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Collective evolution of surface microcrack for compacted graphite iron under thermal fatigue with variable amplitude

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Abstract

With the growing demand of good performance and high reliability of the heated components, the cracking failure caused by the complex thermal loading of variable amplitude has become a crucial problem. The collective evolution of surface microcrack for compacted graphite iron under thermal fatigue with variable amplitude is studied in this paper, which is induced by pulsed laser. The thermal microcrack is analyzed with statistic method and fractal method systematically. The result shows that, the secondary microcrack is the primary crack pattern, and the number of main microcrack is the least. As the test goes on, the fractal dimension increases following the Hill's function. Furthermore, the effect of maximum temperature $T_{\max}$ and superimposed number N_{HCF} on the crack evolution is investigated. $T_{\max}$ in the heating stage mainly affects the number of main microcrack. With the increase of plastic strain amplitude, the fractal dimension increases exponentially, and gradually tends to be the critical fractal dimension D_0 of 1.395. The superimposed number N_{HCF} in the high-cycle stage mainly affects the number of secondary microcrack. The fractal dimension increases exponentially with the increase of N_{HCF} , and tends to be the critical fractal dimension D_0 of 1.404. The analysis of the collective behavior of surface microcrack is helpful for evaluating the damage degree and predicting the lifetime, which can be applied to other materials working under thermal loading of variable amplitude.

Keywords

Thermal fatigue, Variable amplitude, Surface microcrack, Collective evolution, Compacted graphite iron

1. Introduction

Cracking is a common failure for the component working under thermal fatigue[1, 2]. From the crack initiation to the final fracture, the material undergoes microcrack initiation, microcrack growth, macrocrack initiation and macrocrack propagation[3-5]. Although the initiation and propagation of microcrack happen in the initial stage, they are crucial for the further development of crack damage. Researches[6, 7] show that the process of fatigue damage is caused by all cracks, and the microcracks formed on the surface show collective behavior and random statistical complexity[8]. Therefore, the usual fracture mechanics method, based on the situation of a single crack growth, is unsatisfactory for the analysis of microcrack network[9]. From the point of

physics, a cracked solid can be considered as a nonlinear dissipative system, and can be described by fractal theory[10]. Recently, many researchers have focused on the collective evolution of microcrack growth induced by mechanical fatigue[11-13]. However, little attention has been paid to the collective evolution of microcrack network induced by thermal fatigue.

Compacted graphite iron (CGI) is widely used in vehicle industrial, because of its low cost, outstanding casting properties, high thermal conductivity, advanced mechanical performance and so on[14, 15]. Due to its excellent mechanical properties at high temperature, compacted graphite iron is typically applied as the cylinder head of diesel engine. The engine usually works under transient operating conditions, including the start-stop cycles and the regular combustion cycles[16-18], which correspond to the low cycle fatigue (LCF) with larger temperature change ($\sim 400^{\circ}\text{C}$) and longer duration ($\sim 100\text{s}$), and the high cycle fatigue (HCF) with smaller temperature range ($\sim 40^{\circ}\text{C}$) and shorter duration ($\sim 0.1\text{s}$), respectively. Under the thermal loading of variable amplitude, serious cracking damage occurs. In recent years, the studies about the thermal fatigue resistance of cast iron are mainly induced by thermal loading of constant amplitude[19-21]. Wang et al.[22] studied the characteristics of microcrack initiation process for cast iron materials under thermal shock test, and the microcrack networks were analyzed by the quantitative statistic method and fractal method. The thermal loading is usually applied to the specimen periodically by induction heating and water quenching. However, due to the limitations of induction heating, temperature change within milliseconds is hard to achieve, and the operating condition of combustion cycle can not be simulated by the induction heating method.

In recent years, pulsed laser has been applied as one of the ideal heating source for the thermal fatigue experiment of variable amplitude[23, 24], due to its precise controllability for time and space. In comparison with the thermal fatigue test based on the application of continuous laser and beam transformation[25, 26], the main point of pulsed laser is the temporal distribution of laser spot, whereas the former is focused on the spatial distribution of laser spot. Obviously, the pulsed laser heating is more suitable for the actual working condition. Pan et al.[27, 28] developed experimental system of thermal fatigue based on pulsed laser, and thermal cyclic loading of variable amplitude was realized by the proposed method. However, the influence factor of microcrack evolution for compacted graphite iron working under complex LCF and HCF conditions is still not completely understood and studied adequately. What's more, the collective evolution of surface microcrack, especially during the microcrack initiation and propagation stage, is still questionable and uncertain.

The main objective of this paper is to analyze the microcrack evolution of compacted graphite iron during thermal fatigue of variable amplitude, which is induced by millisecond pulsed laser. By the optimization laser parameter and the integration of closed-loop control system, thermal fatigue tests with different experimental parameters are carried out. The effect of the maximum temperature and the number of superimposed cycle on the collective behavior of surface microcrack are analyzed quantitatively, by introducing the statistic method and the fractal method into the analysis. What's more, the relationship between the microcrack evolution and the fractal dimension is discussed.

2. Experimental procedure

The investigated material in this study is an EN-GJV-450 (compacted graphite) cast iron. The

chemical composition and material properties are listed in Table 1 and Table 2. The microstructure of GJV-450 material is displayed in Fig. 1. The graphite is predominantly in a worm-like form with rounded edges (average length of 100 μm), and intermediate in a flaked or spheroidal form. In addition, the samples are chemically etched in order to show and measure the size of eutectic cluster, with three different microstructural images. Average size is calculated based on the above three value, which is about 300 μm . The specimens are cut into a cylindrical shape, with the diameter of 18mm and the thickness of 5mm. The sample surface is polished with sandpaper, and cleaned carefully before the test.

Table 1

Chemical composition of GJV-450 (wt%).

C	Si	Mn	S	P	Cu	Fe
3.27	2.29	0.40	0.017	0.028	0.86	Bal.

Table 2

Material properties of GJV-450 material.

T (K)	K (W/m $\cdot$ K)	C (J/kg $\cdot$ K)	ρ (kg/m 3)	ν	α (K $^{-1}$)	E (GPa)
293	38.0	470	7079	0.25	/	156
373	34.9	500			11.7×10^{-6}	152
673	31.6	595			13.3×10^{-6}	148
823	29.5	675			14.2×10^{-6}	90

Fig. 1. Typical microstructure of GJV-450 material. (a) as polished conditions; (b) after etching.

A Nd:YAG millisecond pulsed laser with wavelength of 1064 nm is applied as the heat source in the thermal fatigue system with variable amplitude, the detailed information of this experimental system is presented in the author's former paper[27]. The experimental system mainly includes six parts, such as pulsed laser, temperature measure instrument, in-situ observation microscope, cooling recirculating device, sample holder and related control software. Surface temperature in the center of specimen is detected by infrared pyrometer, and serves as the process signal transferred to the control software. Compressed air works as the cooling medium to maintain the desired temperature gradients across the sample, which is supplied to the backside of specimen through a special designed nozzle.

In order to simulate the actual working conditions with thermal cycling with different amplitude, more than one set of laser parameters are selected during the experiment process. The combination of the laser parameters and the cooling method is set up according to the requirements, in order to reproduce the same temperature histories with the heated components in combustion engines. To produce the thermal cycles with variable amplitude, a complete testing cycle includes three parts: the heating stage, the high-cycle stage, and the cooling stage, as shown in Fig. 2. The minimum temperature T_{min} and the maximum temperature T_{max} in heating stage is 100°C and 450°C , respectively, if there is no special statement. Therefore, the amplitude of low-cycle stage is the difference between T_{max} and T_{min} , which is about 350°C . The pulse width, repetition rate and average laser power are selected to be 8ms, 20Hz and 180W, respectively, and the temperature-controlled mode is adopted at this stage. Once the sample temperature reaches T_{max} , the laser parameters are changed automatically to another set for smaller temperature change in the high-cycle stage, in which the pulse width, repetition rate and average laser power are 10ms, 4Hz and 60W, respectively. The amplitude of high-cycle stage is about 50°C . After completing the prescribed cycle (10^3 times if there is no special statement) in this stage, the cooling medium is provided automatically, and the cooling stage begins. When the surface temperature drops to T_{min} , a whole cycle of variable loading is completed.

Fig. 2. Schematic diagram of testing cycle for different T_{max} .

In this paper, the surface crack evolution is observed after the specific cycles with optical microscope (OM), in order to analyze the crack information and to calculate the fractal dimension. Firstly, image processing software such as PHOTOSHOP is used to identify the microcrack contour. And then, the MATLAB program is applied for the binary processing of the extracted profile, and the calculation of fractal dimension based on the pixel.

3. Results and discussion

3.1 Process of microcrack evolution

Fig. 3 shows the optical micrograph of the cross section in the center after 40 cycles. A

surface oxidation layer of about $25\mu\text{m}$ is highlighted in Fig. 3, and two cracks are also pointed out. During the test, the surface is oxidized severely, causing the surface graphite decarburization and the oxidation holes formation[29, 30]. At the bottom of the oxidation holes, which are the stress concentration areas in the microstructure, thermal cracks nucleate and propagate along the depth direction. The depth of two depicted crack is $200\mu\text{m}$ and $220\mu\text{m}$, respectively. Considering the sample thickness of 5mm , the induced microcrack can be defined as surface microcrack.

Fig. 3 Microstructure of the cross section in the center after 40 cycles, showing surface oxidation and microcracks.

The process of microcrack evolution is presented in Fig. 4. Because of long time exposure to high temperature environment containing oxygen, the sample surface is severely oxidized. In order to quantitatively analyze the thermal fatigue microcrack, the image processing software is used to extract the contour profile of surface microcrack, as shown in Fig. 5. Considering the initial specimen with no crack, although the equivalent stress does not exceed the yield limit of cast iron, the slip band will occur in the local area of sample surface, especially within the laser spot, due to the inevitable inhomogeneity of the structure or properties. The sample surface is under plane stress state, so it is easy for plastic slip[4]. Repeated cyclic slip strain induces the slip zone of metal, and forms the initiation core of microcracks. As shown in Fig. 5(a), after the first cycle, the microcrack initiation process has begun, indicating that for cast iron material, it is easy to cause microcrack initiation under the thermal cyclic loading of variable amplitude. Accumulated thermal damage mainly includes plastic deformation produced by thermal loading of large amplitude, and elastic deformation caused by thermal loading of small amplitude. Once the microcrack initiates, it will extend along the slip surface, which is the shear stress surface in 45° with the principal stress axis. Once the microcrack initiates in a certain location, the stored strain energy will be transferred to the surface energy for a new crack. Therefore, it is difficult for other new microcrack to initiate around this position. It is found that the interaction between cracks influences the initiation stage rather than the growth stage[31]. After 20 cycles (as shown in Fig. 5(d)), because of the shielding effect, the microcrack initiation stage almost ends, and the microcrack growth stage begins. In addition, when the microcrack propagation in the depth direction is hindered, it is easier to form the microcrack network on the surface.

Fig. 4 Evolution of surface microcracks ($T_{\max}=450^{\circ}\text{C}$, $N_{\text{HCF}}=10^3$). (a) after 1 cycle; (b) after 2 cycles; (c) after 10 cycles; (d) after 20 cycles; (e) after 30 cycles; (f) after 40 cycles.

Fig. 5. Extracted profile of surface microcracks ($T_{\max}=450^{\circ}\text{C}$, $N_{\text{HCF}}=10^3$). (a) after 1 cycle; (b) after 2 cycles; (c) after 10 cycles; (d) after 20 cycles; (e) after 30 cycles; (f) after 40 cycles.

It can be seen in Fig. 5, the length of each microcrack is different. The distribution of microcrack length after different cycles is shown in Fig. 6. It can be seen that, the number of microcrack shorter than 0.1mm is the most, followed by the microcrack with length of 0.1~0.2mm and 0.2~0.3mm, and the number of microcrack longer than 0.3mm is the least. As illustrated above, the average length of graphite phase and eutectic cluster is 0.1mm and 0.3mm, respectively. Therefore, the crack shorter than 0.1mm can be defined as "secondary microcrack", which is equivalent to the size of graphite phase. The secondary microcrack usually appears in the bifurcation of intergranular microcrack in the iron matrix. The crack longer than 0.3mm can be defined as "main microcrack", which is larger than the size of eutectic cluster. The main microcrack mostly occurs between the adjacent eutectic clusters. The main microcrack tends to coarsen with the increasing cycle number, which is possible to become a main crack causing the final fracture. From the results demonstrated in Fig. 6, it can be seen that, the number of secondary microcrack and main microcrack increases as the test goes on. The growth rate is high in the first several cycles, and then decreases gradually. As the test goes on, the number of other microcrack increases generally. However, slight fluctuation is observed, which is due to the continuous propagation.

Fig. 6. Distribution of crack length after different cycles ($T_{\max}=450^{\circ}\text{C}$, $N_{\text{HCF}}=10^3$).

It is worth mentioning that, the difference between the results from this paper and the reference [22] mainly comes from the different concept of crack length. The result of 0.3mm in this paper is the crack length of single crack, whereas the result of 0.119mm in the reference [22] is the average value of almost 70 cracks. Actually, if looking at the Fig.6 and Fig.7 in the reference [22], several cracks of about 0.3mm can be found. Therefore, the difference seems not obviously. In addition, the result from the reference [27] is based on the thermal fatigue test of low-cycle, whereas the result from this paper is based on the thermal fatigue test of combined cycle. Therefore, the similar results after different cycles can be expected. However, the crack patterns of the two kinds of tests are different, which is discussed in this paper.

From the above analysis, there are two characteristics to describe the evolution behavior of thermal microcrack. Firstly, the path of microcrack propagation is not straight, which mainly occurs along the tip of graphite phase and interconnects with each other. Secondly, because of the superimposed cyclic loading, microcrack bifurcation phenomena can be observed. The thermal microcracks show complex collective behavior from initiation to propagation. The whole process is affected by the microstructure, stress strain state and so on. In the case of multiple microcrack propagation, it is not appropriate to use da/dN to describe the crack growth rate, because the crack length is hard to measure. Former results show that, the cracked solid can be regarded as nonlinear dissipative system[32, 33], showing good statistical self-similarity. As a result, fractal theory can be used for microcrack analysis. It provides a new method for quantitatively describing and characterizing the evolution process of microcracks from a collective point. In the fractal theory, fractal dimension is a basic concept quantitatively representing the random shape and phenomenon of self-similarity[34-36].

The fractal dimension of microcrack images are calculated and shown in Fig. 7. It can be seen that, the fractal dimension increases as the cycles going in a non-linear way. In the first several cycles, the fractal dimension increases rapidly, and then increasing tendency slows down. After 40 cycles, the fractal dimension tends to be stable, and approaches to a constant eventually. The growth curve of fractal dimension presents the characteristics of Hill's function, while the coefficients are obtained by fitting and shown in the table in Fig. 7. The "END" value can be considered as the extreme of fractal dimension which is related to the final damage state[8]. The fractal dimension is a function of time, representing the accumulation of thermal fatigue damage, which is an irreversible process of entropy increasing[37, 38]. In the process of microcrack

initiation and propagation, the entropy of the whole specimen system is constantly changing. It is concluded that the change of fractal dimension reflects the gradual evolution of microcrack during the thermal fatigue process, which includes the information of crack density and average crack length. Therefore, the fractal dimension can be regarded as a parameter which represents the damage degree of specimens.

Fig. 7. Variation of fractal dimension with cycles ($T_{\max}=450^{\circ}\text{C}$, $N_{\text{HCF}}=10^3$).

In order to identify the influence factor of microcrack evolution under the complex LCF and HCF conditions, different experimental parameters are selected in the thermal fatigue test. The first parameter is the maximum temperature $T_{\max}$ in the heating stage, which influences the damage degree significantly. Different $T_{\max}$ is realized by changing the laser parameters, whereas the minimum temperature $T_{\min}$ keeps unchanged, as schematically shown in Fig. 2. The second parameter is the superimposed number N_{HCF} in the high-cycle stage, which is one of the important characteristic of variable amplitude. Different N_{HCF} is achieved by controlling different duration of pulsed laser in the high-cycle stage, once the pulse repetition rate keeps as 4Hz, as schematically shown in Fig. 8.

Fig. 8. Schematic diagram of testing cycle for different N_{HCF} .

(a) smaller superimposed number $N_{\text{HCF}1}$; (b) larger superimposed number $N_{\text{HCF}2}$.

3.2 Effect of maximum temperature

In order to investigate the effect of maximum temperature $T_{\max}$ on the microcrack evolution, thermal fatigue experiments with different $T_{\max}$ are carried out. Different cyclic temperature difference is achieved by changing $T_{\max}$. Therefore, the thermal cyclic loading with different strain amplitude can be applied to the specimen surface. $T_{\max}$ is set as 350°C, 400°C, 450°C and 500°C, respectively.

The distribution of microcrack length under different experimental parameters is statistically analyzed and shown in Fig. 9. The length of surface crack is mainly less than 0.1mm, whereas the number of main microcrack is the least. Generally, the number of all kinds of microcrack increases with the test going on, except for several fluctuations. Among all cracks, the increase of main microcrack is obvious. When $T_{\max}$ is 350°C (seen in Fig. 9(a)), there is only one main microcrack after 40 cycles. When $T_{\max}$ increases to 500°C (seen in Fig. 9(d)), nearly 10 main microcracks occurred after 40 cycles. It can be seen that the change of $T_{\max}$ significantly influences the evolution of main microcrack.

Fig. 9. Length distribution of microcracks after specific cycles for different $T_{\max}$.

(a) $T_{\max}=350^\circ\text{C}$; (b) $T_{\max}=400^\circ\text{C}$; (c) $T_{\max}=450^\circ\text{C}$; (d) $T_{\max}=500^\circ\text{C}$.

Due to the randomness of graphite distribution, the microcrack number of each sample is quite different under these four experimental conditions. Therefore, the comparison of microcrack ratio is more meaningful than the microcrack number. The microcrack ratio means the ratio of the number of specific microcrack and the total microcrack. The ratio of main microcrack after 40 cycles is calculated, and the relationship between the ratio and $T_{\max}$ is presented in Fig. 10. The ratio of main microcrack is only 0.01 when $T_{\max}$ is 350°C, while the ratio increases to nearly 0.18

when $T_{\max}$ increases to 500°C. When $T_{\max}$ is below 450°C, the ratio of main microcrack increases linearly with the increasing $T_{\max}$. When $T_{\max}$ exceeds 450°C, the growth rate slows down, and an inflection point is observed.

Fig. 10. Relationship between the ratio of main microcrack and $T_{\max}$.

The variation of fractal dimension for different $T_{\max}$ is demonstrated in Fig. 11, and the parameters of Hill equation are fitted and shown in Table 3. The larger the $T_{\max}$ is, the more microcracks form on the surface after the same cycles, and the larger the fractal dimension is. However, under the premise that $T_{\max}$ does not exceed the phase transition temperature of the material, the increase of $T_{\max}$ will not increase the fractal dimension indefinitely. After sufficient cycles, the fractal dimension for different $T_{\max}$ will eventually tend to be a stable critical value. The “END” value in Table 3 can be considered as this critical fractal dimension. The stress-strain state under different $T_{\max}$ is various, making the reason for the final fractal dimension complicated, especially if considering the nonlinear change of mechanical properties of cast iron at different temperatures.

Fig. 11. Variation of fractal dimension for different $T_{\max}$.

Table 3

Parameters of Hill equation for different $T_{\max}$.

Hill equation		$y=\text{START}+(\text{END}-\text{START}) * x^n / (k^n + x^n)$		
$T_{\max} (^{\circ}\text{C})$	START	END	k	n
350	1.214	1.330	5.776	0.7257

400	1.241	1.366	3.081	1.3650
450	1.249	1.394	4.077	0.9730
500	0.4308	1.434	8.09×10^{-3}	0.3876

The microcrack formed under thermal cycle of variable amplitude is short crack essentially, and the depth or length of crack is equivalent to the size of the plastic zone[39]. One of the main criteria for judging thermal fatigue resistance under multi-dimensional thermal stress, is the range of plastic strain $\Delta\varepsilon_p$, which can be used to determine the failure extent of the microcrack network. Once the microcrack network forms, the notch effect around the crack tip will amplify rapidly, and the stress near the microcrack network will eliminate. After that, the microcrack network will almost develop no longer, and the damage degree tends to be stable. The distribution of $\Delta\varepsilon_p$ for different $T_{\max}$ is simulated numerically, and the results are shown in Fig. 12. The detailed information of the numerical model can be found in the author's former paper[28]. It can be seen that, the larger the $T_{\max}$ is, the greater the amplitude of plastic strain is, causing larger plastic strain regions in the radial and axial direction, and inducing more serious thermal damage. As the test goes on, plastic strain accumulates in the specimen continuously, and cracks continue to propagate.

Fig. 12. Distribution of $\Delta\varepsilon_p$ for different $T_{\max}$. (a) along the distance from center on the surface; (b) along the depth from surface in the specimen center

From the above analysis, it is known that, the amplitude of plastic strain is different for different $T_{\max}$, and the fractal dimension of thermal microcrack is different. Therefore, the relationship between the fractal dimension and the amplitude of plastic strain after the same cycles can be expressed as shown in Fig. 13. Under the thermal cyclic loading of variable amplitude induced by pulsed laser, the fractal dimension of thermal microcrack increases exponentially with the amplitude of plastic strain. The fitting result shows that with the increase of the amplitude of plastic strain, the fractal dimension will gradually tend to be a stable value of 1.395, which can be defined as the critical fractal dimension D_0 . D_0 is not only a mathematical value, but also with specific meaning in physics[22]. In the process of microcrack evolution, it is assumed that the microcrack will not coarsen nor propagate into macrocrack. Because of the shielding effect, there will be a critical condition in the evolution process of microcracks. Under this condition, no new microcrack will initiate, and the specimen will have infinite lifetime, and the corresponding fractal dimension becomes the critical fractal dimension D_0 .

Fig. 13. Relationship between the fractal dimension and $\Delta\epsilon_p$.

The critical fractal dimension D_0 of vermicular cast iron under thermal shock induced by high frequency induction and water quenching is 1.42[22], which is slightly larger than the value obtained in this paper. The first reason is the different heating methods used. The heat influence depth of induction heating is much deeper than that induced by pulse laser heating. Therefore, the thermal damage is more serious and the corresponding D_0 is greater. The second reason is the different cooling methods applied. The cooling rate of water quenching is much higher than that of compressed air in this paper. The tensile stress produced in the cooling stage is greater, and the amplitude of plastic strain is larger, causing larger D_0 .

3.3 Effect of superimposed number

Due to the interaction between crack closure effect and variable loading, the influence of superimposed cyclic loading on the microcrack evolution is complicated, especially for the superimposed number N_{HCF} of high-cycle loading in each cycle. Schweizer et al.[40] indicated that, when the superimposed number of mechanical vibration was over 10^3 per cycle, obvious increase of crack growth rate could be observed. In order to study the influence of N_{HCF} on the microcrack evolution of variable amplitude, the duration of high-cycle stage is set as 125s, 250s, 1250s and 2500s, respectively, i.e., N_{HCF} is 5×10^2 , 10^3 , 5×10^3 and 10^4 , respectively. In addition, the other experimental parameters keep unchanged.

The distribution of crack length under different N_{HCF} is statistically calculated and demonstrated in Fig. 14. The length of surface crack is mainly less than 0.1mm, whereas the number of main microcrack is the least. After 1 cycle, the microcrack network has almost formed. After 20 cycles, the pattern of microcrack network remains unchanged. The increase of loading time mainly results in the initiation and propagation of secondary microcrack. When N_{HCF} is 5×10^2 (seen in Fig. 14(a)), there is only 20 secondary microcracks after 40 cycles. When N_{HCF} increases to 10^4 (seen in Fig. 14(d)), more than 55 secondary microcracks occurred after 40 cycles. It can be seen that the change of N_{HCF} significantly influences the evolution of secondary microcrack.

Fig. 14. Length distribution of microcracks after specific cycles for different N_{HCF} .

(a) $N_{HCF} = 5 \times 10^2$; (b) $N_{HCF} = 10^3$; (c) $N_{HCF} = 5 \times 10^3$; (d) $N_{HCF} = 10^4$.

The ratio of secondary microcrack after 40 cycles is calculated, and the relationship between the ratio and N_{HCF} is presented in Fig. 15. The ratio of secondary microcrack is only 0.3 when N_{HCF} is 5×10^2 , while the ratio is more than 0.65 when N_{HCF} increases to 10^4 . It can be seen that, the proportion of secondary microcrack increases obviously with the increase of N_{HCF} , and this effect becomes significant when N_{HCF} is larger than 10^3 , which is similar to the critical loading frequency found in the thermomechanical fatigue with superimposed mechanical vibration loading[40].

Fig. 15. Relationship between the ratio of secondary microcrack and N_{HCF} .

The variation of fractal dimension for different N_{HCF} is demonstrated in Fig. 16, and the

parameters of Hill equation are fitted and shown in Table 4. The larger the N_{HCF} is, the more the secondary microcracks form on the surface after the same cycles, the larger the fractal dimension is. When N_{HCF} is less than 10^3 , the fractal dimension increases sharply with the increase of N_{HCF} . When the N_{HCF} is larger than 10^3 , the increasing rate of fractal dimension gradually slows down with the increase of N_{HCF} . It can be seen that, the fractal dimension will not increase indefinitely at a specific T_{max} . After sufficient cycles, the fractal dimension for different N_{HCF} will eventually tend to be a stable critical value. The “END” value in Table 4 can be considered as this critical fractal dimension.

Fig. 16. Variation of fractal dimension for different N_{HCF} .

Table 4

Parameters of Hill equation for different N_{HCF} .

Hill equation	$y = \text{START} + (\text{END} - \text{START}) * x^n / (k^n + x^n)$			
N_{HCF}	START	END	k	n
5×10^2	1.206	1.371	21.32	1.163
10^3	1.249	1.394	4.077	0.973
5×10^3	0.0238	1.453	2.698×10^{-4}	0.250
10^4	0.3019	1.484	0.00101	0.239

Additional elastic strain is superimposed on the surface due to the application of thermal loading of small amplitude in the high-cycle stage. Although the elastic strain is below the yield limit of material, it does affect the resulting crack pattern and evolution behavior. The distribution of the amplitude of elastic strain $\Delta\epsilon_e$ is simulated with the numerical model in a former paper[28], and the results are shown in Fig. 17. Compressive elastic strain is produced in the center of specimen (seen in Fig. 17(a)), and gradually increases along the radial direction, finally is converted to tensile strain. It reaches the maximum near the position of $x/R=0.15$, and then decreases gradually. The amplitude of elastic strain almost drops to zero at the position of $x/R=0.35$. The compressive elastic strain is the largest on the surface. As the depth increases, the compressive strain gradually becomes tensile strain, as shown in Fig. 17(b). The maximum amplitude of tensile elastic strain occurs near the position of $y/H=0.1$ and then decreases gradually to zero.

Fig. 17. Distribution of $\Delta\epsilon_e$ for the superimposed cycle. (a) along the distance from center on the surface; (b) along the depth from surface at the center spot.

In order to obtain the critical fractal dimension D_0 at a specific T_{max} , the relationship between the fractal dimension and N_{HCF} after the same cycles is shown in Fig. 18. The fractal dimension increases exponentially with the increase of N_{HCF} . When N_{HCF} is greater than 2×10^3 , with the increase of N_{HCF} , the fractal dimension will gradually tend to be a stable value of 1.404. Similarly, this stable value can be defined as the critical fractal dimension D_0 . When T_{max} is 450°C , the critical N_{HCF} is about 2×10^3 .

Fig. 18. Relationship between the fractal dimension and N_{HCF} .

The collective evolution of surface microcrack follows specific rule, which is helpful for evaluating the damage degree and predicting the lifetime. Firstly, according to the actual working conditions, the thermal fatigue test is carried out in the laboratory, in order to obtain the information of microcrack evolution, such as the variation of fractal dimension and the critical fractal dimension D_0 . Secondly, the damaged surface of actual component is analyzed by the fractal theory, and the fractal dimension is calculated. After that, the fractal dimension of damaged component is compared with results obtained in the laboratory, thus predicting the remaining life and failure probability. Similarly, it is suitable for other materials, such as Aluminium alloy, superalloy, thermal barrier coating and so on, which are also suffered from the cyclic damage induced by thermal loading of variable amplitude.

4. Conclusion

In this paper, the collective evolution of surface microcrack for compacted graphite iron under thermal fatigue with variable amplitude is studied. According to the characteristic parameters during the thermal cyclic loading of variable amplitude, the influence of maximum temperature $T_{\max}$ and superimposed number N_{HCF} on the microcrack evolution is analyzed. The main conclusions are listed as following:

(1) Under the thermal cyclic loading of variable amplitude, microcrack network forms easily on the surface after the first several cycles for cast iron. Among all the thermal microcracks, the number of secondary microcrack is the most, and the number of main microcrack is the least. In the first several cycles, the fractal dimension increases rapidly, and then slows down. After 40 cycles, the fractal dimension tends to be stable, and is eventually close to a constant.

(2) The maximum temperature $T_{\max}$ in the heating stage mainly affects the number of main microcrack on the surface. When $T_{\max}$ is below 450°C , the ratio of main microcrack increases linearly with the increase of $T_{\max}$. When $T_{\max}$ exceeds 450°C , the increase rate will slow down. The greater the $T_{\max}$ is, the more the energy provides for the thermal failure, and the more the amplitude of plastic strain accumulates per cycle. The fractal dimension increases exponentially with the increase of the amplitude of plastic strain, and gradually tends to be the critical fractal dimension D_0 of 1.395.

(3) The superimposed number N_{HCF} in the high-cycle stage mainly affects the number of secondary microcrack on the surface. The increase of the superimposed number N_{HCF} leads to significant increase in the ratio of secondary microcrack, and this effect becomes obvious especially when N_{HCF} is larger than 10^3 . With the increase of N_{HCF} , the fractal dimension increases exponentially. Once N_{HCF} is larger than 2×10^3 , the fractal dimension will tend to be a critical fractal dimension D_0 of 1.404 with the increase of N_{HCF} .

(4) The analysis of the collective behavior of surface microcrack is helpful for evaluating the damage degree and predicting the lifetime, which can be applied to other materials working under thermal loading of variable amplitude.

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Highlights

- The collective evolution of surface microcrack is studied systematically.
- As the test goes on, the fractal dimension increases following the Hill's function.
- $T_{\max}$ in the heating stage mainly affects the number of main microcrack.
- N_{HCF} in the high-cycle stage mainly affects the number of secondary microcrack.
- The results help to evaluate damage degree and predict lifetime of material.