and more serious, against that background hydraulic power station have been received a lot of attention due to it has no pollution to environment. As for the water turbine runner which is main facilities of the hydroelectric generator, the problem of the material damage by the deterioration is serious and it's necessary to spend a lot of expenses and time for those repairing. In addition, as the water turbine runner is often damaged from fatigue crack initiation site where originated at the region of high stress, it's important to shorten the maintenance cycles by improving resistance to fatigue of the region.

In the previous work (Arakawa et al. 2013), paid attention to the ultrasonic shot peening (USP) treatment (Ochi et al. 2001; Bagherifard et al. 2013; Bohdan et al. 2007; N.R Tao et al. 1999) which was used as a fatigue strength improvement method. It's made clear that the fatigue limit of the USP treated material is greatly improved due to compressive residual stress and hardened layer introduced at surface by USP treatment.

Generally, compressive residual stress generated by the surface treatment has a positive effect on fatigue strength of components due to reduce the mean stress (Kamaya et al. 2014) value. The fatigue limit (Fueki et al. 2015) under tension mean stresses value is evaluated by modified *Goodman's* diagram, and that of under compression mean stresses value is evaluated by *Haigh's* diagram in consideration of shakedown behaviour. In general, the higher the compressive mean stresses value, the higher the fatigue limit. According to *Haigh's* diagram, however, the increasing of fatigue limit doesn't occur, if the compressive mean stresses value beyond the compressive yield limit. However, the fatigue limit evaluation method of materials with compressive residual stress at surface introduced by surface treatments has been not yet been established. Furthermore, the most suitable compressive residual stress level which can be introduced by the surface treatments to improve the fatigue strength is also not cleared.

In this study, the objective is to clarify the fatigue properties under compressive mean stresses statement and to establish the accurate evaluation method of fatigue properties of ASTM CA6NM stainless cast steel with compressive residual stress at surface applied by surface treatment

2. Experimental procedure

The material was ASTM CA6NM stainless cast steel which have been used as turbine runner of hydroelectric power generation plant for 27 years. Chemical composition and mechanical properties of this material were given in Table 1 and Table 2, respectively.

The specimen for tension-compression fatigue tests is shown in Fig. 1. All specimens surface were polished by using emery paper (#180~#2000).

Tension-compression fatigue tests were carried out using servo-hydraulic testing machine under various kinds of compressive mean stresses with two kinds of modes, one was the load control mode and another was the strain control mode, respectively.

In this study, the run-out number was defined until $N=1\times10^7$cycles. The fatigue limit was defined as the average of the maximum stress amplitude without specimen failure at $N=1\times10^7$cycles and the minimum stress amplitude at which the specimens fail. The configuration of fatigue test machine is shown in Fig. 2.

Table 1 Chemical composition of ASTM CA6NM [mass%]

C	Si	Mn	P	S	Ni	Cr	N	Al	Ca	O
0.049	0.5	0.83	0.04	0.004	3.62	12.82	0.027	0.01	<0.0005	0.00063

Table 2 Mechanical properties of ASTM CA6NM

Hv	$\sigma_{0.2}$ [MPa]	σ_B [MPa]
280	594	829

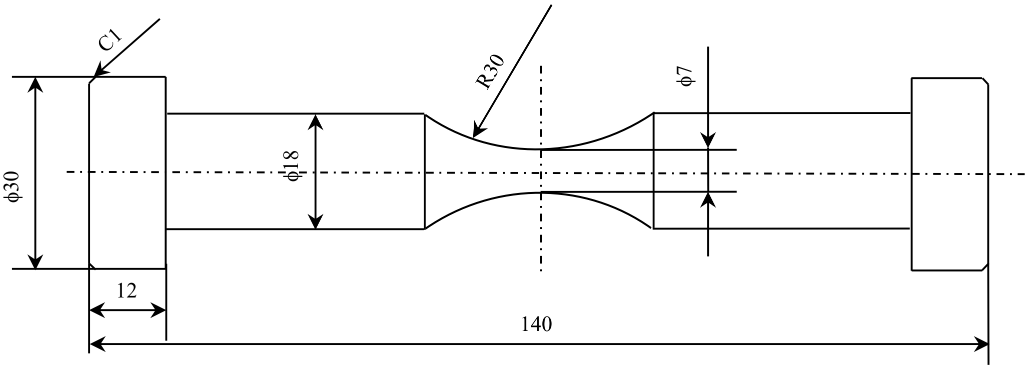

Fig. 1 Schematic illustration of specimen.

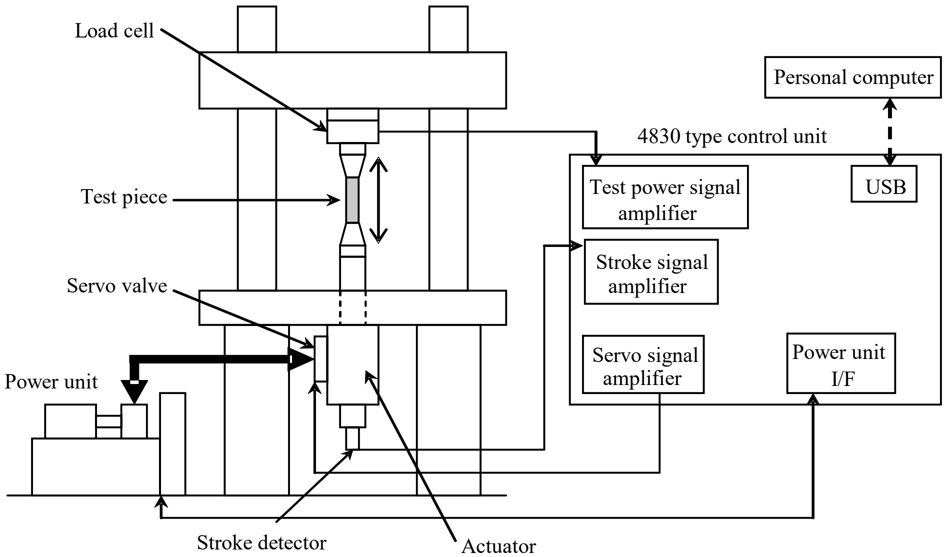

Fig. 2 Test machine configuration

3. Experimental results and discussion

3.1 Fatigue test under the load control mode

Tension-compression fatigue tests were carried out with various kinds of compression mean stress under the load control mode. The result of fatigue tests are shown in Fig. 3， which indicate the relationship between stress amplitude and number of cycles to failure. From these results, it's clear that the fatigue limit is 285, 345, 365, and 435 [MPa] when mean stress is 0, -100, -200, and -300 [MPa], respectively.

From these results under the load control mode, the fatigue limit showed increasing tendency with the increase of the compressive mean stress level.

3.2 Evaluation in fatigue limit diagram under the load control mode

The fatigue limit data were plotted in the fatigue limit diagram, which is shown in Fig. 4, also the relationship between the applied maximum/minimum stress and the number of cycles (mean stress σ_m=-300 [MPa], stress amplitude σ_a=430 [MPa]) is shown in Fig. 5. As in clear in Fig. 4, an obvious trend is observed; the higher the compressive mean stress value, the higher the fatigue limit. According to *Haigh's* diagram, the increasing of fatigue limit didn't occur, even if the compressive mean stress beyond the compressive yield limit, but the fatigue limit under mean stress of σ_m=-300 [MPa], which beyond the compressive yield limit (□) is higher than that of under mean stress of σ_m=-200 [MPa], which is near the compressive yield limit (◇). In other words, the fatigue limit obeys modified *Goodman's* diagram in the compression side too. This is because the setting stress level was loaded simply if the compressive mean stress value beyond the compressive yield limit to be clear from Fig. 5.

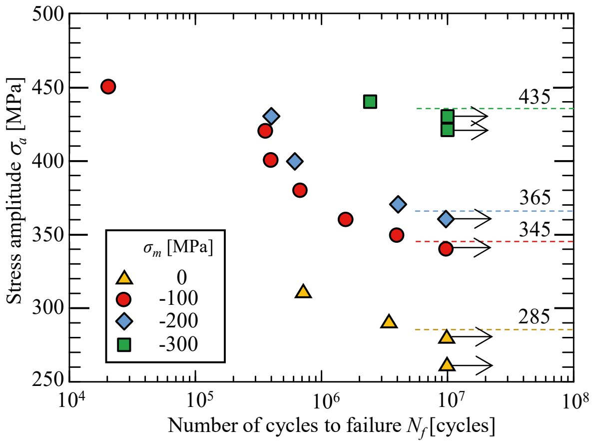

Fig. 3 *S-N* curves.

From these results, it becomes clear that the fatigue limit design using *Haigh's* diagram lead the evaluation of safety side excessively, in the case of the tension-compression fatigue tests under the load control mode which carried out in this study.

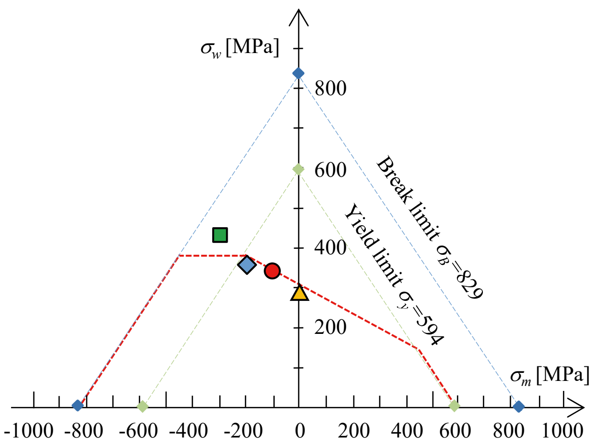

Fig. 4 Fatigue limit diagram.

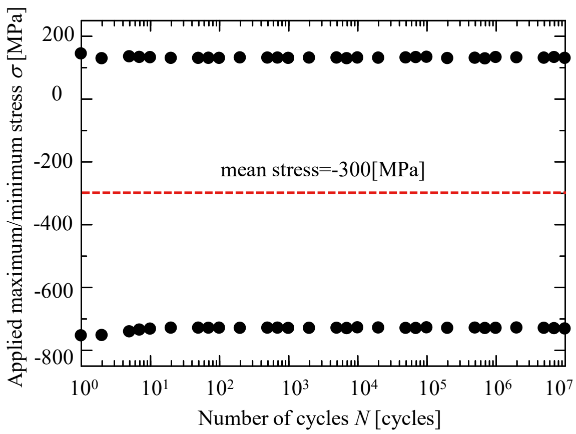

Fig. 5 The relationship between applied maximum/minimum stress and number of cycles.

In order to examine the reason for that, we focused on the relationship between the piston displacement and the applied stress during the fatigue tests under the load control mode. Fig. 6 shows the result under the condition of σ_m=-300 [MPa], σ_a=430 [MPa]. From this figure, it is cleared that maximum and minimum piston displacement changed before the setting stress level was loaded to the specimen. It's thought that the reason of the changing of the piston displacement is that the specimen is yielded to the compression side by the loaded high compressive stress.

From these result, as for the relationship between piston displacement and stress under the load control mode, the behavior that change to the compression side while repeating compression yield is confirmed.

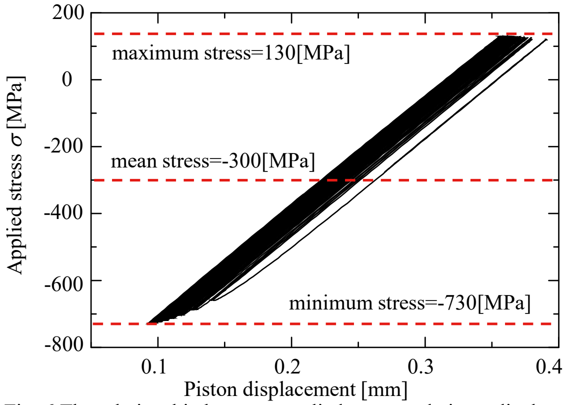

Fig. 6 The relationship between applied stress and piston displacement.

3.3 Fatigue test under the strain control mode

In this section, the piston displacement value for the fatigue tests were set by averaging the piston displacement range in Fig. 6 assuming that specimen was the perfect elastic body. By using those values, controlling the piston displacement, Tension-compression fatigue test under the strain control mode were carried out. Fig. 7 (a) shows the hysteresis loops under the conditions with the maximum piston displacement of -1.57×10^{-2} [mm] and the minimum one of -2.43×10^{-1} [mm], Fig. 7 (b) shows the hysteresis loops under the conditions with the maximum piston displacement of -1.57×10^{-2} [mm] and the minimum one of -2.59×10^{-1} [mm], Fig. 7 (c) shows the hysteresis loops under the conditions with the maximum piston displacement of -3.14×10^{-2} [mm] and the minimum one of -2.75×10^{-1} [mm], Fig. 7 (d) shows the hysteresis loops under the conditions with the maximum piston displacement of 0 [mm] and the minimum one of -2.43×10^{-1} [mm], respectively. All these tests were carried out under load speed of 6.0×10^{-2} [mm/sec] and repetition number of 30 [cycles]. From the results of Fig. 7 (a), Fig. 7 (b) and Fig. 7 (c), specimens yielded greatly at the first cycle of the fatigue tests, then the mean stress didn't change to the tensile side with increasing of the loading cycles and continued to load at the same stress level. Each of these results was affected by the shakedown behavior until the minimum stress became about 750 [MPa]. Though it didn't arrive at the compression yield stress (-594 [MPa]), as for the reason why stopped changing to the tensile side of the mean stress, it's thought that the strength of the materials is improved by work hardening. Also, mean stress changed in the tensile side, from -350 [MPa] (at the first cycle) to -295 [MPa] shows in Fig. 7 (a), from -425 [MPa] (at the first cycle) to -340 [MPa] shows in Fig. 7 (b), from -475 [MPa] (at the first cycle) to -350 [MPa] shows in Fig. 7 (c), by shakedown behavior. In addition, in the case of the strain control mode, number of cycles to failure was 7.2×10^{5} [cycles] whereas the load control mode was non-failured (=fatigue limit) with the same loading condition. As this factor, it's thought that it became the severe stress condition in comparison with the load control mode, by affected by shakedown behavior and mean stress changed in the tensile side. As the results, the fatigue life decreased remarkably, and specimens fractured early.

From these results, considering the experimental results of tension-compression fatigue tests under the strain control mode, it is possible to evaluate the fatigue limit of materials with compressive residual stress at surface applied by surface treatments.

4. Conclusion

Fatigue tests were carried out under the load control mode and the strain control mode with different mean stress values, and the conclusion are as follows.

1. According to Haigh's diagram, the increasing of the fatigue limit didn't occur, if the compressive mean stress beyond the compressive yield limit, but in the case of tension-compression fatigue test under the load control

mode, it’s clear that the fatigue limit showed increasing tendency with the increase of the compressive mean stress level.

2. From the results of hysteresis loops obtained by tension-compression fatigue test under the load control mode, it’s clear that shakedown behavior paid attention in this study didn’t occur and the setting stress level was loaded simply. Therefore the higher the mean stresses value is, the higher the fatigue limit in compression side becomes.
3. According to the hysteresis loops obtained by tension-compression fatigue tests under the strain control mode by controlling the piston displacement, the specimens are affected greatly by shakedown behavior at the first cycle of the fatigue tests and after that it continued to load at the same stress level. As a results, the fatigue life decreased remarkably, specimens fractured early in comparison with a case of fatigue tests under the load control mode. Also, it’s thought that stress which beyond compression yield stress was loaded in the case of strain control mode by the strength of materials improved by work hardening.

From these results, considering the experimental results of tension-compression fatigue tests under the strain control mode, it is possible to evaluate the fatigue limit of materials with compressive residual stress at surface introduced by surface treatment.

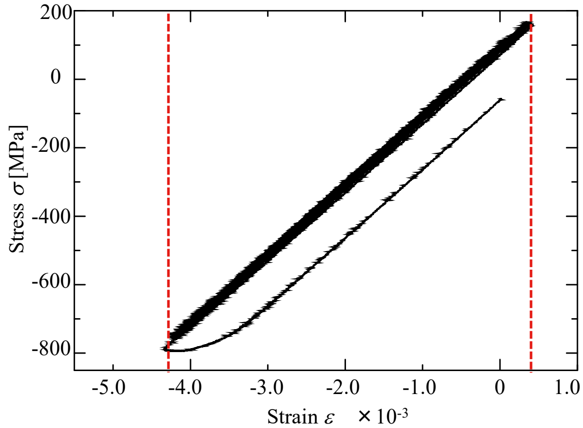

Fig. 7 (a) Hysteresis loops.

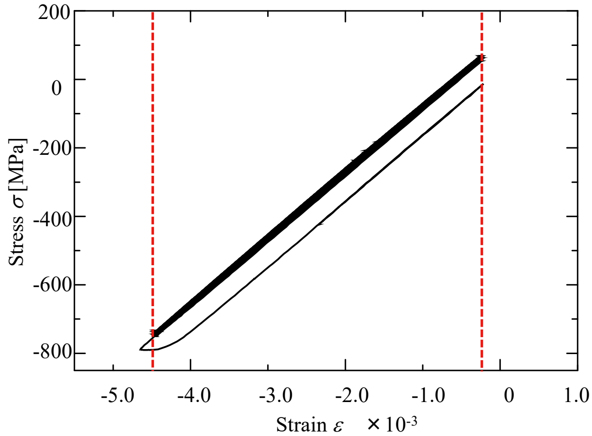

Fig. 7 (b) Hysteresis loops.

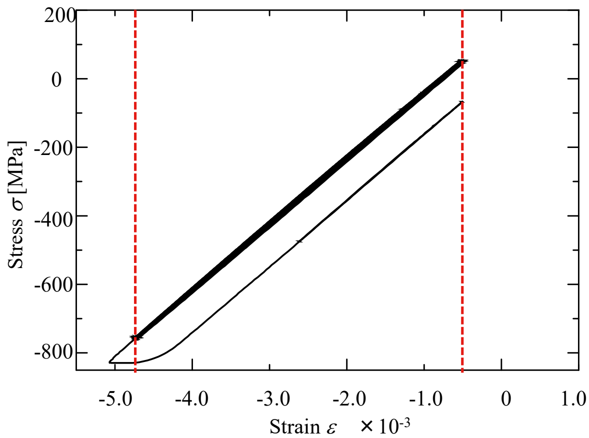

Fig. 7 (c) Hysteresis loops.

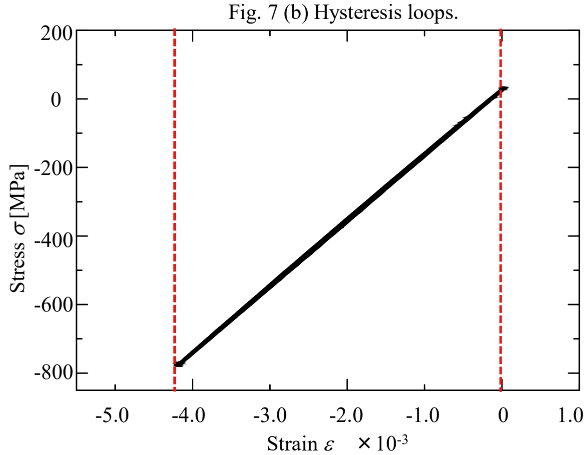

Fig. 7 (d) Hysteresis loops.

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