Monosemousness of Thermal Plastic Strain on Thermal Fatigue Life in Ferrite Ductile Cast Iron*

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Abstract

In this study, the monosemous effect of thermal plastic strain on the thermal fatigue life is newly found on ferrite ductile cast iron around the alpha phase field. At first, the monosemousness is defined and its meaning described. Next, the monosemousness of thermal fatigue is demonstrated by its conditional equation and its existence is verified by the thermal fatigue test on ferrite ductile cast iron. By doing so, the feature on the thermal fatigue of ferrite ductile cast iron is clarified. Generally, it is considered that fatigue life in ferrite-matrix temperature range can be expressed at least by two or more different Arrhenius equations, namely there are two or more different activation mechanisms to govern the thermal fatigue life corresponding to various ferrite temperature ranges. In this case, for determining the life in any various ferrite temperature ranges, it must have at least four or more unknown quantities. If there is the presence of a general equation which is able to replace above described plural equations, then the life can be determined by simple one variable. Here, by introducing conditional equations, it is verified that the general equation is a Coffin and Manson's equation of low cycle fatigue and whole thermal fatigue life can be determined by a variable of thermal plastic strain occurred in thermal cycle. As a result, the law can apply to describe thermal fatigue phenomenon and predict thermal fatigue life monosemously from cyclic thermal plastic strain on ductile cast iron with ferrite matrix.

Key words: Ductile Cast Iron, Thermal Fatigue, Thermal Plastic Strain, Thermal Activation, Thermal Fatigue Life

1. Introduction

As regards ductile cast iron, because of superior mechanical properties and low price, it is widely uses as a leading industrial material. And because of its good heat-resistance, it is applied in several devices served at elevated temperature. Therefore, in recent, some behaviors on the thermal fatigue of ductile cast iron have been investigated and made clear^{(1) ~ (3)}, such as two kinds of serration in cyclic thermal stress, the effect of cyclic temperature on the thermal fatigue life, etc. In the thermal fatigue test, it is clear that there are three different temperature ranges on ductile cast iron with the matrix of microstructure of ferrite. In the thermal fatigue test, the relationships in Arrhenius expression can be derived for thermal fatigue life and for cyclic thermal plastic strain in each range. However, throughout the whole temperature ranges in ferrite matrix, it is found that the thermal fatigue life is governed only by one common function with a variable of cyclic plastic thermal strain. Such phenomenon is newly defined as monosemousness to thermal fatigue life here. And, the conditional equations brought the definition into existence are introduced. Further, the nature of monosemy in thermal fatigue is verified by calculation

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of the equation and by experimental result attained in Manson-Coffin's law. As a result, the law can apply to describe thermal fatigue phenomenon and predict thermal fatigue life monosemously from cyclic thermal plastic strain on ductile cast iron with ferrite matrix.

2. Theoretical Detail

However, as known, plastic strain and thermal fatigue life ⁽¹⁾ can be expressed by Arrhenius form. Therefore, it can be intended to prove from Arrhenius expression to Manson-Coffin's law. At same time, it is shown that theoretical detail for monosemousness thermal fatigue life is derived. If the factors in the above-stated Arrhenius equations as shown in (1), (2) have satisfied the following conditions from (4) to (13). Then, the equation (14) shall exist.

$$\varepsilon_p = A_i \exp(B_i/T) \quad (1)$$

$$N_f = \bar{A}_i \exp(\bar{B}_i/T) \quad (2)$$

$$\varepsilon_p = C_{pi} N_f^{\kappa_{pi}} \dots (\text{Manson - Coffin's law}) \quad (3)$$

$i = 1, 2, 3 \dots$

(4) ~ (7) get from experiment.

$$B_2 = a_B \exp(b_B/T) \quad (4)$$

$$B_2 = \bar{a}_B \exp(\bar{b}_B/T) \quad (5)$$

(4) and (5) are activation energy.

$$A_2 = a_A \exp(b_A/T) \quad (6)$$

$$\bar{A}_2 = \bar{a}_A \exp(\bar{b}_A/T) \quad (7)$$

Substitute (1) and (2) to (3).

$$A_i \exp(B_i/T) = C_{pi} [\bar{A}_i \exp(\bar{B}_i/T)]^{\kappa_{pi}} \quad (8)$$

$$A_i \exp(B_i/T) = C_{pi} \bar{A}_i^{\kappa_{pi}} \exp(\kappa_{pi} \bar{B}_i/T) \quad (9)$$

$$C_{pi} \bar{A}_i^{\kappa_{pi}} = A_i \quad (10)$$

$$\kappa_{pi} \bar{B}_i = B_i \quad (11)$$

If (12) and (13), condition of monosemousness, are established,

$$C_{pi} = \frac{A_i}{\bar{A}_i^{\kappa_{pi}}} = \frac{A_i}{\bar{A}_i^{B_i/B_i}} = C_{p0} \quad (12)$$

$$\kappa_{pi} = \frac{B_i}{\bar{B}_i} = \kappa_{p0} \quad (13)$$

$i = 1, 2, 3 \dots$

Then substitute (8) and (9) to (10), (14) can be attained.

$$\varepsilon_p = C_{p0} N_f^{\kappa_{p0}} \quad (14)$$

But in range 2, $i=2$

$$C_{p2} = \frac{a_A \exp(b_A/T)}{[\bar{a}_A \exp(\bar{b}_A/T)]^{\kappa_{p2}}} = \frac{a_A \exp(b_A/T)}{\bar{a}_A^{\kappa_{p2}} \exp(\kappa_{p2} \bar{b}_A/T)} \quad (15)$$

$$\kappa_{p2} = \frac{a_B \exp(b_B/T)}{\bar{a}_B \cdot \exp(\bar{b}_B/T)} \quad (16)$$

N_f : thermal fatigue life, ε_p : thermal plastic strain, $B_i, \bar{B}_i$: activation energy, T :

peak temperature, $A_i, \bar{A}_i$: coefficient, C_{pi}, C_{p0} : ductile coefficient from Table 1(R: gas constant), κ_{pi}, κ_{p0} : ductile index from Table 1.

Namely, if the monosemous condition is existent, the equation of Manson-Coffin's law shall be established in whole test temperature ranges and the cyclic plastic strain shall monosemously dominate thermal fatigue life.

3. Experimental & Material Detail

The material and the experimental procedure are as reported in the former ⁽¹⁾. The thermal fatigue tests were carried out by a hydraulic servo pulsar Shimazu EHF-ED100kN-TF-20L and the test-pieces are made on spheroid graphite cast iron with ferrite matrix classified as FCD400 in JIS, where the thermal cycle is given repeatedly from the temperature 323 K to the peak temperature selected as a parameter from 673 K to 1023 K at constant rate of 3.1 K/s with triangular thermal cycle form to the specimen with gage length of 15 mm and diameter of 10 mm. The test holds everything except temperature cyclically between room temperature and peak temperature, rising and falling at constant rate. And load, elongation and temperature of gage length are detected.

4. Result & Discussion

By the experiment described above, the following results were obtained. Figure 1 shows the thermal plastic strain versus reciprocal number of cyclic peak temperature. Fig.1-(1) shows the adjoining slopes of thermal plastic strain to the reciprocal number of peak temperature. This diagram shows changing of the thermal plastic strains from each peak temperatures. The slope changes gentle in both ranges, in higher and lower temperature ranges, but greatly in middle range. Fig.1-(2) shows roughly dividing the three peaks temperature ranges from Fig.1-(1). First range is 870 K to 1023 K. Second range is 717 K to 859 K. Third range is 673 K to 706 K. The thermal plastic strains are increasing when the peak temperatures are increasing. From Fig.1-(2) their curves can be expressed in an Arrhenius equation (1), respectively, of which A_i and B_i are constant in the first and the second ranges. But A_2 and B_2 are functions as shown in Eqs. (4) and (6).

And Figure 2 shows the thermal fatigue life versus reciprocal number of cyclic peak temperature also. Fig.2-(1) shows the adjoining slopes of thermal fatigue life to the reciprocal number of peak temperature slopes. This diagram shows changing of the thermal fatigue life from each peak temperatures. The slope changes gentle in both ranges, in higher and lower temperature ranges, but greatly in middle range. It is same as thermal plastic strain.

Figure.2-(2) shows roughly dividing three range peak temperatures from Fig.2-(1) same as Fig.1. First range is 870 K to 1023 K. Second range is 717 K to 859 K. Third range is 673 K to 706 K. The thermal fatigue life is decreasing when the peak temperatures are increasing. From Fig.2-(2) their curves also can be expressed in an Arrhenius equation (2), respectively, of which $\bar{A}_i$ and $\bar{B}_i$ are constant in the first and the second ranges. But $\bar{A}_2$ and $\bar{B}_2$ are functions as shown in equation (5) and (7).

Table 1 shows Activation energy and coefficient value from Fig.1, 2 and 3. High and Low temperature's Activation energies are lower than transition temperature range. Therefore, transition temperature move to activity recognizing from Table1.

(1) Change to adjoining reciprocal number of peak temperature versus slope

(2) Two ranges to reciprocal number of peak temperature versus slope

Figure. 1 The thermal plastic strain versus reciprocal number of peak temperature.

(1) Change to adjoining reciprocal number of peak temperature versus slope

(2) Two ranges to reciprocal number of peak temperature versus slope

Figure.2 The reciprocal number of thermal fatigue life versus reciprocal number of peak temperature.

(1) The thermal plastic life versus reciprocal number of peak temperature

(2) Reciprocal number of thermal fatigue life versus reciprocal number of peak temperature

Figure.3 Transition ranges to reciprocal number of peak temperature.

Table 1. Activation energy and coefficient value from each graph.

□ High Temperature Range			
A(Nf)	A(Ep)	B(Nf) J/mol	B(Ep) J/mol
-0.58	-2.77E+00	-3.80E+03	-2.38E+03
○ Low Temperature Range			
A(Nf)	A(Ep)	B(Nf) J/mol	B(Ep) J/mol
13.39	6.69E+00	-1.42E+04	-9.65E+03
● Transition Temperature Range			
Thermal fatigue life			
bn(Bn(T)) J/mol	an(Bn(T))	bn(An(T)) J/mol	an(An(T))
3.20E+03	4.67E+00	1.14E+04	-1.39E+01
Thermal plastic strain			
b _{Ep} (B _{Ep} (T)) J/mol	a _{Ep} (B _{Ep} (T))	b _{Ep} (A _{Ep} (T)) J/mol	a _{Ep} (A _{Ep} (T))
4.34E+03	2.82E+00	4.89E+04	-6.58E+01

However, Figure 4 shows thermal fatigue life versus thermal plastic strain. The red line shows power of experience data. But Fig.1, 2 and 3 show three range peak temperatures but if the diagram shows thermal fatigue life versus thermal plastic strain, there is no temperature ranges. From the Fig.1, 2 and 3 substitute Manson-Coffin's law then expression by (8) and (9). The transition range is calculating from (4) - (7) then putting to (8) and (9). The (12) and (13) are conjunction from (8) and (9). Table 1 shows ductile coefficient and index from expression (12) and (13).

Figure. 4 Thermal fatigue life versus thermal plastic strain

Calculate from the theoretical detail (12) and (13) single power function with a coefficient and index for over all ranges, in this case showing to Table 2. Coefficient and index values are same value from each peak temperature range. These values are quite smaller than experimental value. But these are 0.57 - 0.67 and 0.023 - 0.192 for FCD450 in alpha range ⁽⁴⁾. From the Table 2, ductile coefficients and ductile indexes are same as coefficient and index of general Manson-Coffin's law.

Figure 5 is shown by these values from Table 2, where white dot shows experiment data and black dot is calculation, triangle shows upper limit from reference ⁽⁴⁾, and rectangle is lower limit from reference ⁽⁴⁾. From Table 2, coefficient and index from experiment and calculation all exist inside the range between upper and lower limits. Therefore, represented by the general Manson-Coffin's law, the nature of monosemy in thermal fatigue is proved empirically and theoretically.

Table 2. Ductile coefficient and ductile index of each temperatures range.

□ High temperature range	
C_{p1}	K_{p1}
0.09	0.68
○ Low temperature range	
C_{p3}	K_{p3}
0.09	0.68
● Transition temperature range	
C_{p2}	K_{p2}
0.09	0.68
Experimental value in the study	
C_{p0}	K_{p0}
0.082	0.59
FCD450 in alpha experimentally ⁽⁴⁾	
C_p	K_p
0.0023 - 0.192	0.57 - 0.67

Figure 5. Thermal fatigue life versus thermal plastic strain with calculation

5. Conclusion

Research on ferrite ductile cast iron performs of thermal fatigue test; the following features of thermal fatigue are clarified in ferrite-matrix elevated temperature range.

Both of the thermally activated relations of the thermal plastic strain to cyclic peak temperature and of thermal fatigue life to cyclic peak temperature are obtained in Arrhenius expressions. And there are three thermally activation ranges and each range has its own Arrhenius expression.

- Here, the monosemousness in thermal fatigue is defined to the effect of only one selected variable on thermal fatigue life.
- Theoretical detail proves to monosemousness condition.
- The relationship between thermal plastic strain and thermal fatigue life throughout whole ranges can be expressed by Manson-Coffin's law with coefficient and index, there all peak temperatures in alpha-phase field.
- Namely, it is made clear that thermal fatigue life depends on monosemously on cyclic

thermal plastic strain, applying by Manson-Coffin's law.

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