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Thermal stress fatigue and low cycle fatigue of cast iron

DR. MASARU KINOSHITA, HIDEKAZU YAMANOUCHI and SHIGERU YAMAMOTO

Nagasaki Technical Institute Mitsubishi Heavy Industries Ltd., Nagasaki, Japan

Summary

Thermal stress fatigue tests and low cycle fatigue tests (both constant strain and constant stress amplitude) have been carried out on a cast iron.

The correlations of these tests in terms of strain and stress amplitude and the work hardening curve are discussed. The concentration of strain distribution in thermal stress fatigue caused by non-uniform temperature distribution along the gauge length, is considered.

Introduction

With the progressive uprating of diesel engines, thermal fatigue of combustion chambers has caused great concern. This report describes the design data obtained by means of constant strain amplitude tests, constant stress amplitude tests, and thermal stress fatigue tests in the plastic range, on a cast iron used for the cylinder liners of a large marine diesel engine.

Testing material and statical tensile test result

The chemical composition of the cast iron used is shown in Table 1, the microstructure in Photo. 1, and the static tensile test results in Table 2. These latter values were the mean of two specimens tested at each temperature. Fatigue specimens were 14 mm outside diameter, 10 mm inside diameter and had a gauge length of 40 mm.

Constant strain and constant stress amplitude fatigue tests

Three testing temperatures, viz. room temperature, 200 °C and 400 °C were selected for the constant strain amplitude and constant stress amplitude tests. Five mean strains, viz. 0% (double reversed cycle), 10%, 20%, 30% and 40% of the static tensile fracture strain at temperature were selected for the constant strain fatigue tests and were denoted ϵ_m 0, ϵ_m 10, ϵ_m 20 ϵ_m 30 and ϵ_m 40 respectively. The test conditions of the constant stress amplitude tests were determined correspondingly.

Thermal stress fatigue test

Thermal fatigue testing equipment was so designed that its rigidity could be changed by inserting a dished spring between the upper plate and the columns. Thus, in these tests, the upper and lower limit temperatures were kept constant, but the strain amplitude varied with the number of the dished springs. Three different mean temperatures, Tm, were selected; viz. 350°, 300° and 250°C.

Experimental results

Constant strain fatigue amplitude test

Examples of the results obtained are shown in Figs. 1 and 2. Straight lines in the figures are drawn on the assumption that the under-mentioned formula, which is widely adopted as a criterion for the fracture condition in constant strain fatigue tests applies, even at different temperatures and in the presence of a mean strain.

$$N^k \Delta\epsilon_a = C \qquad (1)$$

where k and C are constants.

For a given mean strain, a ductile material displays a hysteresis loop like that at zero mean strain after several cycles, but cast iron does not; it displays a mean strain type hysteresis loop as shown in Fig. 3. The tensile mean stress tends to enlarge micro cracks produced by fatigue, making the effect of mean strain more conspicuous than in the case of other materials.

In the case of ductile materials, the plastic range is:

$$\Delta\epsilon_p = \Delta\epsilon_a - \frac{\Delta\sigma}{E} \qquad (2)$$

where $\Delta\epsilon_p$ is plastic strain range, $\Delta\epsilon_a$ is total strain range, $\Delta\sigma'$ is stress range, and E is Young's modulus. However, Young's modulus for cast iron is different in tension from that in compression. The calculated results, taking this into consideration are shown in Fig. 4. This figure shows that the constant k in equation (1) is about 0·5 as proposed by Coffin [1].

When there is a mean strain, constants k and C in equation (1) are changed slightly by the value of the mean strain. This is shown in Fig. 5 for each temperature and mean strain.

By developing Yokobori's theory [2] for constant strain amplitude fatigue without mean strain, we obtain the following equation for the criterion of fracture in constant strain fatigue with a mean strain.

$$N^{1/2} \Delta\epsilon_p = \frac{\sigma_1}{m} - \frac{m}{\sigma_1}\epsilon_m \Delta\epsilon_p \qquad (3)$$

where σ_1 is the critical shear stress for driving a Frank-Read source, m is the strain hardening coefficient, and ϵ_m is mean strain.

Equation (3) explains why the fatigue strength diagram becomes as shown in Fig. 6 when a mean strain is applied.

Constant stress fatigue test

Examples of test results are shown in Figs. 7 and 8; the points show some scatter but, on the whole, the following equation applies:

$$\sigma_a = L \log N + M \qquad (4)$$

where L and M are constants.

When this equation is applied to these test results, L becomes −4·7. This value remains constant despite changes in mean strain and temperature. As shown in Fig. 9, M decreases with increase in mean strain and with rise in testing temperature.

Thermal stress fatigue test

Test results are shown in Figs. 10 to 12 in terms of strain range and cycles to failure.

Discussion

Relation between thermal and low-cycle fatigue

There is little difference in shape between the hysteresis loops for the constant stress amplitude tests and those for the constant strain amplitude tests. The width T of the hysteresis loop in the thermal stress tests is larger than that in the constant strain amplitude tests, its characteristics resembling those of constant stress amplitude tests.

Relation between constant strain and constant stress fatigue

The results of both series of tests when compared in terms of strain amplitude and cycle to failure, were found to agree closely. In Figs. 1 and 2, test points for constant strain fatigue are the experimentally applied values, whereas those for constant stress fatigue are shown in terms of strain range obtained from hysteresis loop width measurements obtained at about the half-life of a specimen.

Relation between thermal and low-cycle fatigue

When comparing thermal stress fatigue and high temperature fatigue, the following points must be considered:

(a) Magnitude of total strain

(b) Effect of strain concentration caused by non-uniform temperature distribution.

(c) Material deterioration due to temperature cycling and other factors.

The hysteresis loops obtained in thermal stress fatigue are similar to those of pulsating stress fatigue, and so the results have been compared with those from high temperature constant strain amplitude tests. From the data in Figs. 1 and 2, the test results of pulsating fatigue at each temperature were obtained, which are shown in Fig. 13 together with the thermal stress test results.

In this figure, measured values of strain amplitude in the thermal stress fatigue tests were shown as open symbols and the high temperature pulsating fatigue strength at 400 °C is shown as a broken line.

As the thermal stress test is conducted by a direct heating method, temperature distribution in the specimen along its gauge length is non-uniform and causes a strain concentration. According to Cottrell [3] and Yokobori, [4] slip of dislocations within grains at high temperature causes deformation of the material, and if this is regarded as a stress dependent rate process, the rate r is as follows, when based on the concept of activation energy.

$$r = A' \exp \left\{ - Q\,(S) \frac{1}{RT} \right\} \qquad (5)$$

where $Q(s)$ is activation energy, S is stress, T is absolute temperature, A is a constant, and R is the gas constant. Taking unit time, we obtain the following equation:

$$\epsilon_p = A' \exp \left\{ - Q\,(S) \frac{1}{RT} \right\} \qquad (6)$$

From this equation, the magnitude of plastic strain ϵ_p under a certain stress and at a certain temperature can be calculated. Since the material shows no clear yield point and it was impossible to make a clear distinction between elastic and plastic strain, the equation becomes, on the assumption that elastic strain is nearly zero:

$$\epsilon = A \exp \left(- \frac{B}{T} \right) \qquad (7)$$

Obtaining the strains corresponding to stresses of 10, 15, 20 and 25 kg/mm^2 from the static tensile curve of the material enables Fig. 14 to be plotted. The values of the constants A and B can be determined from equation (7) by considering the test points in Fig. 14 as a fitting straight line; this is shown in Fig. 15. From this the values of A and B corresponding to the state of stress under a certain temperature condition can be obtained. Considering constant strain fatigue, the values of strain ϵ calculated on (7) agree closely with one another. This method can be used for calculating the true value of strain in the gauge length in the first cycle, which is not affected by the temperature cycle effect. Corrected strains in the thermal stress fatigue tests are shown in Fig. 13 by solid symbols.

When the strain concentration is calculated, taking temperature distribution into consideration, and the true strain in the gauge length is examined, it is found that the agreement with the temperature pulsating fatigue strength is reasonable. This implies that there is little material deterioration on temperature cycling in this cast iron.

Conclusions

Constant strain amplitude fatigue tests, constant stress amplitude fatigue tests and thermal stress fatigue tests were carried out on cast iron; their respective characteristics and mutual relationship were studied. For this cast iron the conclusions are as follows:

(1) In a constant strain test, if the strain is expressed in terms of $\Delta\epsilon_p$ instead of $\Delta\epsilon_a$, k becomes 0·5, showing that cast iron exhibits the same characteristics as ductile materials.

(2) Constant stress fatigue strength can be expressed using the following equation:

$$\sigma_a = L \log N + M$$

The value of L is constant despite changes in mean strain and temperature.

(3) If the relationship between constant strain fatigue tests and constant stress fatigue tests is expressed in terms of strain amplitude, these values agree with each other regardless of the existence of mean strain and high temperature condition.

(4) In thermal stress fatigue, the strain concentration caused by non-uniform temperature distribution can be calculated in terms of a stress-dependent rate process and is compared with high temperature pulsating fatigue. Values obtained agree with each other closely

(5) Thermal stress fatigue strength, which is scarcely affected by material deterioration due to temperature cycling, can be expressed in terms of strain amplitude.

References

1. TAVERNELLI, J. F. and COFFIN, L. F. 'A compilation and interpretation of cyclic strain fatigue tests on metals'. *Trans. ASM*, vol. 51, p. 438, 1959.
2. YOKOBORI, T. 'Proc. symposium on crack propagation', *the College of Aeronautics, Cranfield, England*, p. 510, 1962.
   YOKOBORI, T. 'Introduction to fracture and fatigue of metallic materials' (in Japanese), *Science of Machine*, vol. 13, no. 2, p. 329, 1961.
3. COTTRELL, A. H. 'Dislocation and plastic flow in crystals', *Clarendon Press, Oxford*, p. 195, 1958.
4. YOKOBORI, T. 'Strength, fracture and fatigue of materials' (in Japanese), *Gihodo, Tokyo*, p. 143, 1955.

Table 1
The chemical composition of cast iron (G. %)

C	Si	Mn	P	S	V	Ti
2·78	0·88	0·65	0·263	0·076	0·16	0·02

Table 2
Result of statical tensile test

Testing temp. (°C)	Tensile strength (kg/mm^2)	Strain at fracture (%)
Room temp.	32·5	0·812
	29·8	0·704
100	29·0	0·760
	28·7	0·692
200	28·7	0·840
	30·3	0·900
300	27·0	0·520
	28·9	0·680
400	32·5	1·020
	29·6	0·900
500	25·7	0·916
	29·8	1·240

Photo. 1. Micro structure 100×.

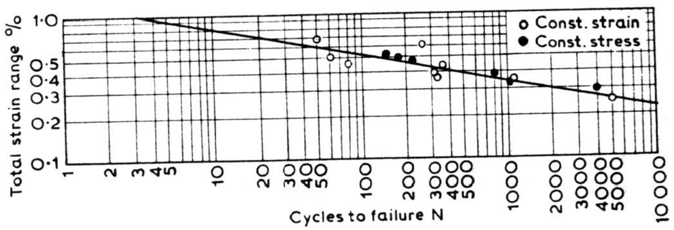

Fig. 1. The correlation of strain range and cycles to failure in constant strain and constant stress fatigue tests (200°C, ϵ_m = 0).

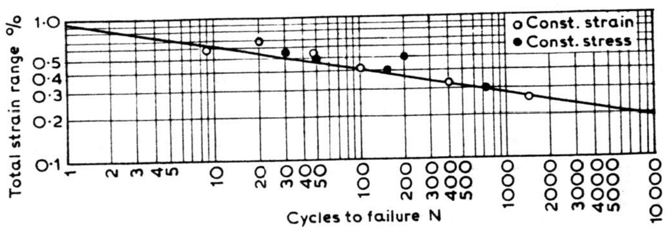

Fig. 2. The correlation of strain range and cycles to failure in constant strain and constant stress fatigue tests (200°C, ϵ_m = 20).

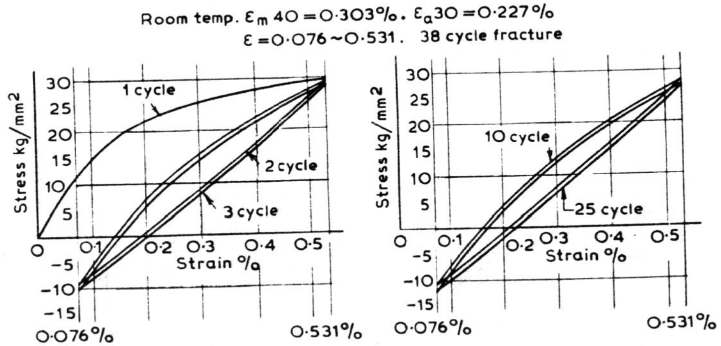

Fig. 3. Hysteresis loop in a constant strain fatigue test.

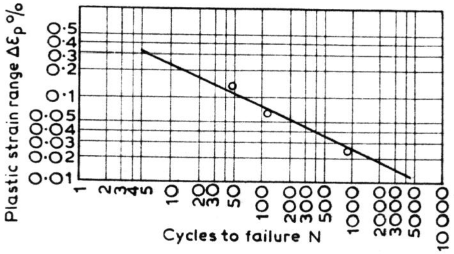

Fig. 4. The correlation of plastic strain range and cycles to failure (mean strain 0%).

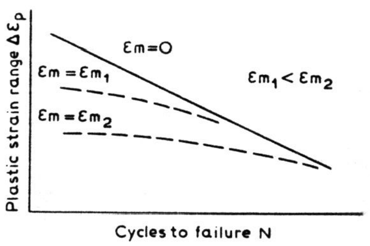

Fig. 5. The correlation of plastic strain range and cycles to failure with a mean strain.

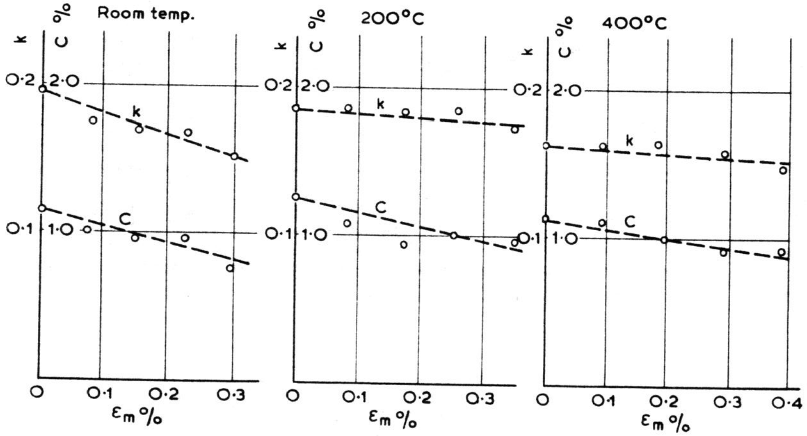

Fig. 6. The correlation of constant *k*, *C* and mean strain on constant strain fatigue.

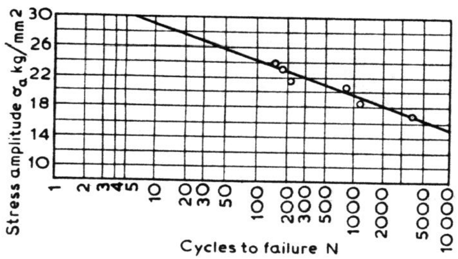

Fig. 7. Experimental results of constant stress fatigue tests (200°C, $\epsilon_{m0} = 0\%$).

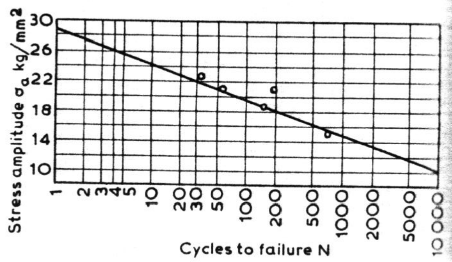

Fig. 8. Experimental results of constant stress fatigue tests (200°C, $\epsilon_{m20} = 0{\cdot}174\%$).

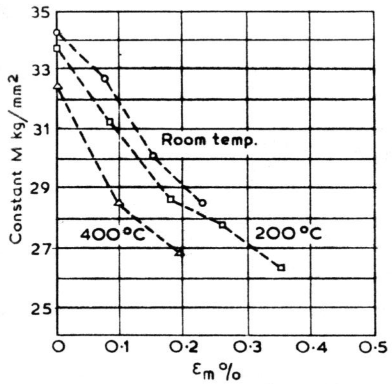

Fig. 9. The correlation of constant *M* and mean strain on constant stress fatigue.

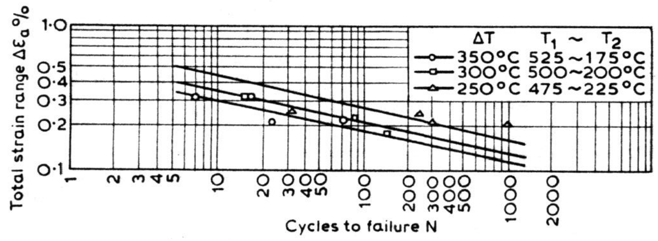

Fig. 10. Experimental results of thermal stress fatigue tests (mean temp. 350°C).

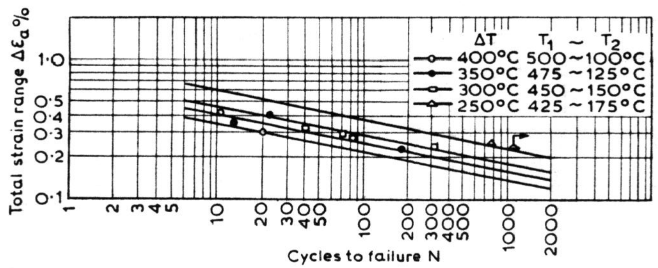

Fig. 11. Experimental results of thermal stress fatigue tests (mean temp. 300°C).

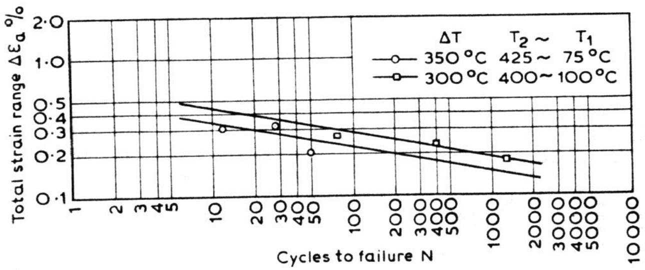

Fig. 12. Experimental results of thermal stress fatigue tests (mean temp. 250°C).

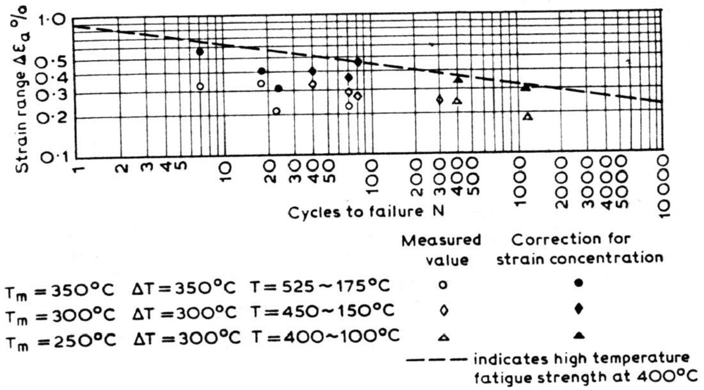

Fig. 13. The correlation of strain range and cycle to failure for thermal stress and high-temperature fatigue.

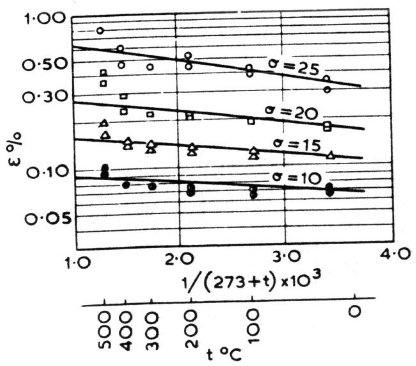

Fig. 14. $\epsilon = A \exp\left(-\frac{B}{T}\right)$ obtained from static stress-strain curve.

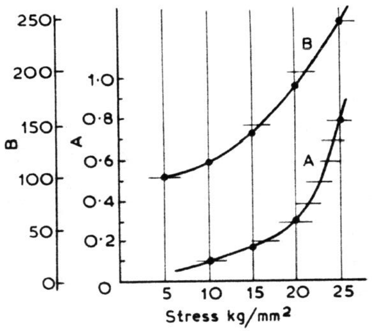

Fig. 15. Constant A and B of $\epsilon = A \exp\left(-\frac{B}{T}\right)$ for various stresses.