

Effect of surface compressive residual stress introduced by surface treatment on fatigue properties of metallic material

Jinta Arakawa¹, Tatsuya Hanaki¹, Yoshiichirou Hayashi², Hiroyuki Akebono^{1*}, and Atsushi Sugeta¹

¹Hiroshima University, Department of Mechanical Science and Engineering, 1-4-1 Kagamiyama Higashi-hiroshima Hiroshima, Japan

² Electric Power Development Co.,Ltd, Chigasaki Kanagawa, Japan

Abstract. This study considers shakedown in evaluating the fatigue limit of metals with compressive residual stress at the surface. We begin by applying tension-compression fatigue tests to ASTM CA6NM under conditions of controlled load and displacement to obtain fatigue limit diagram in compressive mean stress. The results imply that shakedown occurs under the condition of controlled displacement, therefore, shakedown should be considered when evaluating the fatigue limit of metals with compressive residual stress at the surface.

1 Introduction

To date, there have been many attempts to improve the fatigue properties of the materials used to construct industrial equipment, since these materials are subjected to compression and tension, bending, twisting and other forms of stress and strain. Quenching and heat treatment have been found to effectively improve the resistance of metals to compression and tension because the treatment is applied to the entire body of the metal [1-3]. In addition, carburizing, nitriding and shot peening are applied when bending and twisting are anticipated, because these processes increase surface fatigue resistance [4-10]. It is well known that shot peening leads to an elevated surface hardness in conjunction with a high degree of compressive residual stress on the surface of the material, both of which improve fatigue strength [11-14]. There are many different peening techniques, including shot, micro shot, ultrasonic peening, laser, water jet, oil jet and hammer peening. In addition, there have been many reports regarding the fatigue strength of metals subjected to peening, which have demonstrated that peening improves fatigue strength. As noted, peening imparts compressive residual stress to the material surface layer and hence improves fatigue strength. The present work examined the effectiveness of ultrasonic shot peening (USP) at improving the fatigue strength of ASTM CA6NM intended for use in hydraulic turbine runners [20]. According to this work, it is revealed that the shot peened material exhibits greater fatigue strength compared to the untreated metal, with a 60% increase in the fatigue limit. Furthermore, the reason of improved fatigue limit was studied by using modified Goodman line considering shakedown and taking into account for elevated hardness and compressive residual stress. As a result, the equivalent fatigue limit for the USP specimen was calculated to be

508 MPa, which is in good agreement with the experimental result of 540 MPa. Therefore, it is clear that the main factors responsible for improving the fatigue limit were the high hardness and elevated compressive residual stress for the peened metal. According to previous study, the fatigue limit of USP specimen was evaluated by using modified Goodman diagram considering shakedown in the compressive mean stress regime. However, to date, there are a lot of reports of experimental data which is relationship between the fatigue limit and the tensile mean stress, but, in contrast of its case, there have been a very few of reports of experimental data giving the relationship between the fatigue limit and the compressive mean stress. Thus, in order to precisely determine the fatigue strengths of metals based on their compressive residual stress, it is essential to obtain these data, and one goal of the work reported herein was to obtain these values for ASTM CA6NM. In the present study, a tension-compression cyclic test was carried out by using ASTM CA6NM for base material of hydraulic turbine runner to investigate the shakedown behavior.

2 Specimen and experimental procedure

The material employed during this work was cast stainless steel, ASTM CA6NM, and the mechanical properties and chemical composition of this metal are provided in Tables 1 and 2, respectively. Figure 1 presents the shape of the test specimens, which were made by mechanical machining. During the experimental trials, tension-compression fatigue tests were carried out for a mean stress value, σ_m , of -300, -200, -100 or 0 MPa using a hydraulic servo pulsar. The frequency, f , ranged from 10 to 15 Hz and the interrupted number of cycles, N_f , was 10^7 .

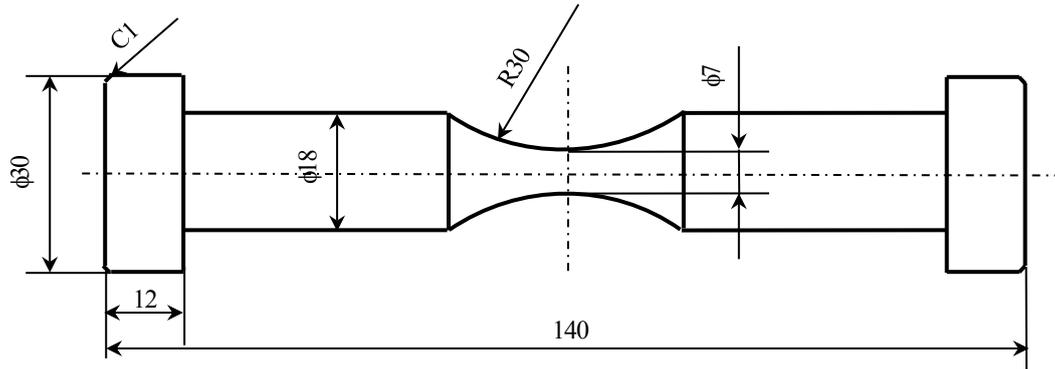


Fig. 1 Schematic diagram showing dimensions of test specimen used for fatigue tests.

Table 1. Mechanical properties of ASTM CA6NM.

HV	Yeild stress	Tensile strength
280	594 MPa	829 MPa

Table 2. 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

3 Experimental results

3.1. Cyclic hardening behaviour of ASTM CA6NM

In our study, in order to know the elastic-plasticity properties subjected to experimental cyclic, the multistage amplitude method was applied to ASTM CA6NM. The multistage amplitude method is that strain amplitudes are changed at the appropriate intervals.

Figure 2 shows the schematic illustration of the multistage amplitude method. Furthermore, Fig. 3 indicates the results obtained by that method, and Fig. 3 collects the loop tips of hysteresis loops. According to Fig. 3, 0.2 % proof stress was 810 MPa, when the applied stress values of loop tips was saturated. The 0.2 % proof stress of 810 MPa is higher than the value of 594 MPa indicated in Table 1. Therefore, it was revealed that ASTM CA6NM exhibited cyclic hardening behaviour, by applying multistage amplitude method.

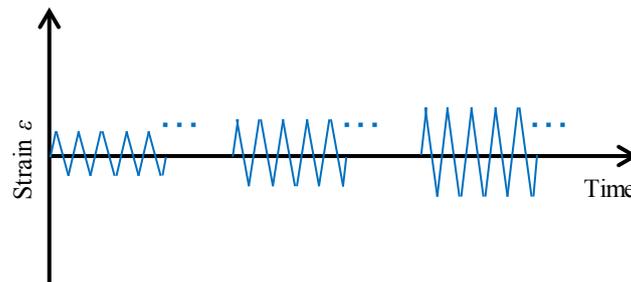


Fig. 2 Schematic illustration of multistage amplitude method.

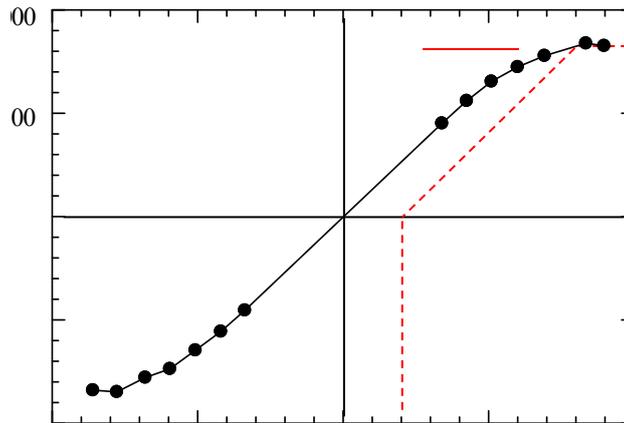


Fig. 3 Loop chips of the last cycle of each strain stage.

3.2. Fatigue limit diagram for ASTM CA6NM under controlled load condition

Stress amplitude versus number of cycle (*S-N*) curves (Fig. 4) were generated by applying a controlled load and σ_m values of -300, -200, -100 and 0 MPa. It is evident from these data that the fatigue limit increased as the mean stress decreased. And also, the fatigue limit was defined the value between a minimum stress amplitude in finite life regime and a maximum fatigue limit in experimental data, based on JSMS standard* “Standard Evaluation Method of Fatigue Reliability for Metallic Materials: Standard Regression Method of *S-N*

Curves”. The associated fatigue limit diagram is shown in Fig. 5, which demonstrates that fatigue limits in the negative mean stress values agree more with a modified Goodman line un-considering shakedown than with that line considering it. Figure 6 plots the relationship between piston displacement and applied stress up to 30 cycles at a σ_m value of -300 MPa and a σ_a value of 430 MPa. These data demonstrate that shakedown did not occur and that the sample was subjected to a fixed stress. Therefore, under conditions involving a controlled load, shakedown does not take place, and the fatigue limit diagram agrees with a modified Goodman line un-considering shakedown.

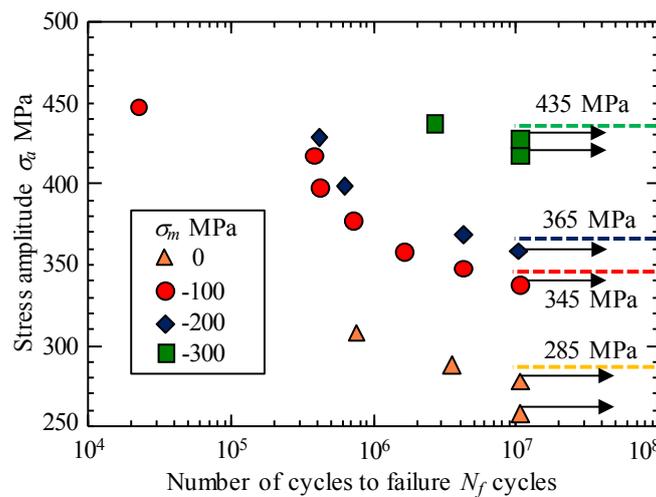


Fig. 4 *S-N* curves for ASTM CA6NM specimen.

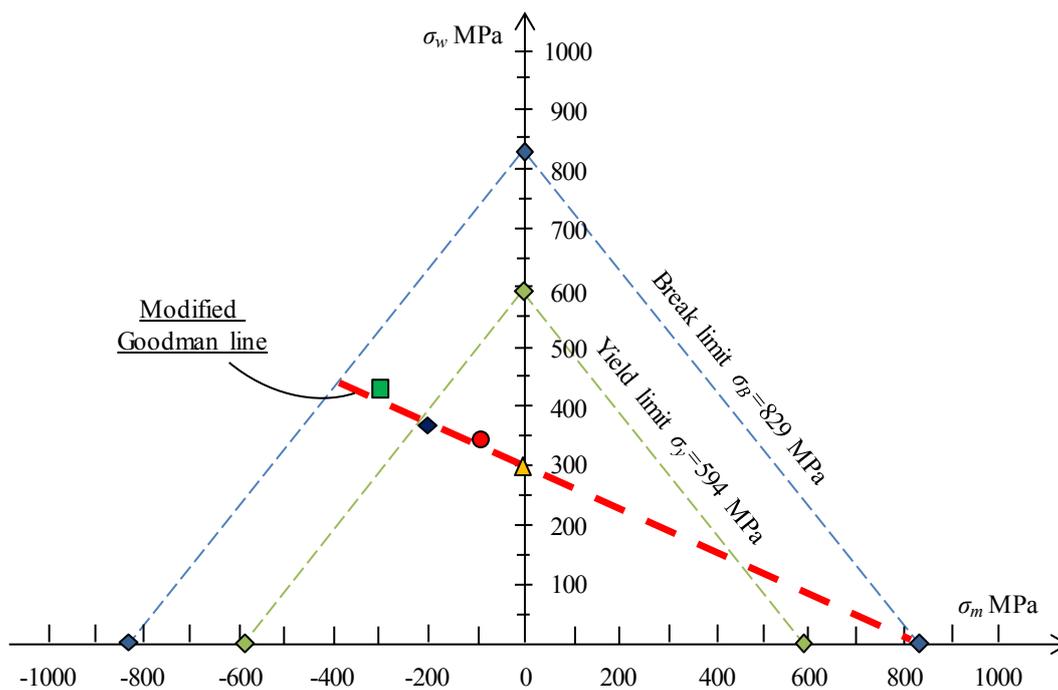


Fig. 5 Fatigue limit diagram for ASTM CA6NM specimen.

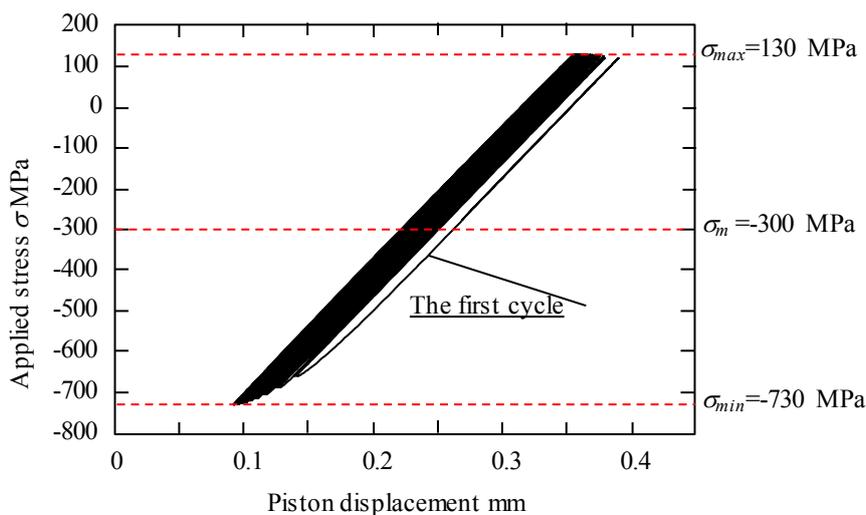


Fig. 6 The relationship between applied stress and piston displacement for ASTM CA6NM specimen.

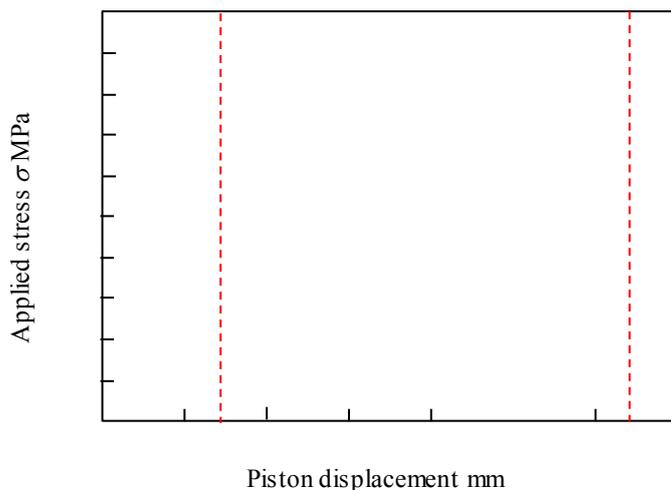
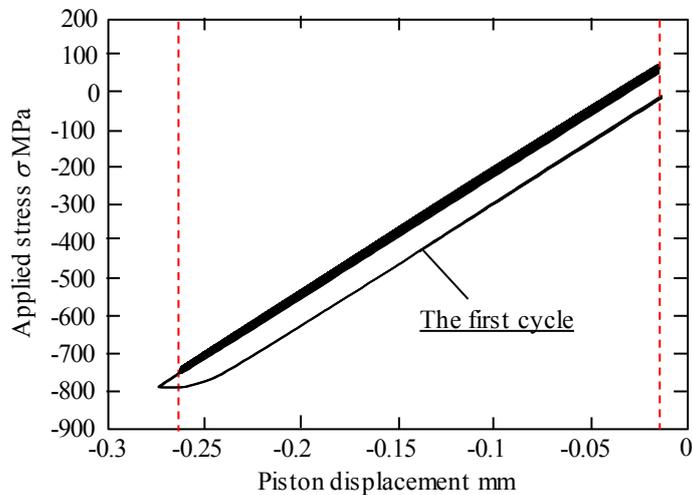
3.2. Hysteresis loop for ASTM CA6NM under controlled displacement condition

In Section 3.1, the fatigue limit was estimated by tension-compression fatigue tests under controlled load conditions. In the trials reported in this section, hysteresis loops were obtained while applying a controlled displacement, in order to investigate the effect of shakedown. The displacement values were determined based on Fig. 6 by assuming complete elasticity. Figures 7(a), 7(b) show the relationships between applied stress and displacement for maximum piston displacements of -1.57×10^{-2} and -3.14×10^{-2} mm, minimum piston

displacements of -2.59×10^{-1} , -2.75×10^{-1} mm and initial mean stress values of -425 and -475 MPa, respectively. Each experiment consisted of 30 cycles. It is evident from these data that the initial loop moved upward during subsequent cycles in whole loop. Therefore, it appears that shakedown occurred under these test conditions (that is, with controlled displacement). The mean stress values in Figs. 7(a) and 7(b) moved from -425 to -340 MPa, and from -475 to -350 MPa, respectively. Additional fatigue tests were conducted applying a σ_m value of -300 MPa and a σ_a value of 400 MPa in conjunction with controlled displacement. These trials resulted in an N_f of 7.2×10^5 cycles. These experimental conditions were equivalent to the fatigue

limit under controlled load conditions. However, the material broke at 7.2×10^5 cycles under controlled displacement conditions. This early breakage is attributed to shakedown, meaning that the mean stress was transitioned to upper. Based on these data, it is

apparent that estimations of the fatigue limit of a metal having a compressive residual stress at its surface layer, for the purposes of evaluating safety, should be conducted based on the associated modified Goodman line considering shakedown due to the appearance of it.



(b) Maximum: -3.14×10^{-2} mm, Minimum: -2.75×10^{-1} mm

4 Conclusions

This study examined the effects of compressive residual stress on metals by conducting tension-compression fatigue tests by using ASTM CA6NM material under either controlled load or controlled displacement scenarios. The conclusions of this work are as below.

1. It is clear that the relationship between the fatigue limit and the mean stress agrees with modified Goodman line un-considering shakedown, when

applied stress condition is controlled load. Therefore, in this condition, it is found that the sample is subjected to fixed applied stress and shakedown doesn't occur.

2. It is revealed that the shakedown occurs in the controlled displacement condition. Therefore, estimation of the fatigue limit of the material with compressive residual stress should be conducted by using modified Goodman line considering shakedown, in order to evaluate the fatigue limit safety.

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