Evaluation of Fatigue Limit of Spheroidal Graphite Cast Iron

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The fatigue limits of various spheroidal graphite cast irons were determined under completely reversed plane bending condition. The relationships between the fatigue limit and microstructural factors such as graphite nodule diameter and matrix hardness were clarified, and the prediction equations of the fatigue limit of the irons were determined. It is observed that the fatigue limit strongly depends on maximum nodule diameter presumed by using extreme statistics, because fatigue cracks initiate from larger graphite nodules just below the specimen surface prior to others. The fatigue limit can be significantly improved by the hardening matrix only in the specimens with a fine nodule size. Austempered cast iron has a higher fatigue limit than other irons although having the same matrix hardness. As a consequence of the quantitative analysis, the prediction equations of the fatigue limits of spheroidal graphite cast irons are given.

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I. Introduction

Spheroidal graphite cast iron has been used widely as an engineering material, because a much wider range of mechanical properties can be achieved by heat treatment. In particular, the interest in austempered spheroidal graphite cast iron, which has outstanding properties of high strength and ductility approachable the properties of a heat-treated wrought steel, has increased for the recent few years. However, it is well known that heat treatment which raises the tensile strength does not cause the fatigue strength in proportion to the increase in tensile strength, and may lower the endurance limit in some cases. While, it is often stated that fatigue accounts for at least 90% of all service failures due to mechanical causes⁽¹⁾. Therefore, to understand the relationships between static properties or microstructural factors and fatigue properties is very important.

The fatigue properties of spheroidal graphite iron were related to graphite morphology including count, size, form (nodularity) and its distribution, and matrix characteristics including hardness, grain size and structural non-uniformity caused by segregation of alloy elements such as manganese, molybdenum. Shiota and Komatsu⁽²⁾ have observed that the reduction in graphite nodule diameter results in reducing the ferritic grain size and increasing the fatigue strength. Niimi *et al.*⁽³⁾ reported that fatigue strength decreases in proportion to the increase in graphite nodule size, but becomes constant where graphite nodule diameter is over 40 μm in unnotched specimens regardless of the matrix structure. Sofue⁽⁴⁾⁻⁽⁶⁾ measured fatigue properties of ferritic and quenched/tempered irons. It was shown that the fatigue limit increases with increasing matrix hardness up to a Vickers

hardness of approximately 500. The fatigue limit decreased with increasing nodule size also. Nonmetallic inclusions had a remarkable effect to lower the fatigue strength, especially when matrix hardness was high. Janowak *et al.*⁽⁷⁾ concluded that fatigue limit is increased with increasing matrix hardness, pearlite content and graphite nodule count. Also, it was clear that increasing quantities of non-nodular graphite or having lower nodularity in a pearlitic iron caused a progressive decrease in unnotched fatigue limit, as reported by Fuller⁽⁸⁾. Voigt *et al.*⁽⁹⁾⁻⁽¹²⁾ have investigated crack initiation and propagation in various spheroidal graphite cast irons with the as-cast, fully pearlitic, quenched/tempered and dual matrix.

These results gave a qualitative understanding of the fatigue properties of the irons. For the iron to be available extensively as a new kind of engineering material, however, a mere qualitative comprehension of the fatigue properties is not able to meet the demands. Therefore, it is very important to quantitatively understand the relations between the fatigue properties and the microstructural factors. This paper presents the fatigue properties of spheroidal graphite cast iron in terms of variables of graphite nodule size and matrix structure or hardness.

II. Experimental Procedures

Pig iron, return materials and Fe-Si alloy were melted by a cupola furnace which is used to produce automobile parts. Commercial Mg-RE-Ca-Fe alloy (1.3 mass%) was added at 1773 K for spheroidizing, and Fe-75 mass%Si alloy (0.5 mass%) was added into the melt for post inoculation. Chemical composition of the iron is: 3.7 mass% carbon, 2.7 mass% silicon, 0.3 mass% manganese, less than 0.04 mass% phosphorus, less than 0.01 mass% sulfur and 0.037 mass% magnesium.

To change the graphite nodule size, the melt was

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poured into four kinds of Y-type molds, as shown in Fig. 1, including three kinds of sand molds 60 mm, 35 mm and 11 mm in thickness, and one kind of permanent mold 11 mm in thickness, respectively.

Roughly-worked tensile and reversed plane bending fatigue specimens, which are just bigger in dimensions than those actually used in their tests, as shown in Fig. 2, were machined from each Y-type block. Then, to change the matrix structure, heat treatments such as quench/tempering, austempering and annealing were performed. The heating cycles are shown in Fig. 3. The tempering temperature after quenching was varied from 473 to 773 K. In the austempering treatment, the specimens were quenched at 1173 K into a salt bath maintained at a temperature in the range from 613 to 683 K, and austempered at this temperature for 1 h. As-cast iron was also used.

To maintain the surface condition constant, all the specimens were polished as smooth as mirror by buffing. Completely reversed plane bending fatigue tests were carried out on plane bending fatigue testing machine (98 J and 2000 rpm). Fatigue limit is defined as the maximum stress of which the number of cycles reached 10^7 stress cycles with no failure.

Fig. 1 Shape and size of Y-block.

Fig. 2 Shape and dimensions of tensile and fatigue specimens.

Fig. 3 Schematic illustration of the heat treatment cycle.

The graphite nodule size was quantified by using an image analyzing system. Diameters of the graphite nodules were measured for 60 fields in each specimen. The mean nodule diameter, d was determined from its frequency distribution diagram which is supposed to obey a normal distribution. The maximum nodule diameter, $d_{\max}$ was presumed from the cumulative distribution of the largest nodule diameter in each field, $d_{\max,i}$ ($i=1 \sim 60$) obeying extreme statistics⁽¹³⁾. Also, the micro-Vickers hardness (HV0.1) of the matrix near the graphite nodule was measured.

III. Experimental Results

Figure 4 shows typical graphite structures obtained from four kinds of molds. The graphite nodule is finest in permanent mold specimen. In sand mold specimens, the graphite nodule size increases with increasing mold thickness. It varied from $12.2 \mu\text{m}$ to $51.4 \mu\text{m}$ in mean nodule diameter according to the results measured by the image analyzing system.

For 32 series of the specimens with four kinds of graphite nodule sizes and eight kinds of matrix structures, the fatigue tests were carried out and their S-N curves were obtained. As an example, the S-N curves for specimens tempered at 673 K is shown in Fig. 5. The S-N curves differ by the mold type, although they have almost the same matrix structure. The same tendency is also observed in the rest of irons.

The fatigue limits of quenched/tempered, austempered, as-cast and annealed irons are plotted against the maximum nodule diameter and the mean nodule diameter as shown in Figs. 6–8, respectively. On the

Fig. 4 Typical graphite microstructures.

Fig. 5 S-N curves for specimens tempered at 673 K.

logarithmic scales, the fatigue limit linearly decreases with increasing maximum and mean nodule diameters for every iron having the same hardness level or matrix structure. For the annealed iron which has the lowest hardness, the fatigue limit falls down at a slow rate with increasing diameter. As the matrix hardness get higher, it shows greater dependence on the graphite nodule size. The quenched/tempered iron exhibits a most remarkable dependence, i.e. the greatest decrease with an increase in graphite nodule size.

In general, the fatigue limit of metals can be improved by hardening the matrix or increasing the tensile strength. The matrix hardness of the irons except for the as-cast and annealed irons differs by the heat treatment condition. Therefore, the matrix hardness must be taken into consideration in determining the contribution of the structural factor to the fatigue limit. The relationships be-

Fig. 6 Influence of the graphite nodule diameter on the fatigue limit of tempered spheroidal graphite cast iron.

Fig. 7 Influence of the graphite nodule diameter on the fatigue limit of austempered spheroidal graphite cast iron.

tween the fatigue limit and the matrix hardness in the quenched/tempered and austempered irons are shown in Figs. 9 and 10, respectively. It is clear that the fatigue limit is not significantly affected by the matrix hardness in the quenched/tempered and austempered irons.

IV. Discussion

1. Effect of graphite nodule size on the fatigue limit

It has been reported⁽¹⁴⁾ that fatigue cracks initiate mostly from the nodule/matrix interfaces perpendicular to the cyclic bending direction. This suggests that the fatigue limit of spheroidal graphite cast iron is greatly

Fig. 8 Influence of the graphite nodule diameter on the fatigue limit of annealed and as-cast spheroidal graphite cast irons.

Fig. 10 Relationship between the fatigue limit and the matrix hardness or tensile strength of austempered spheroidal graphite cast iron.

Fig. 9 Relationship between the fatigue limit and the matrix hardness or tensile strength of tempered spheroidal graphite cast iron.

dominated by graphite morphology.

In spheroidal graphite cast iron, the graphite nodule can be considered as a porosity⁽¹⁵⁾ because its strength is so low compared with the matrix that it is hardly subjected to stress. As shown in Fig. 11, when the plane with a hole receives a uniform tensile stress, σ , the stress concentrates at point A, and the maximum stress, $\sigma_{\max}$ becomes higher to 3σ . Thus it can be explained that fatigue cracks preferentially initiate from the graphite/matrix interface as a result of the stress concentration caused by graphite nodule. However, the stress concentration does not de-

Fig. 11 Stress distribution due to circular holes.

pend on the diameter. The reason why the fatigue limit decreases with increasing nodule diameter is not clear yet. This can be explained by examining the stress gradient around the graphite as follows.

The stress gradient χ at point A is given by the following equation:

$$\chi = 4.7/d \quad (1)$$

This equation means that the larger the diameter of the

hole, the smaller the stress gradient, hence a larger volume around a graphite nodule is subjected to a high stress. Consequently, there will be a greater probability of initiating a fatigue crack. The concept of a highly stressed volume is important when considering the stress gradients due to notches. On the other hand, once the fatigue crack initiated from the graphite nodule, the crack propagation would be faster with a larger nodule. The stress intensity factor, K , which defines the magnitude of the local stress around the crack tip, depends on loading, crack shape, and geometric boundary in the general form given by

$$K = f(g)\sigma\sqrt{\pi a} \quad (2)$$

where a is the crack length including the graphite nodule, $f(g)$ is the correction factor that depends on the specimen and crack geometry.

It has been proved by several investigators^{(16)–(18)} that the crack growth rate of the notched spheroidal graphite cast iron obeys the Paris' equation:

$$da/dN = C(\Delta K)^m \quad (3)$$

Therefore the larger nodule increases the stress intensity factor and the crack growth rate, resulting in reduction of the fatigue limit.

However in this study, as a result of observing the fatigue crack initiation at the specimen surface, the fatigue cracks do not always initiate from the larger graphite nodules. The cracks initiated from the smaller nodules or somewhere in the matrix were also observed. The specimen in which the fatigue cracks initiated at the smaller nodule or the matrix near the eutectic cell boundary was layer-by-layer polished for 30 μm in depth from the surface to observe the interior, as shown in Fig. 12. Actually, the cracked smaller nodule is the larger one as shown in Fig. 12(a), and there is a graphite nodule just below the cracked matrix as shown in Fig. 12(b), which could not be seen from the surface. It is in good agreement with that defects are most detrimental to fatigue when they are situated just below the surface as reported by Endo⁽¹⁹⁾.

2. Effect of matrix hardness and static strength on the fatigue limit

The relations between the fatigue limit and the matrix hardness of all kinds of spheroidal graphite cast irons are shown in Fig. 13. The data on the austempered specimens with solid marks will be discussed in details later, because the austempered irons have a distinctive matrix structure. For the 11 mm permanent mold specimens with the finest graphite nodule size (mean diameter: about 12 μm), the fatigue limit rapidly increases with increasing hardness. When the hardness exceeds about HV500~600, the fatigue limit tends to deteriorate. For the larger nodule size, the increasing rate of the fatigue limit by hardening the matrix becomes slower. Especially for the 60 mm sand mold specimens with the largest nodule size (mean diameter: about 50 μm), the fatigue limit is not improved at all by hardening the matrix and con-

Fig. 12 Graphite morphology under the specimen surface in which the micro-cracks are initiated.

Fig. 13 Relationship between the matrix hardness and the fatigue limit of all kinds of spheroidal graphite cast irons.

versely tends to fall down. Also, as the graphite nodules become finer, the fatigue limit of the iron approaches that of the steel⁽²⁰⁾, with which the fatigue data were dealt statistically.

The relations between the fatigue limit and tensile strength are shown in Fig. 14. In the case of steel⁽²¹⁾, there

Fig. 14 Relationship between the tensile strength and the fatigue limit of all kinds of spheroidal graphite cast irons.

is a linear relationship between tensile strength and the fatigue limit up to 690 MPa in tensile strength. There is the same tendency like the relations between the fatigue limit and hardness in spheroidal graphite cast iron. However, if the strength or hardness is over a certain value, the fatigue limit will not increase corresponding to the static strength⁽²¹⁾, because the notching effect caused by internal structural defects, which can be the graphite nodule or microshrinkage cavity in spheroidal graphite cast iron, becomes significant. The hardness of quenched/tempered as well as austempered irons tested in the present work is of the high level more than HV400. It can be considered that suppressing the initiation of fatigue cracks by strengthening the matrix is canceled with the notching effect caused by the graphite nodule or microshrinkage cavity in this material. Therefore, the fatigue limit of spheroidal graphite cast iron with the same graphite nodule size is hardly affected by the hardness in spite of different temperatures in same heat treatment. It is strongly dependent only on the graphite nodule size as shown in Figs. 9 and 10.

As shown in Figs. 13 and 14, the data on austempered irons deviate from the fitting curves, and all are above their corresponding curves. The same problem has been reported in steels⁽²²⁾ that stainless steels have a higher fatigue limit than others. It is well known that austempered iron would be work-hardened by plastic deformation because it includes a large amount of austenite. Figure 15 shows the change in matrix hardness during the fatigue test of the iron. The matrix hardness progressively increases with increasing number of cycles, and it almost becomes saturated at 5×10^5 cycles. It can be considered that the strain occurs at the matrix near the graphite nodule because of the stress concentration caused by the nodule, then the strain further strengthens the matrix by the austenite to martensite transformation,

Fig. 15 Change in matrix hardness of austempered iron during the fatigue test. [Specimen: austempered at 648 K; 60 mm sand mold]

resulting in relieving the stress concentration. Therefore, the initiation and propagation of fatigue cracks are delayed by the progressively strengthened matrix and the relieved stress concentration. However, because of a lack of data about the effect of work hardening on the fatigue properties of the iron, further researches will be necessary to clarify this problem.

Figure 16 shows in three dimensions the change of the fatigue limit with varying matrix hardness and graphite nodule diameter. It shows a hyperbolic paraboloid in contour. Austempered iron is just the top part of the hyperbolic paraboloid. The tendency of the fatigue limit against the matrix hardness and the nodule diameter is not only shown in the present data, but has been also observed in our previous work⁽²³⁾ that relates the fatigue limit of high-quality iron to the structural factors based on the published data.

3. Prediction equation of fatigue limit

Murakami *et al.*⁽²⁴⁾⁻⁽²⁶⁾ proposed that the fatigue limit of steel can be predicted by the following equation:

$$\sigma_w = 1.43(HV + 120) / (\sqrt{area})^{1/6} \quad (4)$$

where σ_w is the fatigue limit (MPa); HV is the Vickers hardness number of the matrix; $\sqrt{area}$ means a square root of the projected area of inclusion or small defect in the maximum principal stress direction (μm). Endo⁽¹⁹⁾ indicated that the equation is applicable to predicting the fatigue limit of spheroidal graphite cast iron. If spheroidal graphite cast iron is fitting the equation, its fatigue limit will keep a linear relation to the matrix hardness for the same graphite diameter. As mentioned above, however, there is no linear relation between them. In addition, the fatigue limit depends largely on the graphite nodule diameter. For these reasons, to predict the fatigue limits of the irons by using eq. (4) is difficult.

Fig. 16 Influence of the matrix hardness and the graphite nodule diameter on fatigue limit of spheroidal graphite cast iron.

Ignoring the influence of hardness for the same material, the relations between the fatigue limits and nodule diameters are given as follows:

For quenched/tempered iron:

$$\sigma_w = 5924/d_{\max}^{0.63} \quad (r=0.98) \quad (5)$$

$$\sigma_w = 2055/d^{0.62} \quad (r=0.97) \quad (6)$$

For austempered iron:

$$\sigma_w = 1348/d_{\max}^{0.29} \quad (r=0.97) \quad (7)$$

$$\sigma_w = 1066/d^{0.35} \quad (r=0.91) \quad (8)$$

For as-cast iron:

$$\sigma_w = 2287/d_{\max}^{0.46} \quad (r=0.98) \quad (9)$$

$$\sigma_w = 668/d^{0.32} \quad (r=0.98) \quad (10)$$

For annealed iron:

$$\sigma_w = 551/d_{\max}^{0.19} \quad (r=0.99) \quad (11)$$

$$\sigma_w = 458/d^{0.23} \quad (r=0.99) \quad (12)$$

where $d_{\max}$ is the maximum nodule diameter (μm); d is the mean nodule diameter (μm). Because there is a correlation between $d_{\max}$ and d , the fatigue limit can be predicted by either $d_{\max}$ or d . As fatigue cracks initiate from the larger nodules prior to others, the fatigue limit can be more exactly predicted by $d_{\max}$.

As known from Fig. 6, when the maximum nodule diameter in quenched/tempered iron are reduced to about $30 \mu\text{m}$ (or $6 \mu\text{m}$ in mean nodule diameter), its fatigue limit will be approach that of steel (about 690 MPa). The maximum diameter of the inclusion in steel⁽²²⁾ presumed by extremely statistics is about $30 \mu\text{m}$, in good agreement with the result obtained in this work.

Austempered iron has a higher fatigue limit than other irons because of its work hardening during the fatigue test as mentioned above. Therefore, it must be evaluated in a different way from others. To obtain more general prediction equations the relations between $\text{HV} \ln(d_{\max})$ and $\ln(\text{HV}/\sigma_w)$ are arranged and shown in Fig. 17. The

Fig. 17 Relationship between $\text{HV} \ln(d_{\max})$ and $\ln(\text{HV}/\sigma_w)$.

equations can be expressed as follows:

For other irons excepting austempered iron:

$$\sigma_w = 1.80 \text{HV} / d_{\max}^{\text{CHV}} \quad (r=0.96) \quad (13)$$

(C is a constant, and equal to 0.47×10^{-3})

For austempered iron:

$$\sigma_w = 2.45 \text{HV} / d_{\max}^{\text{CHV}} \quad (r=0.97) \quad (14)$$

(C is a constant and equal to 0.54×10^{-3})

The dependence of the fatigue limit on the diameter is different as the matrix hardness varies, then it is given as the form of $d_{\max}^{\text{CHV}}$. Therefore, the fatigue limit of austempered iron can be predicted by using eq. (14), and that of others can be done by using eq. (13).

V. Conclusions

The details of effects of microstructural parameters on the fatigue limit of spheroidal graphite cast iron have been studied. The important conclusions in the study are summarized as follows:

(1) The fatigue limit of spheroidal graphite cast iron depends strongly on graphite nodule size. On the logarithmic scales, the fatigue limit linearly decreases with increasing maximum or mean nodule diameter for every matrix structure. Also, the dependence of the fatigue limit on the nodule diameter is greater as the matrix becomes harder.

(2) The fatigue limit is significantly improved by hardening the matrix to approximately $\text{HV} 500 \sim 600$ only in the irons with a fine nodule size such as a permanent mold and a sand mold 11 mm in thickness.

(3) Austempered spheroidal graphite cast iron has a higher fatigue limit than others with the same hardness, because of its large work hardening capacity.

(4) Fatigue cracks initiate from the larger nodules

just below the specimen surface prior to others.

(5) Improving the fatigue limit can be achieved by reducing the nodule diameter as much as possible and adjusting the matrix hardness to a corresponding value.

(6) The fatigue limit of spheroidal graphite cast irons can be predicted by the respective equations given above, according to the kind of the matrix, or by the equations: $\sigma_w = 1.80HV/d_{\max}^{\text{CHV}}$ (for other irons excepting austempered iron) or $\sigma_w = 2.45HV/d_{\max}^{\text{CHV}}$ (for austempered iron).

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