Thermal fatigue life prediction

VERIFICATION OF COFFIN - MANSON'S LAW IN THE RANGE Of α↔γ TRANSFORMATION ON FERRITE MATRIX DUCTILE CAST IRON

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ABSTRACT

In the study, the thermal fatigue tests on ferritic ductile cast iron were carried out. In the test, the gauge length of specimen was axially fixed completely and repeated thermal cycle is given at constant heating and cooling rate. As a result of experiment, the both relations, cyclic fatigue life to cyclic peak temperature and typical plastic strain per cycle to peak temperature are obtained. Along with increasing of cyclic peak temperature, the cyclic plastic strain increases and the fatigue life decreases, sharply in lower temperature, and gently in higher temperature in ferrite (α) matrix range; but the fatigue life rises and the plastic strain drops in lower α↔γ transformation range; and the fatigue life decreases and the plastic strain increasesagain in higher α↔γ transformation range and subsequently in austenite (γ) range. But the relationship between the fatigue life and the plastic strain is expressed in full-logarithmic straight line with constant coefficient and exponent all over the above described ranges. It means that the thermal fatigue life is dominated directly by a factor of cyclically produced plastic strain. And the coefficient and the exponent can calculated by the data obtained from tensile test at the room temperature as proposed by Coffin and Manson.

KEYWORDS

Ductile cast iron; Thermal fatigue test; Fatigue life; Fractography of thermal fatigue; Thermal strain; Thermal activation energy; Plastic strain; Low cycle fatigue; Coffin-Manson's model.

INTRODUCTION

Because of the superior mechanical properties and its low price, ductile cast iron is utilized widely as a leading industrial material. And several studies on its strength at elevated temperature were reported [1,2,3,4,5,6]. In the former report [7] on thermal fatigue, two kinds of serration in cycling thermal stress, visual crack on specimen and the effect of cyclic peak temperature on the fatigue life were introduced. In the study, Continously, the effect of cyclic peak temperature on fatigue life, the cyclic plastic strain produced in the thermal cycle effected by its test tempearature, and the relationship with its thermal fatigue life around the α↔γ transformation are investigated and discussed.

MATERIALS AND EXPERIMENTAL PROCEDURE

The material and experimental procedure are as reported in the former [7]. The thermal fatigue tests were carried out on spheroidal graphite cast iron with ferrite matrix classified as FCD400 in JIS, where the thermal cycle is given repeatedly from the temperature 323K to the peak temperature selected as a parameter from 673K to 1273K at constant rate of 3.1K/s with triangular thermal cycle form to the specimen with the gauge length of 15 mm and the diameter of 10 mm which is controlled to be constrained axially completely so the displacement of the gauge length is always kept zero in the test. And the thermal fatigue life N was decided by the number of thermal cycles to failure in the test.

EXPERIMENTAL RESULTS AND DISCUSSION

Fatigue Life versus Cyclic Peak Temperature

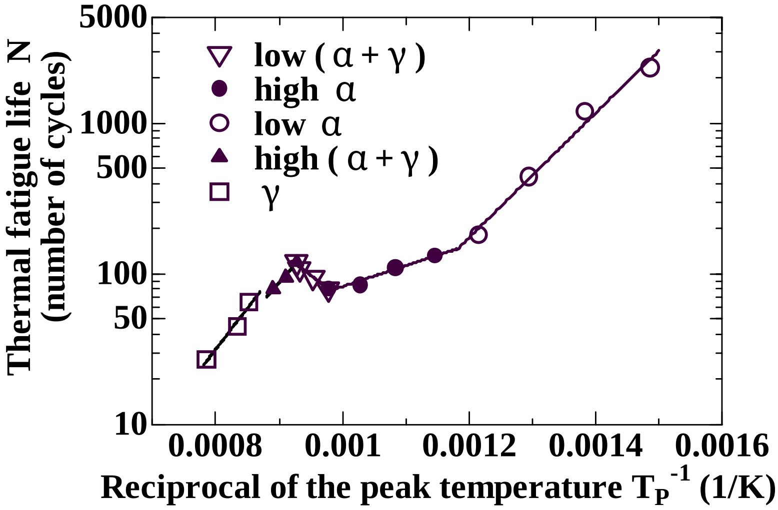

Fig.1 The diagram of thermal fatigue life versus the reciprocal of cyclic peak temperature of thermal fatigue on ferritic ductile cast iron.

As shown in the Fig.1, the relation of thermal fatigue life N to the cyclic peak temperature T_P is obtained, which can be divided roughly into 3 ranges. The first one is the range from 673K to 1023K where the fatigue life decreases with the increase of cyclic peak temperature. The second one is the range from 1023K to 1078K where the cyclic life increases with the increase of peak temperature. And the third one is the range above 1078K, where like the first range, the life decreases with increase of the cyclic peak temperature. Further, the first range can be divided into two sub-ranges, respectively from 673K to 823K and from 873K to 1023K, where the slope of the curves is different each other. And the third range also can divided into two sub-ranges, 1078K to 1123K and over 1173K to 1273K. The relationships over all ranges can be expressed in Ahhrenius equation (1),

$$N = A_N \bullet \exp(Q_N / RT_p) \qquad (1)$$

where N: thermal fatigue life, R : gas constant, 8.31451 J/mol·K, Q_N : thermal activation energy for thermal fatigue life, KJ/mol, and A_N: coefficient. The data Q_N and A_N for the ranges are as shown in Table 1.

Temperature Range	673K-823K	873K-1023K	673K-1023K	1023K-1078K	1078K-1123K	1078K-1273K	1173K 1273K
Q_N in kJ/mol	79.5	26.5	58	-60.8	88.5	84.1	104
A_N	1.85×10^{-3}	3.42	0.055	9.87×10^{4}	0.0062	0.0102	0.0014

Table 1 Activation energies and coefficients for each range in equation (1).

Thermal Plastic Strain per Cycle versus Cyclic Peak Temperature

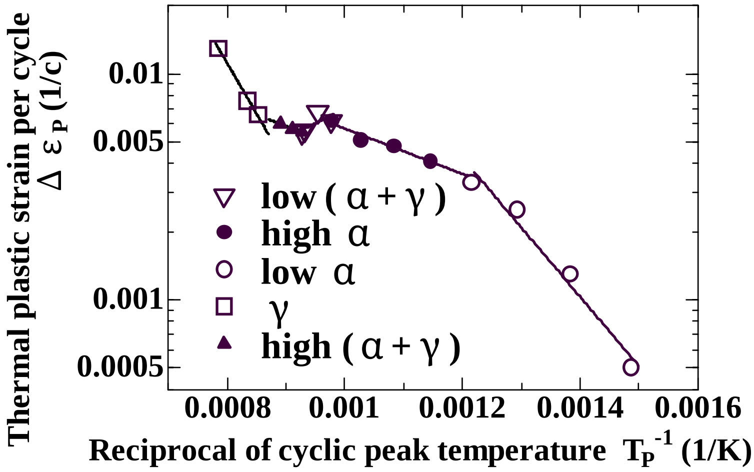

Fig.2 The diagram of thermal plastic strain per cycle versus the reciprocal of cyclic peak temperature of thermal fatigue on ferritic ductile cast iron.

The cyclic thermal plastic strain $\Delta\varepsilon_P$ is attained by the difference of thermal expansion between two points where thermal stress vanishes to zero in each thermal cycle. Then the diagram of $\Delta\varepsilon_P$ versus T_P was obtained as shown in Fig.2, the relationship can be divided also into five divisions as described above and can be expressed as in the equation (2),

$$\Delta\varepsilon_P = A_P \cdot \exp(Q_P / RT_p) \qquad (2)$$

where Q_P : thermal activation energy for $\Delta\varepsilon_P$, and A_P : the coefficient, as shown in Table 2.

Temperature Range	673K-823K	873K-1023K	673K-1023K	1023K-1078K	1078K-1123K	1078K-1273K	1173K-1273K
Q_P in kJ/mol	-58.8	-19.2	-38.1	24.3	-19.6	-47.1	-85.9
A_P	20.6	0.0578	0.666	3.76×10^{-4}	0.0485	0.956	41.9

Table 2 Activation energies and coefficients of the equation (2) for each range

	Activation energy in kJ/mol						
Matrix	Self-diffusion	Grain boundary	Diffusion of carbon	Q_N	$-Q_P$	Tensile strength	Tensile deform
in α	251-264		80	26.5-79.5	19.2-58.8	60.7	357
in γ	234-310	159	148	104	85.9	58.7	313

Table 3 Activation energies for ductile cast iron

Comparing activation energies, Q_N and Q_P are about one third or one fourth to that for self-ciffusion and near that of carbon and tensile strentgth as shown in Table 3 [1,8].

Thermal Fatigue Life versus Plastic Strain per Cycle

As for the diagram of fatigue life and plastic strain per cycle as shown in Fig.3, the larger the plastic strain is, the lower the fatigue life is and the relation can be expressed roughly just by a straight line in full logarithmic scale all over the temperature ranges by the equation (3) in a single power function with a constant coefficient and an exponent for all ranges, in this case, κ_P :0.59 and C_P:0.082. These are 0.57–0.62 and 0.023–0.192 for FCD450 in α range [6].

$$\Delta \varepsilon_p \cdot N^{k_p} = C_p \qquad (3)$$

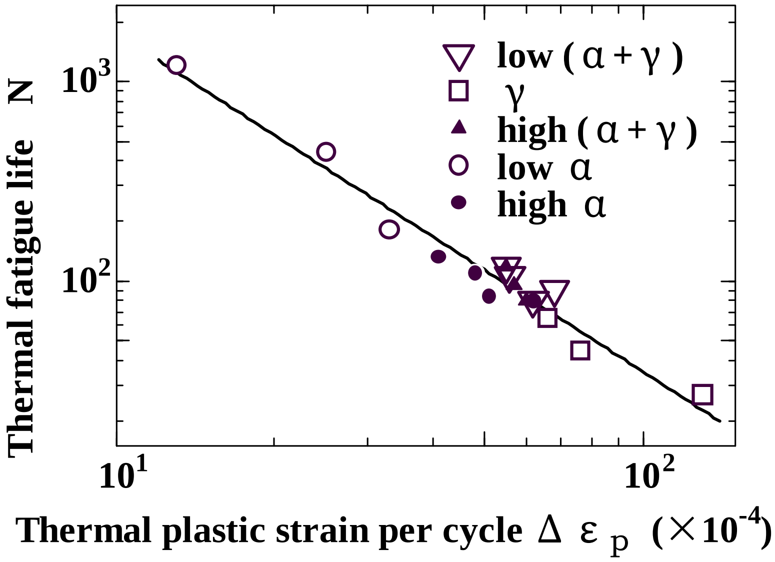

Fig.3 The diagram of thermal fatigue life versus thermal plastic strain per cycle

Change of Microstructure in Transformation Range on Thermal Fatigue

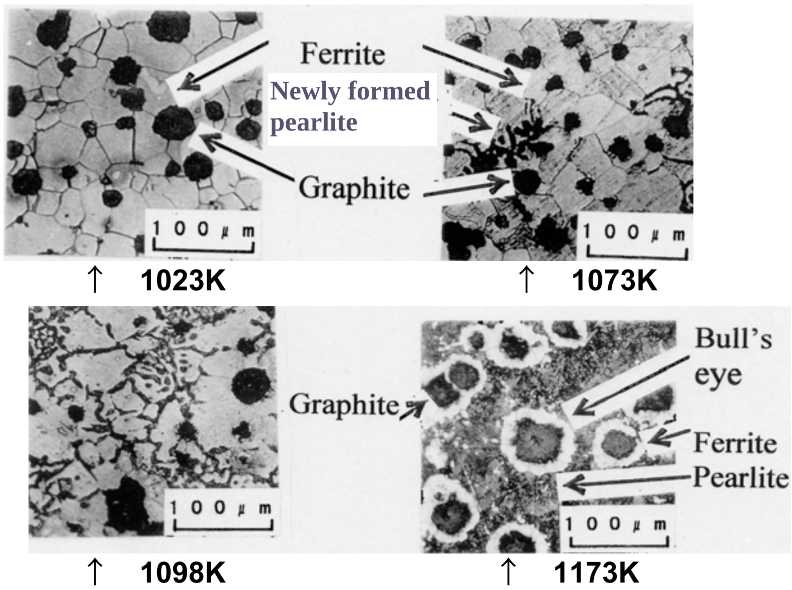

Photo 1. Microstructure changed with different peak temperature around α↔γ transformation.

As shown in Photo 1, when the cyclic peak temperature reaches and over 1023K, the element of carbon flows out from the spheroidal graphite, along the boundaries and diffuses into the ferrite inner grains, then forms austenite, which precipitates into pearlite while cooling process in each repeated thermal cycle. As the peak temperature approaching 1173K, the diffused carbon near the spheroidal graphite is absorbed again to form the structure of Bull's eye. In this way, the α↔γ transformation occurs within the temperature range from 1023K to 1173K in the thermal fatigue test.

Fractography on Thermal Fatigue

Thermal fatigue fracture are as shown in Photo 2. In the peak temperatures range of 673K-1023K, there are two kinds of plastic fracture pattern caused by a great deformation of ferrite matrix around nodular graphite, one is trans-granular plastic fracture at lower temperatures presented by the picture at 753K, and the other one is inter-granular plastic fracture at higher temperatures by that at 843K which is effected by the weakening of grain boundary at elevated temperature. From 1073K to 1123K, as the picture at 1078K, it shows the fracture of coexistance of α and pearlite transformed from γ matrix during cyclic cooling. And at 1223K, it shows the fracture of pearlite matrix transformed from austenite grains.

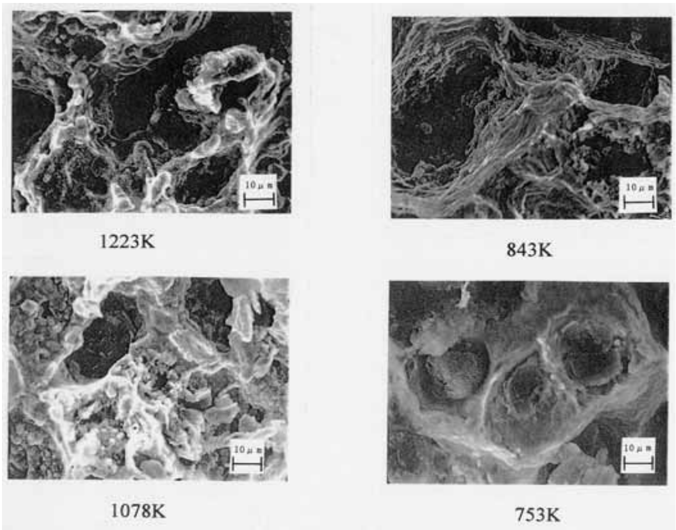

Photo 2. SEM pictures of fracture surface at different cyclic peak temperatures of thermal fatigue test on ductile cast iron.

Discussion

As for the equation (3) related to N and $\Delta\varepsilon_P$ that is the same as the Coffin Manson's model [9,10,11,13], the exponent κ_P is 0.5 proposed by Coffin [9] and 0.6 or 0.5 - 0.7 by Manson [12] that is near the experimental value of 0.59 attained here. As to C_P, it is 0.1 calculated from the tensile elongation ε_T of 20% as ε_f and that is 0.093 from the rate of reduction φ of 17% by the equation (4) suggested by Coffin and it is 0.06 calculated by the equation (5) proposed by Manson that is near the value of 0.082 attained in the test.

$$C_P = \varepsilon_f / 2 = (1/2)\ln(100/(100-\varphi)) \qquad (4)$$

$$C_P(\%) = (\varepsilon_f(\%))^{0.6} \qquad (5)$$

It means the thermal fatigue life can be predicted roughly by the tensile test data at room temperature.

In the transformation range fom 1023K to 1173K, the plastic strain decreases and the fatigue life increases with increase of the peak temerature from 1023K to 1073K that is basically caused by the contracting of phase transformation [13] of matrix from ferrite into austenite and by the establishment of the equilibrium between both strengths of grain boundary and inner grain through the strengthening of carbon-riched grain boundary. But once the pearlite precipitates along grain boundary and spreads to the inner grain, the plastic strain increases and the fatigue life decreases again along with the increase of cyclic peak temperature. In this way, the effect of the state of grain boundary determines the thermal fatigue in transformation.

CONCLUSIONS

By performing thermal fatigue test on ferritic matrix ductile cast iron, the main results are obtained as follows.

1. The thermally activated relationships between the thermal fatigue life and the cyclic peak temperature and between the typical thermal plastic strain per cycle and the cyclic peak temperature are introduced and expressed in Ahrrenius formula in all ranges.
2. The attained relationship between the thermal plastic strain and the fatigue life can be expressed roughly by one straight line in full-logarithic scale with invariable coefficient and exponent all over the temperature ranges including transformation. The coefficient and the exponetn are in agreement with the Coffin-Manson's law.
3. Thermal fatigue fractures changed around the phase transformation range.

REFERENCES

[1] K.Chijiiwa and M.Hayashi, Mechanical Properties of Ductile Cast Iron at Temperaturs in the Region of Room Temperature to Liquidus. Journal of The Faculty of Engineering, The University of Tokyo (B), Vol. 35, No.2, 1979, pp.205-230.
[2] K.Chijiiwa and M.Hayashi, Mechanical Properties of Ductile Cast Iron at Temperaturs in the Region of Room Temperature to Liquidus. Imono, Vol. 51, 1979, pp.395-400.
[3] K.Yasue, M.Isotani, Y.Kondo, N.Kawamoto, Thermal Fatigue of Spheroidal Graphite Cast Iron. Imono, Vol. 54, 1982, pp.739-743.
[4] M.Nakashiro, M.Kitagawa, Y.Hukuhara, S.Oohama, Thermal Fatigue and High Temperature Low Cycle Fatigue Properties of Spheroidal Graphite Cast Iron. Transaction of Iron and Steel, Vol. 70, 1984, pp.1230.
[5] N.Takeshige, Y.Uosaki, H.Asai, Thermal Fatigue Behavior of Heat Resistant Cast Iron for Automobile. Prepr. of Jpn. Soc.Mech.Eng.No.940-10, 1994, pp.56-58.
[6] K.Yasue, H.Mtsubara, M.Isotani, Y.Kondo, Temperature Dependence of Low Cycle Fatigue Life in Cast Iron. Imono, Vol. 52, 1980, pp.669-674.
[7] M.Hayashi, Features on Thermal Fatigue of Ferrite Matrix Ductile Cast Iron, K.-T. Rie and P.D.Portella (ed.), Low Cycle Fatigue and Elasto-Plastic Behaviour of Materials, Oxford Elsevier Science Ltd.1998, pp.161-166.
[8] W.HumeRothery, The Structure of Alloys of Iron, Pergamon Press,1966.
[9] L.F.Coffin,Jr., A Study of the Effects of Cyclic Thermal Stresses on a Ductile Material, Trans. ASME, Vol. 76, No.6, 1954, pp.923-950.
[10] L.F.Coffin.,Jr., and J.F.Tavarnelli, Cyclic Straining and Fatigue of Metals, Trans. Met. Soc. AIME, Vol.215, No.5, 1959, pp.794-807.
[11] S.S.Manson, Behavior of Materials under Conditions of Thermal Stress. NACA Tech. Note, 2933, 1954.
[12] S.S.Manson, Fatigue: A Complex Subject – Some Simple Approximations, Exper. Mechanics, Vol.5, No.7, 1965, pp.193-226.
[13] S.S.Manson, Thermal Stress and Low-Cycle Fatigue. McGraw-Hill Book Co., 1966.

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