considered a reliable one, as the shearing stresses τ_s and τ_y are obtained respectively from the experiments of the same type. And also Nakanishi's theory is considered to be correct, because the stress relation by this theory agrees well with the experimental results as shown in Fig. 8.

Another interesting problem can be observed in the pressure-strain relation of the elastic state; the pressure-strain relations are not elastic up to the yield point but deviate a little from the elastic line at the early stage as shown in Fig. 2. Fig. 9 shows a typical example. Two sheets of wire gauges were pasted respectively on the opposite sides of the outer diameter of the cylinder, and the strains were measured simultaneously. In this figure, both the pressure-strain relations shift slightly from the elastic line at point A, and then again from line AB at B, and the pressure p_A at A is just a half of p_B at B. The discontinuity at B is already known as the effect of the surface layer⁽⁴⁾, but the discontinuity appearing at A has

not been explained yet. The stress at the yield point must be influenced more or less by this effect, but the influence was not ascertained in the author's experiments. It is probably due to the fact that the thickness of the surface layer was so thin compared with that of the cylinder wall that the influence could hardly be observed.

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References

- (1) F. Nakanishi: *Jour. Japan Soc. Mech. Engrs.*, Vol. 53, No. 374(1950), p. 62.
- (2) M. C. Steele and L. C. Eichberger: *Trans. ASME*, Vol. 79, No. 7(1957), p. 1608.
- (3) F. Nakanishi: *Trans. Japan Soc. Mech. Engrs.*, Vol. 18, No. 65(1952), p. 67.
- (4) F. Nakanishi and Y. Sato: *Proc. 5th. Japan Nat. Congr. Appl. Mech.* 1955, (1956), p. 169.

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Fatigue and Dynamic Creep Properties of 13 Cr Steel at Elevated Temperature under Combined Stresses of Static Tension and Alternating Bending*

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The fatigue and dynamic creep tests were made under the simulated service condition of turbine blades, i.e. combined stresses of static tension and alternating bending at an elevated temperature of 450°C. The frequency of alternating bending stress was 780 c.p.m. and the test period was 0.2 to 200 hours.

The results are summarized as follows:

1. Alternating bending stress superimposed on static tensile stress reduces the fatigue life.
2. Alternating bending stress which is combined with static tensile stress does not always increase creep strain. In the range of small stress ratio (alternating bending stress divided by static stress) alternating bending stress blocks the increase in creep strain.
3. The hindrance of increase in creep strain by alternating bending stress is explained by the hardening effect of materials by stress alternation.

1. Introduction

Turbine blades are subjected to combined

stresses of static tension due to centrifugal force and alternating bending due to vibration. Although comparatively many investigations have been carried out for the dynamic creep and rupture of materials under axial pulsating or alternating stresses^{(1)~(6)}, the study of creep and rupture under combined stresses of static tension and alternating

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bending is rare. In order to carry out the fatigue test under such stress condition, one of the authors and his co-workers have developed a new fatigue testing machine for combined static tension and alternating bending⁽⁷⁾, and reported the results of fatigue tests with 13 chromium steel at an elevated temperature⁽⁸⁾. However, dynamic creep properties are also one of the most significant problems as well as fatigue, but the study of this problem has not been made yet. This report deals with this problem. The dynamic creep properties of 13 Cr steel were studied and the results are discussed together with the results of a fatigue test.

2. Testing apparatuses

(a) Testing machine

Details of the testing machine used is as reported previously⁽⁷⁾. Fig. 1 shows its schematic diagram. Although this is the side view of the machine, the parts near the specimen 6 (i.e. 5, 9, and 10) are shown in a horizontal view to demonstrate the construction. A static tensile load is applied to the specimen 6 by the dead weight 8 through the lever 7, and an alternating bending of constant amplitude is applied by use of the forced vibration induced by the rotating eccentric mass 2. The frequency of alternating bending is 780 c.p.m.

(b) Furnace, apparatus for measurement and control of temperature

The specimen was heated by an electric furnace, with the temperature being controlled within $\pm 2^\circ\text{C}$ at 450°C automatically by a temperature regulator of the thyatron type⁽⁹⁾. The measurement of temperature was made by an alumel-chromel thermocouple and a potentiometer.

Fig. 1 Schematic representation of testing machine

(c) Measurement of Creep Strain

The creep strain was measured by means of the microscope. As shown in Fig. 2, two rods were fixed to both ends of gauge length of specimen and the relative movements of the thin plates with a sharp edge attached to both ends of these rods were measured by the microscope. The satisfactory sensitivity (2/100 mm) was obtained by this method even under the vibration of the edges due to alternating bending.

3. Tests and results

(a) Test material

Test material was a 13 Cr steel commonly used for blades of steam turbine manufactured by the Steel Works of Sumitomo Metal Industries. Its chemical composition and mechanical properties at room temperature are summarized in Tables 1 and 2.

(b) Test specimen

The shape of the specimen is illustrated in Fig. 3. The specimen (a) is for a fatigue test and (b) is for a dynamic creep test. The effective gauge length of specimen (b) is 12.6 to 13.8 mm as shown in Appendix.

(c) Test results

Test conditions are summarized in Table 3.

Fig. 2 Apparatus for measurement of elongation

Table 1 Chemical composition

C	Si	Mn	P	S	Ni	Cr	Fe
0.15	0.46	0.36	0.027	0.012	0.36	11.97	bal.

Table 2 Condition of heat treatment and mechanical properties at room temperature

Yield point	63.3 kg/mm ²
Tensile strength	74.6 kg/mm ²
Elongation	29.4 %
Reduction of area	66.9 %
Condition of heat treatment	950°C 30 min. oil quench 750°C 60 min. temper

In this Table, the stress ratio A_b is the ratio of alternating bending stress σ_{ba} at the surface of specimen to static tensile stress σ_t . In the specimens (a), those of 4 mm in thickness were used for the test of $A_b=0, 0.24, 0.60$ and those of 6 mm in thickness were used for $A_b=8.0$. The test results are shown in Figs. 4 to 8. Figs. 4 and 5 are the fatigue test results, where the former illustrates the relation between number of cycles to fracture

Fig. 3 Test specimens

Table 3 Test conditions

Test temperature	450°C
Frequency of alternating stress	780 c.p.m.
Stress ratio A_b	0, 0.24(0.25), 0.60, 8.0
Duration of tests	up to 200 hours

Fig. 4 Relation between static tensile stress and number of cycles to fracture with the stress ratio as parameter

Fig. 5 Relation between maximum stress and number of cycles to fracture with the stress ratio as parameter

Fig. 6 Creep curves for static creep tests

Fig. 7 Creep curves for dynamic creep tests under combined static tensile and alternating bending stresses (Stress ratio $A_b=0.25$)

N and static tensile stress σ_t , and the latter the relation between N and maximum stress $\sigma_t + \sigma_{ba}$. Figs. 6, 7, and 8 show the creep curves in dynamic creep tests. The curve for $A_b = 0$ in Fig. 4 is the results of static creep rupture tests. In the Figure the number of cycles to fracture N are calculated from the time to rupture by taking into account the fact that the frequency of cycles is 780 c.p.m.

4. Discussion

(a) Results of fatigue test

The following tendency is noted concerning the fatigue strength in Fig. 4. As the amplitude of alternating bending stress superposed on a definite static stress increases, the fatigue life decreases appreciably, provided the magnitude of static stress is kept constant. In other words, when the life is prescribed, the allowable value of static tensile stress decreases for the larger amplitude of bending stress. It is interesting to note that the peak of the combined stress affects the fatigue life. It is evident in Fig. 5. The maximum life was obtained under the stress ratio of $A_b = 0.6$. These are the same trends as in the results Lazan et al obtained with an Al alloy 24S-T4.

(b) Results of dynamic creep test

Fig. 6 shows the creep curves under stress ratio of $A_b = 0$, that is, for static tensile stress, and Figs. 7 and 8 show those of dynamic creep under the stress ratios of $A_b = 0.25$ and 0.60 , respectively. As is seen in these Figures, the dynamic creep curves under combined stresses of static tension and alternating bending are similar in their shape to those under static tensile stress. Fig. 9 is derived by using Figs. 6, 7, and 8. This Figure is convenient for comparing the magnitude of a static component of stress in the dynamic creep test with the static stress in the ordinary creep test to introduce the same amount of strain in a definite time.

Fig. 8 Creep curves for dynamic creep tests under combined static tensile and alternating bending stress (Stress ratio $A_b = 0.6$)

The above statement is self-consistent in the Figure. The open and the solid circles refer to the time of 50 and 10 hours, respectively. This Figure can be looked at from a different standpoint. Let us compare the case of $A_b = 0.25$ with that of $A_b = 0$. Take a definite value of σ_t on the abscissa and compare the values of strain given by both series of lines of different A_b , then it is found that the lines belonging to $A_b = 0.25$ gives a higher strain than the lines for $A_b = 0$ for respective time in the range of large stress, but the inverse trend appears in the range of small stress. In other words, the alternating bending stress superimposed on static tensile stress accelerates the creep in the range of large stress and decelerates in the range of small stress. The stress at the transition of 50 hours is same as that at 10 hours, being 43 kg/mm². Under the stress ratio $A_b = 0.60$, the accelerating effect of alternating stress appears over the whole stress range tested, but the trend of acceleration diminishes with the decrease in static stress.

Fig. 10 is a diagram to illustrate these effects quantitatively; ψ_b on the ordinate is a ratio of the static tensile stress σ_t in the dynamic creep test to the statically applied tensile stress $(\sigma_t)_0$ in the ordinary creep test which induces the same strain.

Fig. 9 Strain versus static tensile stress diagram

Fig. 10 Value of ψ_b obtained by experiments.

as that of dynamic test of σ_t combined with σ_{ba} in a definite time, namely,

$$\psi_b = \sigma_t / (\sigma_t)_0$$

According as ψ_b is less or more than unity, the alternating bending stress accelerates or decelerates the creep, respectively. In both cases of $A_b = 0.25$ and 0.60 , the smaller strain gives a larger value of ψ_b . The larger value of ψ_b means the smaller creep-accelerating effect of alternating stress.

(c) Stress range diagram

The results described above were shown again in Figs. 11 and 12 as the stress range diagrams, which are often used as the basis of design under dynamical stress conditions. Fig. 11 is the diagram for 50 hour life and Fig. 12 for 10 hour life. The solid circles are for fracture and open circles are for 2 percent and 1 percent allowable strain. From these diagrams we can know the allowable stress ranges for fracture or for 1 percent or 2 percent allowable strain in 10 hours or 50 hours. In the actual case, the life of structure member is prescribed in terms of fracture or strain from design basis. The common area in the Figure enclosed by the fracture curve and the limiting strain curve gives the safe range of combined stress. The bulge of the limit strain curve to the right of the diagram shows the decreasing effect of alternating bending

Fig. 11 Stress range diagram for 50 hr life

Fig. 12 Stress range diagram for 10 hr life

stress on the creep in the range of small stress.

(d) Strengthening due to alternation of bending stress component

In the preceding discussion, the creep decelerating effect of alternating bending stress is recognized in the small stress range. In other words the material was strengthened by alternation of bending stress component, which was superposed on static tensile stress. This was examined to some extent in the following.

As the reason of this fact, the hardening of material by the alternation of stress may be supposed. When an alternating bending stress is applied to a specimen, the alternating stress in the cross section is zero at the center and has a maximum value at the surface. So, if hardening had occurred by alternating stress, the hardness at the surface must be higher than at the center of the specimen. Fig. 13 is an example of the distribution of Vickers hardness of specimen tested. The upper and lower Figures are those of the specimen tested under static tensile stress alone and under combined static tension and alternating bending, respectively. As is known from the Figures, the hardness at the surface is somewhat larger than at the center in the case with alternating bending stress, whereas somewhat less in the case without alternating bending stress. These results substantiate the hardening effect of alternating stress.

The increase in dynamic creep strength by alternating stress such as found in the present study has been reported in the dynamic creep test under axial pulsating stress with some heat resistant alloys⁽⁴⁾⁽⁵⁾. As the reason of this phenomenon, the acceleration of precipitation hardening or other metallurgical change was cited. To study

Fig. 13 Distribution of hardness in the cross section of specimen tested

the structural change in this series of tests, the microstructure is examined with specimens tested, but any notable change could not be found. However, precipitation hardening may occur in the stage of submicroscopic change as is the case of duralmin. There would be no doubt, in the present series of tests also, that the strengthening and hardening by alternating stress may be supposed to arise from structure changes which can not be detected by the microscope.

5. Conclusion

Fatigue and dynamic creep tests were carried out under the simulated service condition of turbine blades, that is, under combined stresses of static tension and alternating bending at an elevated temperature of 450°C. The following results were obtained.

1. Alternating bending stress superimposed on static tensile stress reduces the fatigue life.
2. Alternating bending stress which is combined with static tensile stress does not always increase creep strain. In the range of small stress ratio (alternating bending stress divided by static stress) alternating bending stress blocks the increase in creep strain.
3. The hindrance of increase in creep strain by the alternating bending stress is explained by the hardening effect of materials by stress alternation.

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Appendix

As the test pieces used in this test had a fillet on both ends of parallel part, the effective gauge length had to be calculated. To carry out this calculation the following assumptions were postulated.

1. The stress in the cross section of specimen is uniformly distributed and is equal to the load divided by the area of cross section.
2. The strain at any cross section depends only on the stress in that cross section and is not influenced by the adjacent part.

Denote the stress, strain and area of any cross section in the fillet part as σ , ϵ and S , respectively, and those in the parallel part as σ_0 , ϵ_0 and S_0 .

Table 4 Effective gauge length

Stress ratio	Static tensile stress kg/mm ²	Effective gauge length mm
0	40.1	13.8
0	42.0	13.8
0	44.1	13.8
0	46.0	13.8
0	48.0	13.0
0.25	40.0	13.8
0.25	42.5	13.8
0.25	45.0	13.0
0.25	46.0	12.6
0.25	47.0	12.6
0.60	34.7	13.8
0.60	38.1	13.8
0.60	40.0	13.8
0.60	41.8	13.0

Then, as the load P is equal throughout the whole cross section,

$$P = \sigma S = \sigma_0 S_0 \quad \therefore \sigma / \sigma_0 = S_0 / S$$

From the results shown in Fig. 6,

$$\epsilon = \sigma^\alpha$$

$$\text{So,} \quad \epsilon / \epsilon_0 = \sigma^\alpha / \sigma_0^\alpha = S_0^\alpha / S^\alpha$$

Denoting the length and elongation of fillet part as l and Δl ,

$$\Delta l = \int_0^l \epsilon dl = \int_0^l (S_0 / S)^\alpha dl = \epsilon_0 l_e$$

$$\therefore l_e = \int_0^l \frac{dl}{(S / S_0)^\alpha}$$

where l_e is the length of parallel part which has the same elongation as the fillet part. Thus, denoting the length of parallel part L_0 , the effective gauge length L_e becomes

$$L_e = L_0 + 2l_e$$

The dependence of effective gauge length on α has to be noted. As the value of α differs according as the range of stress in the test as shown in Fig. 6, the integration must be done separately for both stress ranges. The calculated results are shown in Table 4.

References

- (1) Hempel u. Tillmanns: *Mitt. K.W.I. Eisenforschung*, Bd. 18(1936), S. 163.
- (2) Bernhardt u. Hanemann: *Z. für Metalkunde*, Bd. 30 (1938), S. 401.
- (3) Hempel u. Krug: *Mitt. K.W.I. Eisenforschung*, Bd. 24(1942), S. 71.
- (4) B.J. Lazan: *Proc. ASTM*, Vol. 49(1949), p. 757.
- (5) B.J. Lazan and E. Westberg: *Proc. ASTM*, Vol. 52 (1952), p. 837.
- (6) F.W. DeMoney and B.J. Lazan: *Proc. ASTM*, Vol. 54(1954), p. 769.
- (7) T. Nishihara, S. Taira, K. Tanaka, and Y. Murata: *Jour. Japan Soc. Test. Mater.*, Vol. 5, No. 34(1956), p. 410.
- (8) T. Nishihara, S. Taira, K. Tanaka, and Y. Murata: *Jour. Japan Soc. Test. Mater.*, Vol. 5, No. 35 (1956), p. 489.
- (9) T. Nishihara, S. Taira, K. Tanaka, and K. Hironaka: *Jour. Japan Soc. Test. Mater.*, Vol. 2, No. 3 (1953), p. 47.