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FEATURES ON THERMAL FATIGUE OF FERRITE MATRIX DUCTILE CAST IRON

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ABSTRACT

In the study, the thermal fatigue tests on ferrite matrix ductile cast iron were carried out as the specimens were axially constrained completely at room temperature. Then, the topics were studied as follows, the dependence of thermal fatigue life on the peak temperature of thermal cycle, the ordinary serration and the peculiar serration of thermal stress cycle, change of visual fatigue cracks and fracture pattern, the influence of dynamic strain aging, and microstructure change caused by polygonization or by $\alpha \Leftrightarrow \gamma$ transformation on thermal fatigue. Furthermore, the activation energy for thermal fatigue in Arrhenius equation in each temperature range was investigated and discussed.

KEYWORDS

Ductile cast iron, Thermal fatigue test, Fatigue life, Microstructure, Thermal stress, Thermal activation energy, Ordinary serration, Peculiar serration

INTRODUCTION

As known, ductile cast iron is stronger than conventional gray cast iron and it is superior in wear-resistance, shock, heat, cast-ability and price etc. what make it lead industrial material used widely. For example, it is utilized as heat-resisting material for some machinery components such as exhaust pipe and other engine parts of automobile. So, several studies on its strength at elevated temperature were reported [1～4]. Whereat, the phenomenon of stress serration versus strain appeared at temperatures from 423K to 673K and the brittleness at 673K were observed at ferrite cast iron. Regards to thermal fatigue on ductile cast iron, there were a few researches reported, so far [5,6,7]. In the report [5], the thermal fatigue test under the condition of completely constrained strain was carried out on ferrite matrix ductile cast iron and the Manson-Coffin's equation was introduced to conjecture the thermal fatigue life. It was reported [6] that fatigue crack growth rate in out-of-phase type was faster than that in in-phase type. The another report [7] showed that the thermal fatigue life was affected by the peak temperature of thermal cycle, by heating duration and peak-temperature holding duration, and the effect of phase type of temperature versus stress, and then proposed the life prediction equation.

In the study, thermal fatigue tests were carried out on ferrite matrix spheroidal graphite cast iron under the condition of complete constrained strain, which was set up at zero at room temperature, and the lowest temperature was kept at 323K in each thermal test cycle. And the several features on thermal fatigue were studied.

EXPERIMENTAL PROCEDURE

Specimen

Chemical composition and static mechanical properties of experimental material, which was classified into FCD400 in JIS, are shown in Table 1 and Table 2 respectively. The diameter of graphite and that of ferrite grain are about 22 μm and about 27 μm, respectively.

Table 1 Chemical composition of specimen of ductile cast iron (mass%).

C	Mg	Mn	Si	P	S	Fe
3.68	0.041	0.14	3.09	0.065	0.007	Residue

Table 2 Static mechanical properties on specimen of ductile cast iron.

Tensile strength (MPa)	0.2%Proof strength (MPa)	Elongation (%)	Reduction rate (%)
408	320	20	17

Each specimen for thermal fatigue test was machined from a cast rod, with 30 mm in diameter and 170 mm in length. And the specimen configuration was with gage length of 15 mm and central diameter of 10 mm. The central part 35 mm long was axially machined with the curvature radius of 60 mm. And its surface roughness was finished below 0.2 μm. To avoid the breaking out of gage length by bulging phenomenon and/or by high temperature brittleness during thermal fatigue test, such curvature was given. In this case, the stress concentration factor was about 1.035 [8].

Experimental Equipment

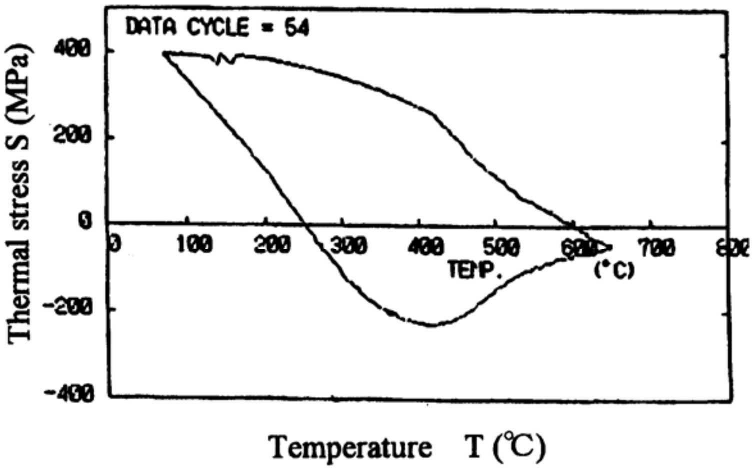
The test machine utilized in the thermal fatigue tests was a hydraulic servo-pulsar, Shimazu EHF-ED100kN-TF-20L, with maximum load capacity of±10t. Temperature of specimen was measured by an R-type thermocouple with 0.3 mm in diameter, which was spot-welded at a point on the central circumferential surface of specimen. The specimen was repeatedly heated by high frequency induced alternate current and cooled by compressed air blowing. The scattering of temperature along gauge length was within ±5K. During thermal fatigue test, the output of displacement of gage length from strain transducer was controlled to be zero, so the test was constrained completely. In this way, the thermal stress was generated repeatedly by thermal cycles. The load was detected by load-cell. And all data was treated by microcomputer.

Experimental Condition

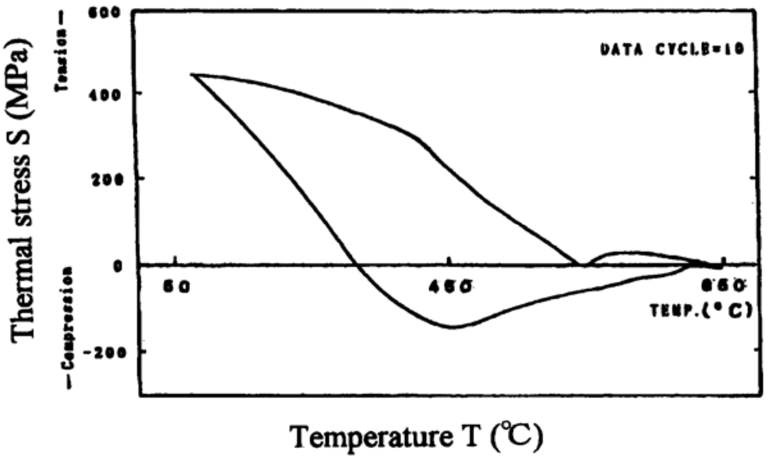
The repetition of thermal cycle, heating from lowest temperature up to peak temperature then cooling down to lowest temperature in triangle wave, was given to the completely constrained specimen. Heating and cooling speed was kept at 3.1 K/s and holding duration was zero at the peak or at the lowest temperature. In all thermal fatigue tests, the lowest temperature was fixed at 323K and peak temperature was selected as variable parameter, from 673K to 1223K. The thermal fatigue life was decided by the number of thermal cycles, when the peak stress was equal to or less than the value of 3/4 the maximum of peak tensile thermal stress.

EXPERIMENTAL RESULTS AND DISSCUSSION

Thermal Stress Cycle



a) 923K



b) 1123K

Fig.1 Examples of thermal stress cycle of peak temperature at a) 923K and at b) 1123K and at the lowest temperature of 323K in thermal fatigue test.

One example of thermal stress cycle on the thermal fatigue test of peak temperature at 923K was shown in Fig.1a), in which the ordinate showed thermal stress generated in gauge length of specimen and abscissa showed the temperature. The cycle was described in counter clockwise in the thermal fatigue tests. While temperature ascending from the lowest temperature, the thermal stress descended due to compression of thermal expansion of specimen; as the temperature ascending further until the peak temperature, then reversely the stress ascended due to reducing of yield stress of specimen. While the temperature started falling, the thermal stress ascended due to contraction of specimen; with further falling of temperature, the thermal stress increased. And when the thermal stress became larger than the yield point of specimen, then the curve rose gently until the lowest temperature. Namely, the thermal stress was compression as heating and in the upper half of cycle toward to tension as cooling which meant that the thermal fatigue test was belong to out-of -phase type. In this case of the peak temperature at 923K, the serration appeared at peak left side of the curve. Because the flow resistance of specimen became smaller at elevated temperature, the absolute value of the maximum thermal stress in tension was larger than that of the minimum in compression in each thermal fatigue cycle.

The shape of the thermal stress cycle at the peak temperature above 1098K was different from others at the other peak temperatures. Because the microstructure of specimen transformed from ferrite to austenite, the sudden shrink of specimen happened to increase the thermal stress, and vice versa.

Ordinary Serration in Thermal Stress

There was no any special phenomenon found in the thermal stress cycle at the peak temperature from 673K to 753K. At the peak temperature from 773K to 823K, the small serration like ripple was found near the peak stress in the initial life stage, but the serration disappeared in intermediate life stage. And the ordinary serration appeared at the peak temperature from 843K to 1078K. The serration appeared within the temperature range from 333K to 458K in each cycle. As known, the ordinary serration was caused by the dynamic interaction between the migration of dislocations and the interstitial atoms in crystal.

Visual Fatigue Crack

After the visual crack was found, it took tens to hundreds cycles for the specimen to fail, in the peak temperature range from 673K to 773K. However, in the peak temperature range from 798K to 1223K, the specimen broke just soon after the crack was detected. In the case from 673K to 773K, the material was strengthened by the solid solution that easily initiated a leading crack and the propagation of the crack took a large part of fatigue life. As for the case from 798K to 1223K, the specimen became easy to flow by the softening of crystals and grain boundaries themselves, and easy to cause brittle oxide layer at specimen surface, so that many micro-voids and micro-cracks were generated and grew. The crack coalescences occurred. And the cracks became visual at the final stage of fatigue life just before its failure. A great deal of hair like cracks appeared on the surface of specimen above 1023K.

Peculiar Serration

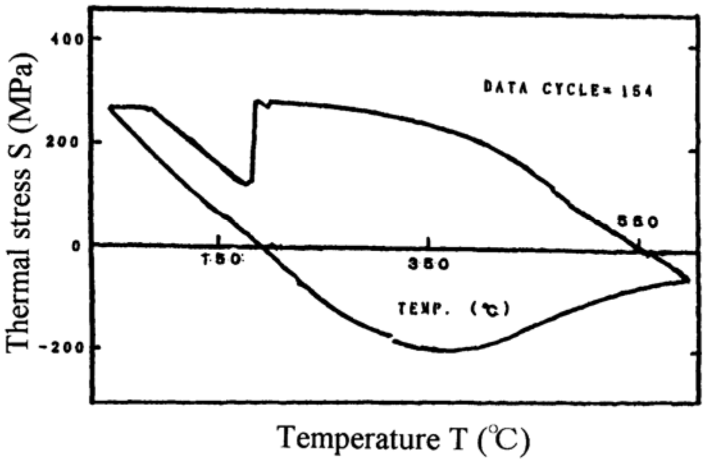


Fig.2 An example of the peculiar large serration appears in thermal stress cycles of thermal

fatigue of the peak temperature at 843K.

Here, particularly being worthy of note, a peculiar large serration was discovered at the peak temperatures above 798K, as shown in Fig.2, at several final cycles, namely at the final stage of fatigue life. The peculiar serration led to the rupture of specimen. This kind of serration appeared at temperature range from 333K to 538K and stress range from 468MPa to 670MPa, in the thermal cycle. But this kind of peculiar serration disappeared at the peak temperature below 798K or above 1098K.

As mentioned above, the fact of the phenomenon of the peculiar serration coincided with the appearance of ordinary serration. So the peculiar serration might be related to dynamic strain aging. The peculiar serration may be caused by the formation of macro-crack through the process of initiation, growth, coalescence of micro-voids or micro-cracks and the dynamic strain aging mechanism. Particularly, it could be construed that the “abrupt big fall”, peculiar serration, was caused by the abrupt coalescence of micro-cracks and micro-voids. And/or the peculiar serration was caused by the great deal of instantaneous migration of a large number of dislocations, which were multiplied and stored in material and were adhered by activated interstitial atoms at the final stage of fatigue life. In the final fatigue stage these adhered dislocations were released abruptly.

Fatigue Life versus Peak Temperature

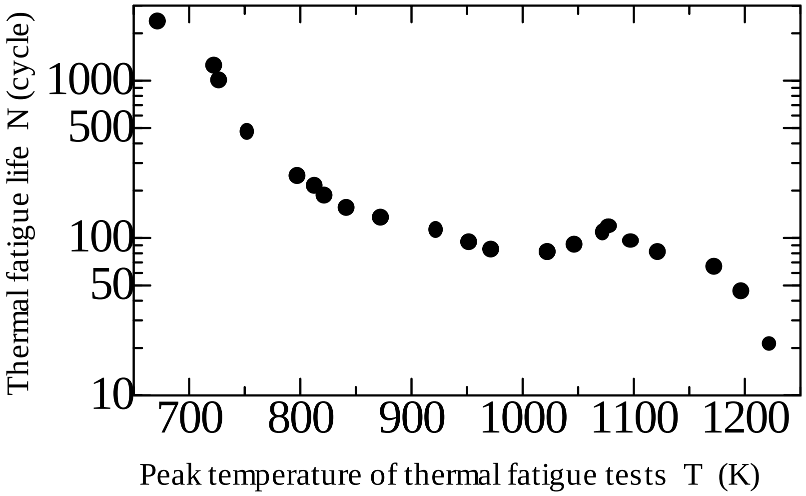


Fig 3 The curve of the thermal fatigue life versus the peak temperature on ferrite ductile cast iron.

As shown in Fig.3, the relationship of thermal fatigue life to the peak temperature could be divided into 3 ranges, the first range was α range from 673K to 1023K where the life decreased with the increase of peak temperature, the second was $\alpha \Leftrightarrow \gamma$ range from 1023K to 1073K where the life increases with increase of temperature and the third was γ range above 1078K that was the same as the first range. The relationship in each range could be represented by the equation (1),

$$N = A \cdot \exp(Q / T) \tag{1}$$

where, N: thermal fatigue life, R: gas constant, 8.31451 J/mol･K, Q : thermal activation energy, KJ/mol and A: coefficient. The relationship of fatigue life versus the peak temperature was linear in each range. But in the first range the activation energy was large at low temperature and became smaller at high temperature. The values in each range are as shown in Table 3.
The equation (1) was the same form as Ahhrenius equation that clearly showed the thermal fatigue was affected by the micro-mechanism of thermal activation process.

Table 3 The values of activation energy and coefficient of each ranges in equation (1).

	Lower α range	Higher α range	All α range	α ⇔ γ range	γ range
Q:	83	26.7	58	−63	109
A:	9.7×10^{-4}	0.3	5.5×10^{-2}	1.3×10^{5}	6.5×10^{-4}

SUMMARY

By performing thermal fatigue tests on ferrite matrix ductile cast iron, the main results are attained as follows.

1. The shape of thermal stress cycle is affected by the transformation of microstructure.
2. The ordinary serration appears at peak temperatures from 773K to 1078K.
3. The peculiar serration appears at peak temperatures from 843K to 1078K.
4. Visual crack is found early and lasts long at low peak temperatures in the test. And at high temperatures, visual crack is found at final stage just before the failure of specimen.
5. The relationships of peak temperature to fatigue life are attained.

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