Expanding the concentrated load $P$ acting on a rail into Fourier integral, and calculating by the same method as above-mentioned, the bending moment $M$ of the rail becomes

$$M = \frac{P}{\pi} \int_{0}^{\infty} \frac{A^2 \cos \lambda x}{k - \lambda^4} \, d\lambda$$  \hspace{1cm} (28)

Substituting (6) into $k$ of Eq. (28), we have

$$M' = \frac{P a}{\pi} \int_{0}^{\infty} \frac{\lambda \alpha \cos \frac{\lambda a}{a}}{\sinh 2\alpha \left( \frac{b}{a} \right) + 2 \alpha \left( \frac{b}{a} \right)^2 + \alpha^3} \, d\lambda$$  \hspace{1cm} (29)

where

$$\sqrt{\frac{E I}{E I}} = a, \quad a \alpha = \alpha$$

Eq. (29) is the extension of Biot's formula and if $b/a \to \infty$, we have

$$M = \frac{P a}{\pi} \int_{0}^{\infty} \frac{\alpha \cos \frac{\lambda a}{a}}{1 + \alpha^3} \, d\lambda$$  \hspace{1cm} (30)

This is coincident with Biot's formula which was calculated for an infinite beam resting on the top of a wall infinitely high and long.

5. Conclusion

In the crane girder etc., it is found that the direct stress which occurs in the web of the girder subjected to wheel load can be calculated with sufficient approximation under the above-mentioned assumptions (i)~(iv). In the case of a simply supported girder, we may consider that the direct stress in the neighbourhood of loading point is nearly equal to the value when the girder is rested on the rigid foundation.

Acknowledgement

For this calculation, thanks are due to Prof. Ishibashi of Kyushu University and Prof. Udoguchi of University of Tokyo for his advice and help. The author also wishes to thank Head designer Hiraguri, Dr. Kobori, Dr. Miyamoto, and Mr. Makino of the Kameari Works of Hitachi Ltd. for their constant encouragements, and Mr. Nakazawa for his help in numerical calculations and experiments.

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The Effect of Atmosphere on Fatigue Strength of Carbon Steels at Elevated Temperature*

By Kichiro Endo**

Fatigue tests of carbon steels were carried out at 550°C under rotating bending and also under repeated torsion in town gas to reduce air oxidation, as a first step to study the effects of atmosphere on fatigue strengths at elevated temperatures. For long lives under low stresses, the strength was higher in gas than in air, and the influence of corrosion fatigue due to oxidation was found in air at high temperature. Meanwhile the strength was lower in gas than in air for short lives under high stresses, and the S-N curves in air and in gas cross each other. This may be attributed to the hydrogen embrittlement resulting from the decomposition of water vapor. The S-N curve at elevated temperatures may take a considerably different shape if the effects of oxidation by air are removed, and its slope becomes more gentle after a long time.

1. Introduction

Studies on high temperature fatigue are considerably advanced, but these have been generally carried out in air and the effect of atmosphere is not much considered. Corrosion in high temperature atmospheres has been discussed under static conditions(1). Some papers are found

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on the effects of oxidizing environments on the strengths of creep rupture and the importance of the problem is emphasized(5) because it has much in common with stress-corrosion cracking.

Regarding the fatigue, the corrosion fatigue at room temperature has already been investigated. It was reported(5) that when fatigue tests were made in vacuum to remove the air oxidation the strengths of Cu-alloy, Al-alloy and the like were significantly higher than those in air and steels were also strengthened to some extent more than in air. These tests were carried out at room temperature. At elevated temperatures, too, the fatigue strength of a carbon steel was measured higher in nitrogen environment than in the air above 250°C(6). However this result was due to a rapid method measuring the deflection of specimens under rotating bending and may be different in conditions from the result of endurance tests for a long time. Further, McKeown, et al.(6) conclude that the corrosion fatigue strength can be substituted for the fatigue strength at elevated temperatures from the evidence that the endurance limit of Al-Cu-alloy for turbine blade is not decided at 400°C because test specimens are oxidized continuously. And they discuss the high temperature strengths of materials with corrosion fatigue tests in a solution of NaCl at room temperature.

The corrosion by environment has thus severe effects on the fatigue strength at elevated temperatures. Since corrosion resistant materials like stainless steel are reduced in fatigue strengths at room temperature due to corrosion fatigue(6), fatigue strengths of these materials may be affected also by atmosphere at elevated temperatures. Accordingly, usual S-N curves of high temperature fatigue in air are considered to consist of two elements of real high temperature fatigue and corrosion fatigue.

The author made high temperature fatigue tests of carbon steels in a non-oxidizing environment, as a first step to study the effects of atmosphere on fatigue strengths at elevated temperatures. It is very difficult to obtain completely inert environment and when it fails the test results are much affected. However the influence of degree of incompleteness of inert environment seems rather small as mentioned later, so the town gas is used to get a simple non-oxidizing environment in the present research.

Endurance tests were first made under rotating bending. Since the temperature was not measured directly in the rotating test specimens, repeated torsional tests were supplemented where test specimens did not rotate itself.

2. Rotating bending fatigue tests

Chemical compositions and mechanical properties of the test material are shown in Table 1. Tests are made on the Ono's rotating bending fatigue testing machine with test specimens shaped as in Fig.1. Cylindrical electric furnace has a radial hole to introduce a thermocouple in its middle position and another radial hole at right angles to the former for the entrance of gas. Lids of asbestos are attached at both ends of the furnace to prevent wasteful outflow of gas but to avoid contacts with the test piece. Town gas is allowed to flow into the furnace at the rate of 600 cc/min from the time the temperature in the furnace attains 250°C continuously to the time of fracture of the specimen. Tests are started after 1 hr from the time of the test temperature reaching 550°C in about 4 hr. Gas leaking out from ends of the furnace is fired for the sake of safety.

It is difficult to control the temperature of specimens under rotating bending, so the following procedures are used. A thermocouple of Chromel-Alumel is made movable by rack and pinion up- and downward in an insulating pipe which is placed in the radial hole of the furnace. First, the difference is calibrated between the temperature measured by the thermocouple pressed on the surface of test specimen and the temperature of the specimen obtained by the thermocouple whose junction is sunk into the specimen. The former

![Fig. 1 Test piece for rotating bending fatigue tests](image)

<table>
<thead>
<tr>
<th>Chemical composition %</th>
<th>Heat treatment</th>
<th>Mechanical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Mn</td>
<td>Si</td>
</tr>
<tr>
<td>0.17</td>
<td>0.42</td>
<td>0.144</td>
</tr>
</tbody>
</table>
is a little higher than the latter and the difference varies according as the gas is allowed to flow in or not.

Then, a new test piece is set on the testing machine. The temperature indicated by the thermocouple pressed on the surface of the test piece at a stop is equalized to the temperature calibrated as before. The thermocouple is pulled up 3~4 mm above the test piece and the test piece is started to rotate under no load. When the test piece is rotated, the temperature of atmosphere near the test piece rises somewhat due to the circulation of environments and it is settled to a constant value after about 10 min. The automatic control instrument is set to the temperature measured just now. After that, the testing machine is stopped quickly, the thermocouple is pressed on the test piece, and the temperature is checked on the surface of the test piece against the fixed value. This process is repeated until the temperature becomes equal to the fixed temperature. After these preparations, load tests are started.

The fatigue tests are made at 550° ±2°C, the cycle frequency being 2690 r.p.m. The S-N curves are shown in Fig. 2 together with the one at room temperature.

3. Torsional fatigue tests

It was not feasible to measure directly the temperature of test pieces under rotating bending as stated before, and the test results seemed rather lacking in accuracy. And so fatigue tests were made under repeated torsional moments when the thermocouple was stuck directly to test pieces.

Table 2 shows the properties of the test material, from which the test pieces are prepared as is shown in Fig. 3. The temperature of test piece is measured and controlled by using a thermocouple of Chromel-Alumel whose junction is fastened on the test piece. These are covered by a ribbon of asbestos.

Tests are carried out by the testing machine worked out previously at our laboratory where the torsional moments given to test pieces are estimated by elastic deformation of the torsion bar connected to the one end of the test piece. In the machine, the moments can not be decided statically because of creep deformation of test pieces at elevated temperatures. And a device composed of electric contacts and micrometers is made to measure the moments during a run at the regular velocity of 1 810 c.p.m. Shearing stresses discussed later are the nominal stresses calculated elastically from these moments. Further, the test pieces are subjected to axial tension to permit their thermal expansion and to stop the machine automatically when the test pieces break down. The tensile stress is, however, only 0.1 kg/mm², distributing uniformly on the critical section, and the magnitude may be out of the question.

The other process of tests is the same with the rotating bending fatigue tests mentioned before. Fig. 4 shows the S-N curves obtained at 550°C and at room temperature.

4. Consideration on the test results

Numbers of repetition in the tests seem...
insufficient to discuss the fatigue strength at elevated temperatures. Nevertheless, it may be known that the strength is higher in gas than in air for long lives under low stresses. While for short lives under high stresses, the strength is lower in gas than in air, and S-N curves for both cases cross each other. The tendency is the same under rotating bending fatigue tests as under torsional fatigue tests where the temperature of test pieces is measured with accuracy, and this proves the accuracy of the former test procedure.

Test pieces tested in high temperature air are covered with coarse dark brown oxide. The surfaces of test pieces tested in town gas to reduce the content of oxygen are stained slightly with soot which is supposed by formed due to the decomposition of methane.(9) Under the soot, the test pieces of short lives have fairly coarse black films and the ones of long lives have fine grey films on their surfaces. Neither carbonizing nor decarbonizing is detected at the surface layer by the microscopic observation.

Even though town gas may contain sulphur, it is attributed to the reduction of oxidation attack that the fatigue strength is higher in gas than in air under tests of long time. And the fatigue in high temperature air is considered to be affected considerably by the corrosion fatigue.

For short life tests under high stresses, however, the fatigue strength is significantly lower in gas than in air. One of the reasons for the strength in gas being lower may be embrittlement by nascent hydrogen which is generated through the high temperature steel-steam reaction from the water vapor of combustion gas. Ferrous oxide grows on the surface of steel simultaneously with this reaction, and equilibrium is attained with passage of time.

It is reported(9) that hydrogen ion gives more damage to fatigue strength than sulphide ion. A paper(10) is also published reporting that an oxide film made by heating ferrous alloys in steam is protective against the further reaction or the damage by hydrogen. Furthermore, a report(11) states that hydrogen embrittlement induced by cadmium plating of the surface of test specimens reduces the fatigue strengths for short lives under high stress level but this influence disappears for long lives under low stress. These evidences explain the S-N curves intersecting at medium lives as shown in Fig.2 and Fig.4.

Shepard and Schalliol(12) made stress-rupture tests of a carbon steel in argon gas used as an inert atmosphere. Argon gas was treated to avoid oxidation by passing it through hot steel

wool. The unoxidized specimens stressed in the treated argon gas failed in less time than the specimens stressed in raw argon gas. The damage caused by the treated argon gas was attributed to the hydrogen resulting from the decomposition of water vapor by the hot steel wool treatment. And yet the stress-rupture life was significantly longer in helium of special purity than in the air. Further, stress-rupture tests were made by Wilkes(23) in an oxidizing atmosphere and also in a reducing atmosphere. The tests show that the stress required to cause rupture is less for oxidizing condition than for reducing condition under low stresses, while reverse is the case under high stresses. The both rupture curves tend to cross each other after 10~100 hr for various heat resistant alloys. Wilkes ascribed it to some unusual action taking place in the early hours of the test.

Since the fatigue is more sensitive to the surface conditions than the creep, it is not
surprising to find phenomena mentioned above. And when the present test results are indicated on a stress-time basis as shown in Fig. 5, S-N curves in air and in gas cross each other within 20~30 hr.

Oxidation reduces the sharpness of cracks and may be considered to lower the stress concentration factor or to decrease the velocity of crack propagation. However these do not explain the crossing of S-N curves.

The real S-N curve at elevated temperatures is located somewhat above the one in air at high stress levels and must approach the one in town gas for low stresses as is shown by the dotted lines in Fig. 2 and Fig. 4. These S-N curves come nearly parallel to the abscissa after a long time and suggest the existence of endurance limit. The S-N curve in air at elevated temperatures is considered to correspond to the S-N curve of corrosion fatigue under high temperature oxidation, and the relation to the real S-N curve coincides with the author's experiences on corrosion fatigue. Accordingly, it may also be concluded that the effect of cycle frequency on the fatigue strength at high temperatures includes the frequency effect of corrosion fatigue.

5. Conclusion

Fatigue tests of carbon steels were carried out at 550°C under rotating bending and also under repeated torsion in town gas to reduce air oxidation. The fatigue strength was higher in gas than in air for long lives under low stresses, and the influence of corrosion fatigue due to oxidation was found in air at high temperatures. Meanwhile for short lives under high stresses, the strength is lower in gas than in air, and the S-N curves in air and in gas cross each other. This may be attributed to the hydrogen embrittlement resulting from the decomposition of water vapor. Similar results are found in stress-rupture tests. The S-N curve at elevated temperature may take a considerably different shape if the effects of oxidation by air are eliminated, and its slope becomes more gentle after a long time, suggesting the existence of an endurance limit.

Further studies will be pursued by the author on various heat resistant alloys and on corrosive environments such as fuel ashes and the like.

Thanks are due to the Education Ministry for allocation of the Science Research Funds for the present research.

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