JMEPEG (2008) 17:352–362
DOI: 10.1007/s11665-008-9231-7

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1059-9495/$19.00

Influence of Graphite Nodules Geometrical Features on Fatigue Life of High-Strength Nodular Cast Iron

Nuno Costa, Nuno Machado, and Filipe Samuel Silva

(Submitted November 6, 2007; in revised form March 7, 2008)

This paper is concerned with the evaluation of different fatigue strength theories to predict the fatigue life of high-strength nodular cast iron. There have been some studies on the effects of the shape and size of graphite nodules, and of microstructure, on the fatigue strength of nodular cast iron. However, there is not a consensus on how to correlate the fatigue limit with material intrinsic properties or with external features such as considering graphite nodules as defects. Some researchers found good correlations between fatigue strength, σ_{w0}, and the geometrical aspects of the graphite nodules, considering it as internal material defects. It will be shown in this study that geometrical features such as shape, size, and relative position seem to be adequate to be included in those predictions. In this article, a high-strength cast iron, with rupture strength of about 1300 MPa and Young's modulus of about 160 GPa, has been used. Correlations both with intrinsic properties as well as with other geometrical effects have been made. A comparison of different theories has also been carried out.

Keywords automotive, defects geometry, fatigue strength, nodular cast iron

1. Introduction

Cast irons have been widely used for various engineering applications because of several manufacturing and engineering advantages such as low manufacturing cost, good wear resistance, and easy fabrication of machine components with complicated shapes. Recent technical demands for improving the performance of engineering components have brought up the need for proper estimation of components/system life to avoid sudden or unexpected failure of equipments. The ability of any system to perform its required function without failure remains a challenging concern for design engineers. Fatigue remains the main source of unexpected failures in mechanical components as the majority of structures are subjected to cyclic/alternating stress. Consequently, fatigue life can be satisfactorily considered as a measure for the reliability of mechanical components. Unfortunately, cast irons are susceptible to brittle fracture caused by the presence of graphite inclusions which play the role of microscopic stress concentrators and promote the processes of nucleation and growth of cracks. There exist many studies on the effects of the shape and size of graphite nodules, of casting defects (microshrinkage) (Ref 1-13) and of microstructure (Ref 1, 6, 9) on the fatigue strength of nodular cast iron.

The relationships between fatigue strength and yield stress, σ_y, ultimate tensile strength, σ_u, and hardness, H_B or H_v, have been of interest for a long time. Because fatigue crack initiation is mainly caused by slip within grains, most researchers think that the yield stress, which has a relationship with the start of slip in grains, has the strongest correlation with the fatigue limit. However, other correlations have been obtained among ultimate tensile strength, σ_u, hardness (H_B or H_v), and fatigue limit, σ_{w0}. Some empirical equations have been used, for example: $\sigma_{w0} \approx 0.5\sigma_u$ and $\sigma_{w0} \approx 1.6H_v \pm 0.1H_v$ (σ_{w0} in MPa; H_v, Vickers hardness, in kgf/mm^2) (Ref 1).

There are some authors who proposed simple prediction equations for the fatigue limit. Sofue (Ref 2, 3) proposed an equation where the mean average diameter and the nonpropagating crack length are the main factors influencing the fatigue limit of cast iron. The value of nonpropagating crack length was expressed graphically as a function of the Vickers hardness, H_v, of the material; therefore, fatigue strength is given as a function of Vickers hardness and mean average diameter. Sofue applied the equations to different nodular cast irons with different graphite nodules diameter and different microstructures. He obtained good accuracy in the fatigue limit prediction with his experimental results. His model takes into consideration the mean graphite nodules diameter. Niimi et al. (Ref 4) also studied the fatigue strength of nodular cast iron, focusing on the size of graphite nodules. As Sofue, Niimi also adopted the average size of nodules as the representative graphite nodule size. Murakami (Ref 1) carried out detailed and systematic experiments, and proposed a simple equation as a function of hardness, H_v and the square root of the maximum projected area onto the principal stress plane of the defect, $\sqrt{area}$ (Ref 1). The low strength associated with graphite nodules makes it mechanically equivalent to a defect or a hole (Ref 12). Endo (Ref 13, 14) carried out experiments where he compared the fatigue strength of nodular cast iron specimens

This article was presented at Materials Science & Technology 2007, Automotive and Ground Vehicles symposium held September 16–20, 2007, in Detroit, MI.

Nuno Costa and **Nuno Machado**, MAHLE – Engine Components S.A., Murtede, Portugal; and **Nuno Costa** and **Filipe Samuel Silva**, Department of Mechanical Engineering, Minho University, Campus de Azurém, Guimaraes 4800-058, Portugal. Contact e-mail: nuno@dem.uminho.pt.

containing graphite nodules at surface with electropolished cast iron specimens without graphite nodules at surface; thus, the graphite nodules of the latter specimens became stress-free vacant pores. A comparison of the fatigue strength of these two types of specimens did not show a difference in fatigue strength between the specimens containing graphite nodules and the specimens without graphite nodules at the specimen surface. This means that the graphite nodules can be considered as defects (Ref 13, 14).

Murakami (Ref 15) did numerical analysis that showed the interaction effect between two cracks. If the space between these two cracks is equal or smaller than the size of the smaller crack, then it should be considered an equivalent crack that should contain the two cracks and the space between them. In this case the stress intensity factor is estimated taking into consideration the equivalent crack. If the cracks are very close to each other, then the stress intensity factor increases significantly. Furthermore, the cracks are likely to coalesce by fatigue crack growth in a small number of cycles. On the other hand, if the space between the two cracks is big enough (bigger than the size of the smaller crack), then the stress intensity factor is approximately equal to that of the larger crack in isolation.

Table 1 Mechanical properties of the nodular cast iron—ISO 6621-3:2000 (E)

Material	Class	Subclass	Young's modulus *E*, GPa	Tensile strength σ_u, MPa
Nodular cast iron	50	MC53	160	1300

In this study, a comparison will be made between some of the different previous theories. Correlations both with intrinsic properties as well as with other geometrical effects such as graphite nodules dimensions and its relative position will be established. It will also be shown that the very high scatter found in fatigue life results on cast iron may also be explained based on the graphite nodules' geometrical features and with defects.

2. Materials and Experimental Details

The present study has been conducted with 20 samples of a nodular cast iron (according to Standard ISO 6621-3:2000(E)) constituted by a martensitic matrix. This material is used for automotive components. The mechanical properties of the materials are listed in Table 1. The bulk material of the different specimens exhibits graphite nodules with very different mean diameter as shown in Fig. 1(a) and (b). Three-point bending fatigue tests (Fig. 2a) were conducted in air at room temperature on samples with rectangular cross section, using a sinusoidal signal with a frequency of 25 Hz and load ratio *R* = 0.3. Samples were machined from the bulk of a centrifugal casting pipe at different positions as shown in Fig. 2(b).

All defects found on specimens (see Fig. 3) were measured and taken into consideration along with the graphite nodules because all are considered defects in this study. The tested samples at the stress level σ_{max} = 800 MPa and σ_{max} = 716 MPa were observed on the optical microscopic according to the scheme shown in Fig. 4. The stress distribution under bending loading is also represented in Fig. 4. An area of about 0.6 mm × 1 mm near the surface (see Fig. 4), which includes

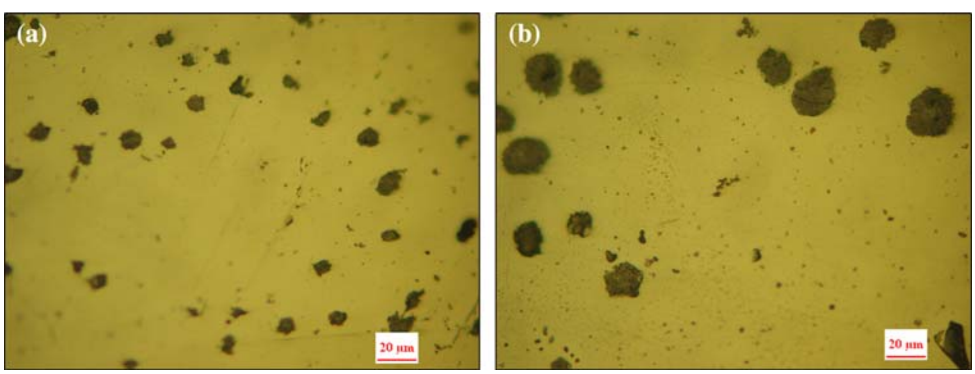

Fig. 1 Nodular cast iron, bulk microstructure: (a) mean average diameter 10 μm; (b) mean average diameter 21 μm

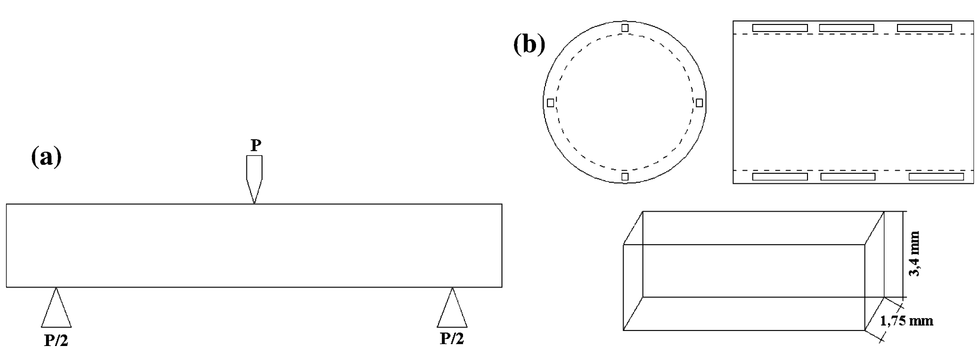

Fig. 2 (a) Three-point bend set-up; (b) Nodular cast iron, casting pipe, and samples

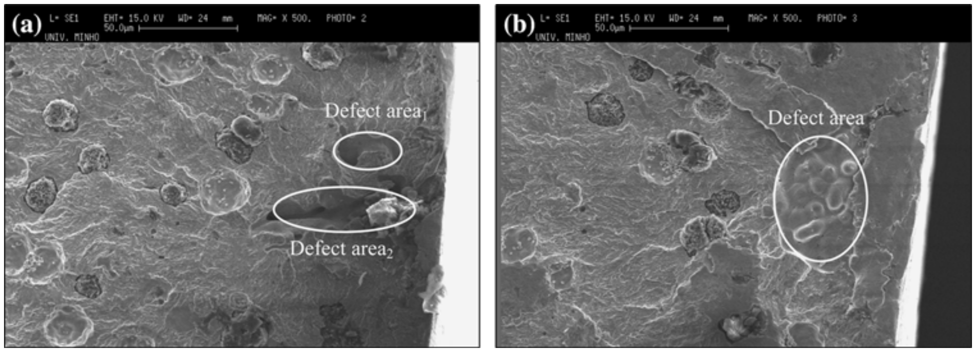

Fig. 3 (a) Fracture surface of sample 4 (defect $area_1$ = 543 μm^2; defect $area_2$ = 1.300 μm^2); (b) fracture surface sample of sample 6 (defect area = 2.684 μm^2)

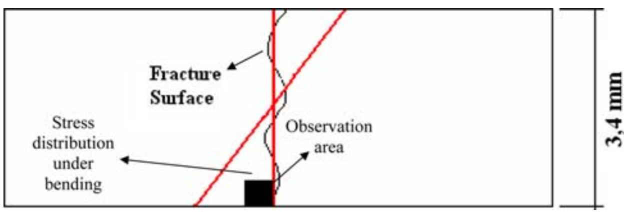

Fig. 4 Scheme of the area used for optical observation (A = 0.6 mm × 1 mm)

stress levels above 65% of maximum stress, was used for geometrical nodule analysis.

The hardness was measured on all samples. The hardness values are the average of five measurements in each sample and were made in the material excluding the graphite nodules.

3. Results and Discussion

3.1 S-N Curve

Fatigue test results are presented in Fig. 5, where the number of cycles to failure is plotted versus the maximum nominal stress. The results show a large fatigue scattering for all the stress levels. It is possible to observe that the fatigue scatter happens for high stress levels as well as for stress levels near the fatigue limit, although the scattering is higher when the stress level is lower. It is possible to observe in Fig. 5, that the total life of the specimens tested at σ_{max} = 800 MPa changes from 54,000 cycles to 197,000 cycles, while the specimens tested at σ_{max} = 716 MPa changes from 52,000 cycles to 2,600,000 cycles. Because of this high scatter, two stress levels were selected (σ_{max} = 800 MPa and σ_{max} = 716 MPa) for the study. The scatter of the samples was correlated with the hardness and inherently with intrinsic properties (yield strength and rupture strength) as well as with other geometrical features and with defects.

In Table 2 it is possible to observe the total life of each specimen as well as the hardness and some geometrical properties of the graphite nodules of each sample.

3.2 Hardness of the Matrix

Table 2 shows the hardness values for all samples. All the values of hardness are similar. Thus, there is no correlation

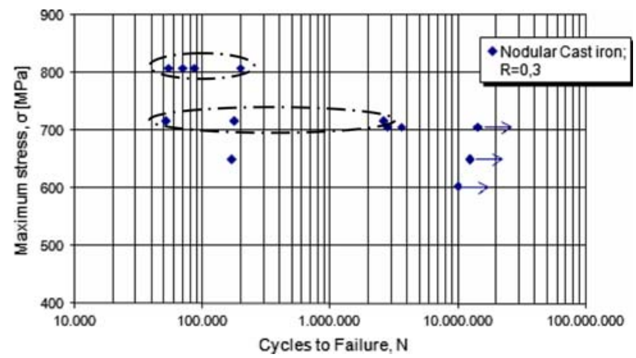

Fig. 5 Martensitic nodular cast iron *S-N* curve

between hardness of the specimens and respective fatigue life. This means that the fatigue life scattering is not due to mechanical intrinsic properties, as obtained by hardness such as yield or rupture strength. Then, fatigue life difference between specimens tested at the same stress level should be due to geometrical features such as the distribution of the graphite nodules, defects, or others.

3.3 Influence of the Distance Between Graphite Nodules and Its Relative Position on Local Stress Level

A finite element analysis was done to understand the influence of the relative position of the graphite nodules (in relation to the load direction) for five different relative positions of the graphite nodules, as shown in Fig. 6, and the influence of the distance between the graphite nodules in each case, on the local stress level. The relative position changes from 0° to 90° where 0° means that both graphite nodules are collinear with the load direction (Fig. 6a) while 90° represents the case where the nodules are perpendicular to the load direction (Fig. 6e). The distance between the two graphite nodules, a, changes from 0.25*d to 4*d, where d is the diameter of the smaller graphite nodule and D is the diameter of the bigger graphite nodule.

Figure 7 shows the influence of the relative position between two graphite nodules on the local stress level. It is possible to observe that there is no influence on the local stress level when the relative position between graphite nodules is 0° or 22.5° for all distances between graphite nodules. It is also possible to observe that the influence of the relative position increases with the value of the angle and as the distance

Table 2 Mechanical and geometrical properties of the graphite nodules

Sample number	Max. stress, MPa	Hardness H_v	Hardness STD	Total life (cycles)	Graphite nodules Minimum diameter, μm	Graphite nodules Maximum diameter, μm	Graphite nodules Average diameter, μm
1	800	331	12.74	70,672	5.8	29.1	13.7
2	800	338	6.57	54,618	5.9	32.1	18.4
3	800	327	6.57	87,175	6.4	26.1	14.2
4	800	343	10.40	197,598	6.6	26.5	16.2
5	716	336	23.00	2,641,519	5.9	23.2	11.7
6	716	334	12.00	52,038	8.0	31.5	18.5
7	716	338	6.93	178,120	6.3	28.6	14.7

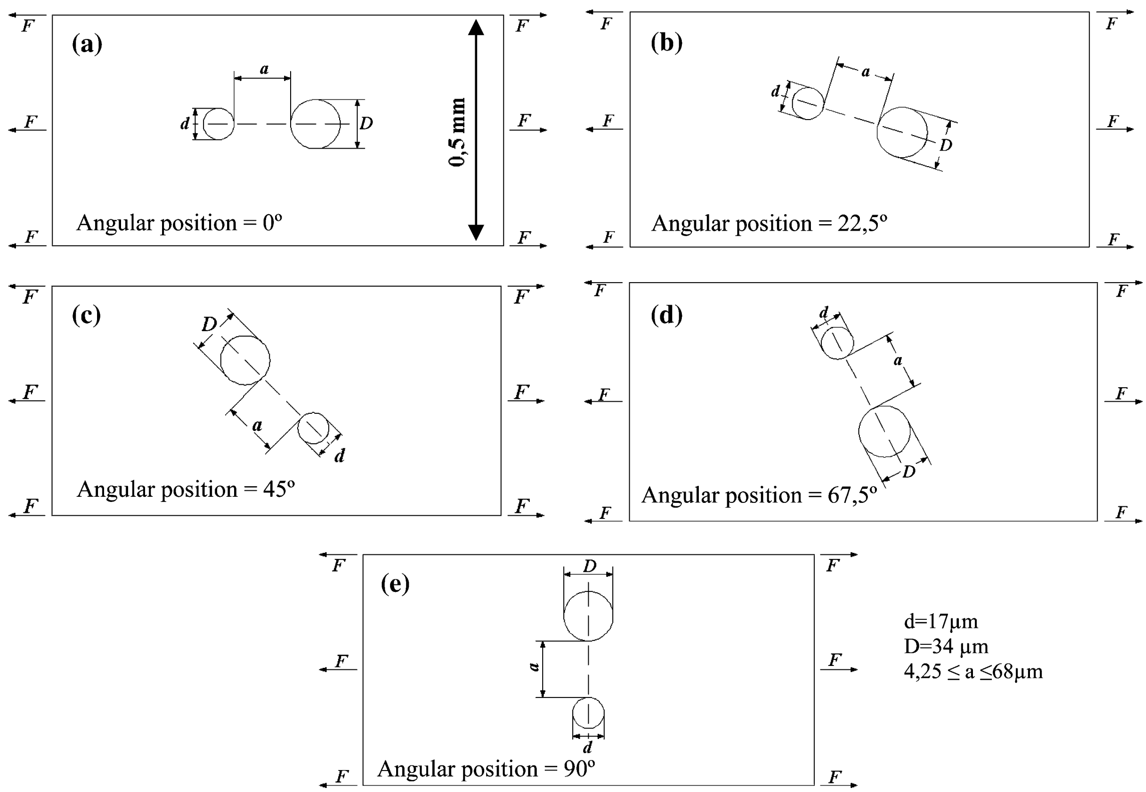

Fig. 6 Interaction effect between adjacent graphite nodules (relative position change from 0° to 90°) on local stress level on optical observation area (see Fig. 4)

between nodules decreases. It is also evident that the relative position has a substantial influence on local stress level only for values of distance, a, between nodules less then $1*d$. This means that the critical situation is when the relative position is between 45° and 90° and the distance is less than $1*d$ (see Fig. 7).

In section "S-N Curve" it was shown that there is a very high scattering on the fatigue life of nodular cast iron samples. In section "Influence of the Distance Between Graphite Nodules and Its Relative Position on Local Stress Level" it was shown that the relative position and distance between graphite nodules have a substantial influence on the local stress level.

In the following sections ("Correlation of Experimental Results with Other Models" and "Other Interactions Between Adjacent Graphite Nodules") a correlation between these geometrical features and the fatigue life scattering will be established. The correlation between Sofue's and Murakami's models and the experimental results will be analyzed. Some modifications will also be presented to the Murakami's model. At last (in section "Factor ψ") it will be presented a factor, ψ, that gives an improved sensibility between fatigue life and graphite nodules' geometrical features.

3.4 Correlation of Experimental Results with Other Models

3.4.1 Sofue's Model. Sofue (Ref 2, 3) carried out detailed and systematic experiments, and proposed a simple prediction equation for the fatigue limit. It was based on the average nodule diameter, D_g, and the nonpropagating crack length, l_{cm}. He applied its equation to different nodular cast irons having different microstructures and graphite nodule sizes. The value of l_{cm} was expressed graphically as a function of the Vickers hardness, H_v, of the material; therefore, fatigue strength was given as a function of H_v and D_g. As shown in Table 2, the material Vickers hardness, H_v, is similar for all the specimens analyzed in this study. Thus, only D_g should influence the fatigue strength and therefore the fatigue life scattering. For this reason an analysis of the graphite nodules diameter was done to verify the accuracy of this model with the experimental results. The analysis was done on an observation area according to the scheme in Fig. 4, for the two stress levels.

Figure 8(a) shows a distribution of the graphite nodule diameter for the samples tested at 800 MPa, and Table 3 details

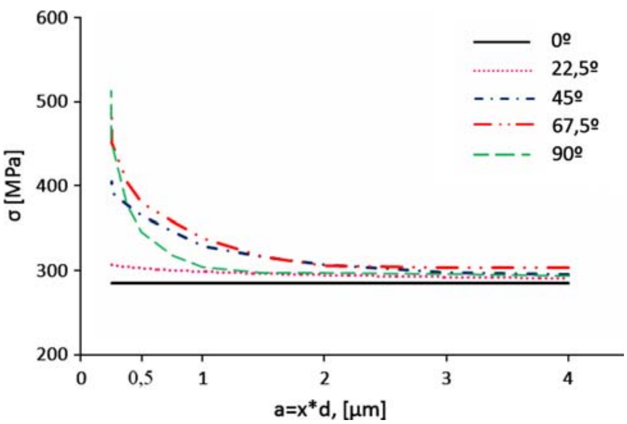

Fig. 7 Numerical simulation with the influence of relative position between two graphite nodules (distance and angular position) on the stress level

its values. It is possible to observe that sample 2 has the higher value both for the maximum and for the average graphite nodule diameter. It is also possible to observe that sample 1 has the minimum value for the average graphite nodule diameter followed by sample 3 and then by sample 4. In Fig. 8(b) and Table 3 it is possible to observe that the behavior for the average and for the maximum graphite nodule diameter is the same, e.g., sample 6 has the higher values while sample 5 has the lower values.

- Stress level: σ_{max} = 800 MPa

A correlation between D_g (average nodule diameter) and fatigue life was not found for this stress level. Analyzing Table 3 and Fig. 8(a) it is possible to observe that if the average diameter were taken into consideration to correlate with the fatigue life, the behavior in terms of fatigue life of the four samples would be: sample 2 should have the lower fatigue life, followed by sample 4, then by sample 3, and finally by sample 1; sample 1 should be the sample with higher fatigue life.

If, instead of the average diameter, the maximum diameter was considered for the correlation then the fatigue life behavior should be: Sample 2 should have the lower fatigue life, followed by sample 1, then by sample 4, and finally by sample 3; sample 3 should be the sample with higher fatigue life.

Thus, these results (taking into consideration the average diameter or the maximum diameter of the graphite nodules) demonstrate that there is no correlation between Sofue's model and the experimental results of this study.

Furthermore, it is interesting to note that the results are different if the value of the representative defect size is the average diameter of nodules, or the maximum size of the nodules.

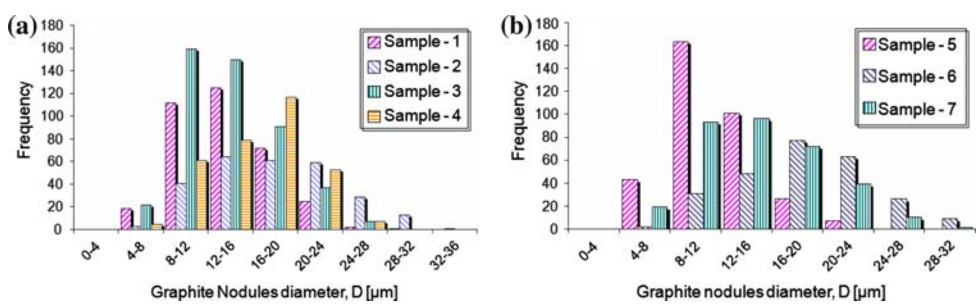

Fig. 8 Histogram of graphite nodule diameter distribution for samples tested at two different stage levels: (a) σ_{max} = 800 MPa; (b) σ_{max} = 716 MPa

Table 3 Geometrical properties of the graphite nodules

			Graphite nodules		
Sample number	**Max stress, MPa**	**Total life (cycles)**	**Average diameter, μm**	**Maximum diameter, μm**	**Max diameter Ave. diameter**
1	800	70,672	13.7	29.1	2.1
2	800	54,618	18.4	32.1	1.7
3	800	87,175	14.2	26.1	1.8
4	800	197,598	16.2	26.5	1.6
5	716	2,641,519	11.7	23.2	2.0
6	716	52,038	18.5	31.5	1.7
7	716	178,120	14.7	28.6	1.9

- Stress level: σ_{max} = 716 MPa

For this stress level it is possible to define a good correlation between both average diameter and maximum diameter of the graphite nodules with fatigue life. Taking into consideration the average graphite nodules diameter and considering that higher the average diameter lower the fatigue life, then the fatigue behavior should be: Sample 6 should have the lower fatigue life, followed by sample 7, and sample 5 should have the highest fatigue life. If the maximum graphite nodules diameter were considered, and higher the maximum diameter lower the fatigue life, then the fatigue behavior should be: sample 6 should have the lower fatigue life, followed by sample 7, and sample 5 should have the highest fatigue life. In both cases the predicted fatigue life has the same behavior of the experimental results.

It is worth to note that the sensibility of the fatigue life in relation to geometrical features is expected to be higher for lower stress values than for high stress values. As the model is for low stress values, for the fatigue limit, it can be concluded that the model correlates properly fatigue life with average nodules diameter.

3.4.2 Murakami Model—Square Root of the Equivalent Projected Area onto the Principal Stress Plane of the Defect. *Interaction Between Adjacent Graphite Nodules (a ≤ 1*d) Independently of Relative Position.* If a graphite nodule is close to another graphite nodule or near a cavity, then the interaction between the graphite nodules or a cavity causes an increase in the value of the stress intensity factor compared

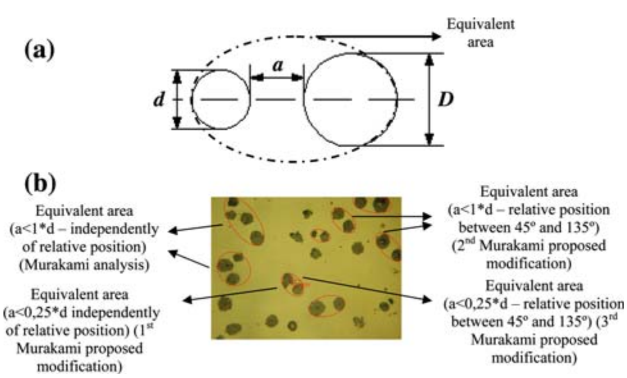

Fig. 9 (a) Interaction between adjacent cracks (the equivalent area is the sum of the two cracks plus the space between them); (b) example of the calculation of equivalent area for the four different situations

with that for the isolated graphite nodule case. This was demonstrated by the finite element analysis (section "Influence of the Distance Between Graphite Nodules and Its Relative Position on Local Stress Level"). Murakami (Ref 12) has done numerical analysis which shows that the interaction effect between two cracks or between a crack and a cavity can be estimated using the following rule of thumb: if there is enough space between the two cracks (or cavities) to insert an additional crack (cavity) of the same size as the smaller crack (cavity), then the stress intensity factor is approximately equal to that for the larger crack (cavity) in isolation. That is, the interaction effect is negligibly small. However, if these cracks (cavities) are closer to each other than in the case described above, then the stress intensity factor increases significantly, and cracks so near to each other are likely to coalesce by fatigue crack growth in a small number of cycles. In this case an equivalent crack (cavity) equal to the sum of the cracks (cavities) plus the distance between the cracks (cavities) should be considered. In Fig. 9 it is possible to observe a scheme of this rule.

Murakami (Ref 1) proposed a simple prediction equation for the fatigue limit. This equation is based on the square root of the equivalent projected area onto the principal stress plane of the defect, $\sqrt{area_{eq.}}$, and the material hardness, H_v. As shown in Table 2, the material Vickers hardness, H_v, is similar for all the specimens. Thus, only the $\sqrt{area_{eq.}}$ should influence the fatigue strength and therefore the fatigue life scattering. For this reason an analysis of the equivalent projected area onto the principal stress plane of the defect was done to verify the accuracy of this model with the experimental results. The analysis was done according to the scheme in Fig. 4.

Figure 10(a) shows a distribution of the equivalent graphite nodules area, $area_{eq.}$, for the samples tested at 800 MPa. On the histogram it is possible to observe that sample 2 has the higher value for the equivalent graphite nodule area. Sample 1 has the minimum value for the equivalent graphite nodule diameter followed by sample 3 and then by sample 4. Figure 10(b) shows the behavior of the samples tested at 716 MPa. It is possible to observe that sample 6 has the higher equivalent graphite nodule area, while sample 5 has the lower value for the equivalent graphite nodule area.

- Stress level: σ_{max} = 800 MPa

A correlation between equivalent area, $area_{eq.}$, and fatigue life was not found for this stress level. Analyzing Fig. 10(a), it is possible to observe that the behavior in terms of fatigue life of the four samples (if considered that higher the maximum

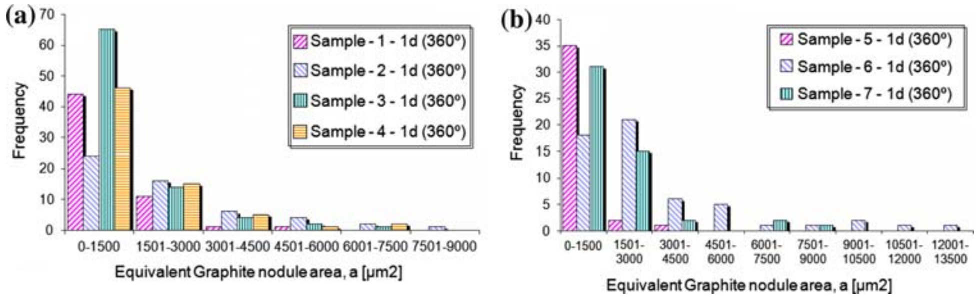

Fig. 10 Histogram of equivalent graphite nodule area (for $a \leq 1*d$, independently of relative position) for samples tested at two different stage levels: (a) σ_{max} = 800 MPa; (b) σ_{max} = 716 MPa

equivalent area, $area_{eq.}$, lower the fatigue life) should be: sample 2 should have the lower fatigue life, followed by sample 4, and followed by sample 3; sample 1 should be the sample with higher fatigue life. This means that there is no correlation between the prediction and the experimental results.

- Stress level: σ_{max} = 716 MPa

For this stress level it is possible to establish a good correlation between the prediction and fatigue life results (if considered that higher the maximum equivalent area, $area_{eq.}$, lower the fatigue life). Then the fatigue behavior should be: Sample 6 should have the lower fatigue life, followed by sample 7, and sample 5 should have the highest fatigue life.

From the analysis of sections "Sofue's Model" and "Murakami Model" it is possible to conclude that both Sofue's and Murakami's models have a good correlation with the experimental results for stress levels near to the fatigue limit, but there is no accuracy for stress levels above the fatigue limit. As these models were established for the fatigue limit it can be considered that they have a good correlation with experimental results.

Taking into consideration the rule used by Murakami (interaction between adjacent cracks) and the numerical analysis shown in section "Influence of the Distance Between Graphite Nodules and Its Relative Position on Local Stress Level", in sections "Others Interactions Between Adjacent Graphite Nodules" and "Factor ψ" the accuracy of the Murakami's rule incorporating some modifications will be discussed.

3.5 Others Interactions Between Adjacent Graphite Nodules

According to Ref 16, to improve the nodular cast iron mechanical properties, it should have a lower frequency of graphite nodules and lower equivalent areas. The lower equivalent areas mean that there are no adjacent graphite nodules ($a \leq 1*d$). Taking this aspect in to consideration, a factor ψ will be defined. The factor ψ defines, conjointly, the frequency of graphite nodules and its equivalent area. The factor ψ is calculated based on the values of intersection points between the tendency line and both axes, x and y. So, the factor ψ could be calculated by the following equation:

$$\psi = x * y \quad \text{(Eq 1)}$$

Value x is calculated when $y = 0$, and y is calculated when $x = 0$.

Factor ψ increases as both the frequency of equivalent nodules and the equivalent area of the nodules increase. Factor ψ will be used to define the sensibility of Murakami's model with and without modifications.

In the following subsections the histograms where it is possible to observe the tendency lines for all the samples, from where factor ψ was determined will be presented.

3.5.1 Interaction Between Adjacent Graphite Nodules ($a \leq 1*d$) Independently of Relative Position. Figure 11(a) and (b) shows the histograms with tendency lines where frequency versus equivalent *graphite nodules area* (*for $a \leq 1*d$, independently of relative position*) is plotted, as used by Murakami.

The factor ψ, as obtained by histograms in Fig. 11(b) are plotted in Fig. 17 along with other values obtained from other interactions between adjacent graphite nodules.

3.5.2 Interaction Between Adjacent Graphite Nodules ($a \leq 0.25*d$) Independently of Relative Position. This analysis is similar to the previous one (section "Murakami Model"), but in this case only the graphite nodules with distances between them smaller than 0,25*d are taken into consideration. When this happens a new equivalent area, $area_{eq.}$ was calculated. Figure 12(a) shows the results of the specimens tested at σ_{max} = 800 MPa and Fig. 12(b) shows the results of the specimens tested at σ_{max} = 716 MPa. From the histogram (Fig. 12a) is possible to observe that sample 2 has the higher value for the equivalent graphite nodules area. It is also possible to observe that sample 1 has the minimum value for the equivalent graphite nodules area followed by the sample 4 and then by sample 3. Figure 12(b) shows that sample 6 has the higher equivalent graphite nodules area, while sample 5 has the lower value for the equivalent graphite nodules area.

- Stress level: σ_{max} = 800 MPa

A correlation between equivalent area, $area_{eq.}$, and fatigue life was not found for this stress level. Analyzing Fig. 12(a), it is possible to observe that the behavior in terms of fatigue life of the four samples (if it is considered that higher the maximum equivalent area, $area_{eq.}$, lower the fatigue life) should be: Sample 2 should have the lower fatigue life, followed by sample 3, and then followed by sample 4; sample 1 should be the one with higher fatigue life. This means that there is no correlation between the prediction and the experimental results. As in Fig. 11, Fig. 12 also shows the tendency lines for all the samples.

- Stress level: σ_{max} = 716 MPa

For this stress level it is possible to establish a good correlation between the predicted results and fatigue life. Taking into consideration the equivalent area, $area_{eq.}$, and considering that higher the maximum equivalent area, $area_{eq.}$, lower the fatigue life, then the fatigue behavior should be:

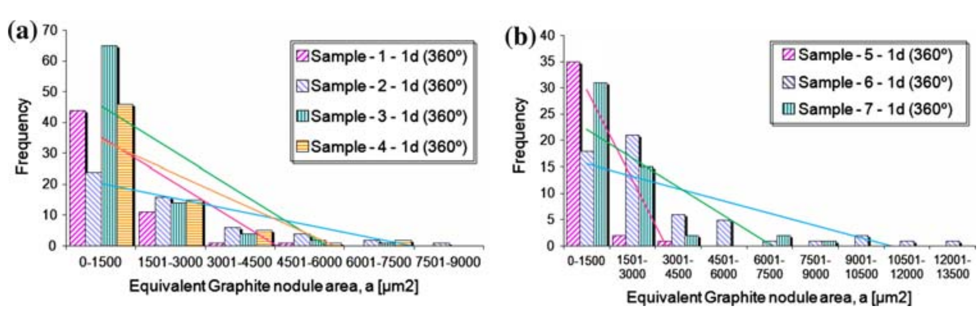

Fig. 11 Histogram of equivalent graphite nodule area (for $a \leq 1*d$, independently of relative position) for samples tested at two different stage levels: (a) σ_{max} = 800 MPa; (b) σ_{max} = 716 MPa

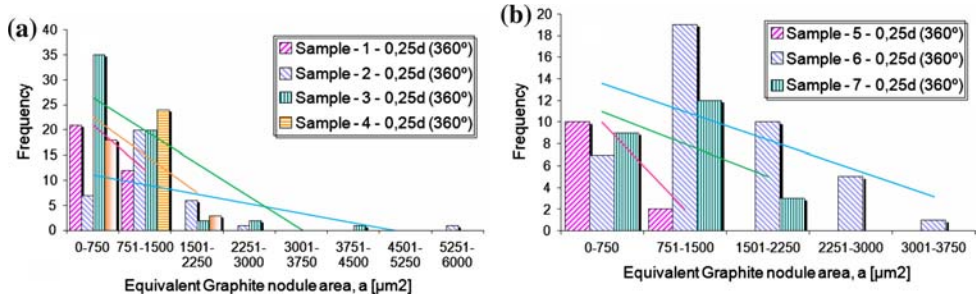

Fig. 12 Histogram of equivalent graphite nodule area (for $a \leq 0.25*d$, independently of relative position) for samples tested at two different stage levels: (a) σ_{max} = 800 MPa; (b) σ_{max} = 716 MPa

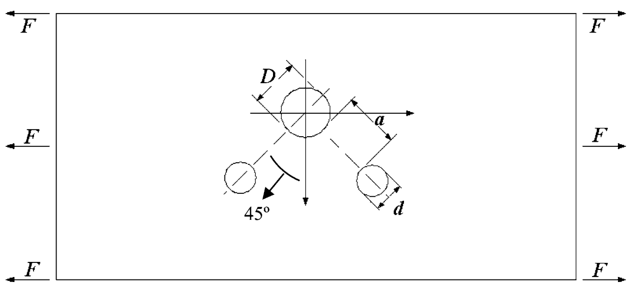

Fig. 13 Graphite nodules relative position between 45° and 90°

The sample 6 should have the lower fatigue life, followed by sample 7, and sample 5 should have the highest fatigue life.

The factor ψ, as obtained by histograms in Fig. 12(b) is plotted in Fig. 17 along with other values obtained from other interactions between adjacent graphite nodules.

3.5.3 Interaction Between Adjacent Graphite Nodules ($a \leq 1*d$) and for Graphite Nodules Relative Position Between 45° and 90° in Relation to the Load Direction. The method followed in this case was similar to the first one (section "Murakami Model"), but in this case only the graphite nodules with angular position between 45° and 90° were taken into consideration. When the position between two or more graphite nodules has a distance $a \leq 1*d$ and an angle between them of 45° to 90°, as shown on Fig. 13, a new equivalent area, $area_{eq.}$ was calculated.

Figure 14(a) shows a distribution of the equivalent graphite nodules area, for the samples tested at 800 MPa. From the histogram it is possible to observe that samples 2 and 3 have the higher values for the equivalent graphite nodules area. It is also possible to observe that sample 1 has the minimum value for the equivalent graphite nodules area followed by sample 4. Figure 14(b) shows the behavior of the samples tested at 716 MPa. It is possible to observe that sample 7 has the higher equivalent graphite nodules area, while sample 5 has the lower value for the equivalent graphite nodules area.

- Stress level: σ_{max} = 800 MPa

As in the previous results, also in this case a correlation between equivalent area, $area_{eq.}$, and fatigue life was not found. Analyzing Fig. 14(a), it is possible to observe that the behavior in terms of fatigue life of the four samples (if it is considered that higher the maximum equivalent area, $area_{eq.}$, lower the fatigue life) should be: samples 2 and 3 should have the lower fatigue life, (the fatigue life should be the same for the two samples), and sample 1 should have the highest fatigue life. This means that there is no correlation between the prediction and the experimental results.

- Stress level: σ_{max} = 716 MPa

For this situation it is not possible to establish a correlation between the predicted results and fatigue life. Taking into consideration the equivalent area, and considering that higher the maximum equivalent area, lower the fatigue life, then the fatigue behavior should be: sample 7 should have the lower fatigue life, and sample 5 should have the highest fatigue life.

Although a correlation was not established between the maximum equivalent area and fatigue life, it will be shown in section "Factor ψ" that if factor ψ (frequency also included in analysis) is considered, there exists a good correlation.

The factor ψ, as obtained by histograms in Fig. 14(b) is plotted in Fig. 17 along with other values obtained from other interactions between adjacent graphite nodules.

3.5.4 Interaction Between Adjacent Graphite Nodules ($a \leq 0.25*d$) and for Graphite Nodules Relative Position Between 45° and 90° in Relation to the Load Direction. The method followed in this case is similar to the last one followed in the preceding section. The difference between both is the distance between graphite nodules is now $0.25*d$ instead of $1*d$. When the position between two or more graphite nodules has a distance $a \leq 0.25*d$ and the angle between them is between 45° and 90° in relation to the load direction, a new equivalent area was calculated. From the histogram (Fig. 15a) it is possible to observe that samples 2 and 3 have higher value for the equivalent graphite nodules area. It is also possible to observe that sample 1 has the minimum value for the equivalent graphite nodules area followed by sample 4. Figure 15(b) shows that sample 6 has the highest equivalent graphite nodule area, while sample 5 has the lowest value for the equivalent graphite nodule area.

- Stress level: σ_{max} = 800 MPa

As in others sections ("Sofue's Model", "Murakami Model", "Interaction Between Adjacent Graphite Nodules ($a \leq 0.25*d$) Independently of Relative Position", and "Interaction Between Adjacent Graphite Nodules ($a \leq 1*d$) and for Graphite Nodules Relative Position Between 45° and 90° in Relation to the Load Direction"), in this case also a correlation between equivalent area and fatigue life was not found. Analyzing Fig. 15(a), it is possible to observe that the behavior in terms of

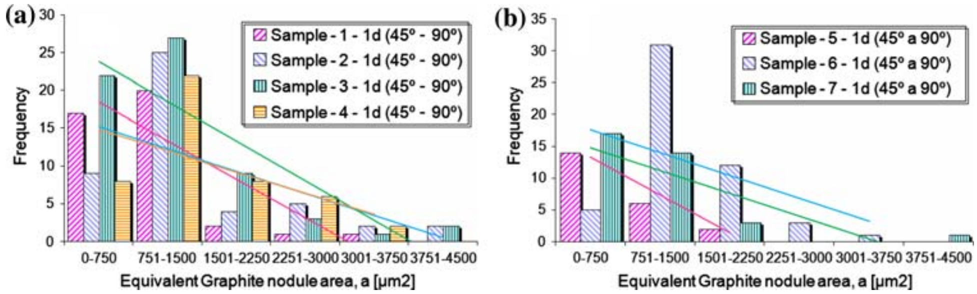

Fig. 14 Histogram of equivalent graphite nodule area (for $a \leq 1*d$, and for graphite nodules relative position between 45° and 90° in relation to the load direction) for samples tested at two different stage levels: (a) σ_{max} = 800 MPa; (b) σ_{max} = 716 MPa

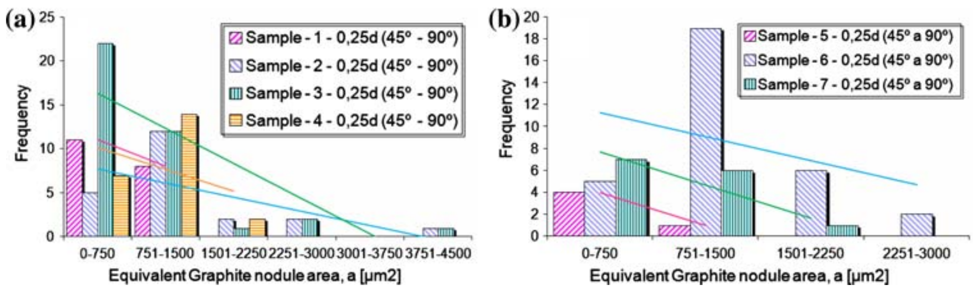

Fig. 15 Histogram of equivalent graphite nodule area (for $a \leq 0.25*d$, and for graphite nodules relative position between 45° and 90° in relation to the load direction) for samples tested at two different stage levels: (a) σ_{max} = 800 MPa; (b) σ_{max} = 716 MPa

fatigue life of the four samples (if it is considered that higher the maximum equivalent area, $area_{eq.}$, lower the fatigue life) should be: samples 2 and 3 should have the lower fatigue life (the fatigue life should be the same for the two samples), and sample 1 should have the highest fatigue life. This means that there is no correlation between the prediction and the experimental results.

- Stress level: σ_{max} = 716 MPa

As in others sections ("Sofue's Model", "Murakami Model", and "Interaction Between Adjacent Graphite Nodules ($a \leq 0.25*d$) Independently of Relative Position"), in this case also it is possible to establish a correlation between the predicted results and fatigue life. Taking into consideration the equivalent area, and considering that higher the maximum equivalent area, lower the fatigue life, then the fatigue behavior should be: sample 6 should have the lowest fatigue life and sample 5 should have the highest fatigue life.

Also for this section the factor ψ was calculated (based on Fig. 15b), and will be presented, and the accuracy of factor ψ with the experimental results in the section "Factor ψ" will be presented.

The factor ψ, as obtained by histograms in Fig. 15(b) is plotted in Fig. 17 along with other values obtained from other interactions between adjacent graphite nodules.

As observed in sections "Murakami Model", "Interaction Between Adjacent Graphite Nodules ($a \leq 0.25*d$) Independently of Relative Position", "Interaction Between Adjacent Graphite Nodules ($a \leq 1*d$) and for Graphite Nodules Relative Position Between 45° and 90° in Relation to the Load Direction", and "Interaction Between Adjacent Graphite Nodules ($a \leq 0.25*d$) and for Graphite Nodules Relative Position Between 45° and 90° in Relation to the Load Direction" for high stress level (800 MPa) and short fatigue lives, there is no correlation between the predicted results and the experimental results. It is widely accepted that as the stress level reaches the nominal yield stress (for intermediate and short fatigue lives) the influence of the defects became lower and eventually negligible (Ref 17). This phenomenon can be easily observed on the *S-N* curves on this work where for high stress levels the fatigue life scatter is lower than for low stress levels or for tests with and without notches where the difference in fatigue life is much smaller for short lives then for long lives. For this reason only the stress level of 716 MPa will be taken into consideration on the factor ψ analysis (section "Factor ψ").

3.6 Factor w

Figure 16 shows an equivalent stress value for each tested sample. The equivalent stress value was obtained through the *S-N* linear regression curve of the nodular cast iron (see Fig. 5). For each sample, according to its fatigue life, the equivalent stress level was calculated, as shown in Fig. 16. So, the equivalent stress levels for the three samples tested at a nominal stress of 716 MPa are:

- Sample 5 → Total life = 2.641.519; equivalent stress = 683 MPa;
- Sample 6 → Total life = 52.038; equivalent stress = 775 MPa;
- Sample 7 → Total life = 178.120; equivalent stress = 746 MPa;

Using Eq 1, it is possible to calculate the factor ψ for each sample. The normalized factor ψ is calculated through the ratio

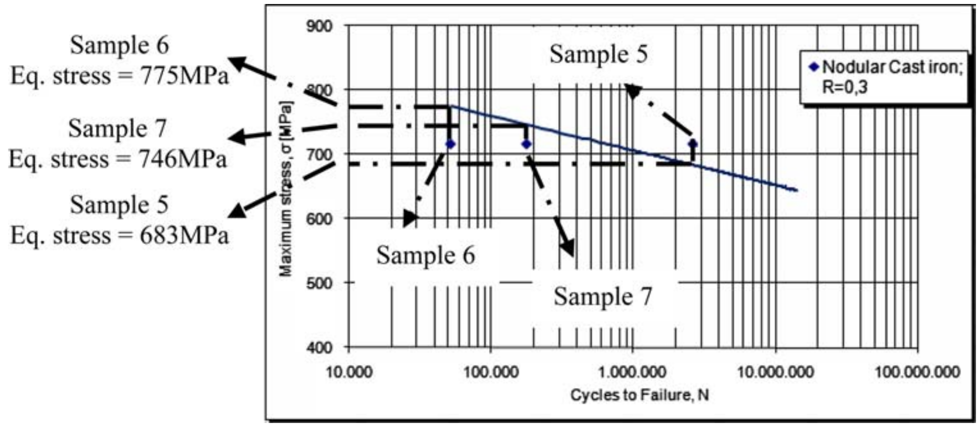

Fig. 16 Equivalent stress for each sample life

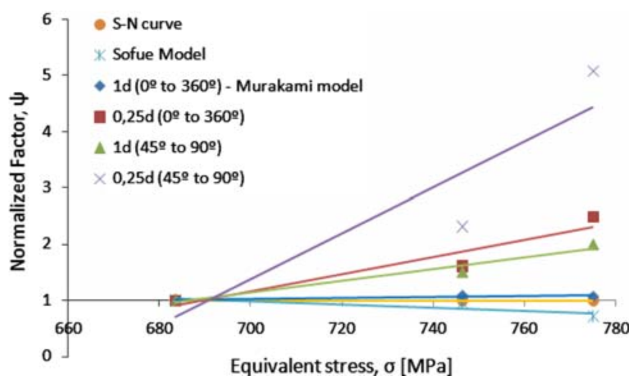

Fig. 17 Normalized factor ψ

between each factor ψ and the minimum factor ψ of all samples, and can be expressed by the following equation:

$$\text{Normalized factor } \psi_i = \frac{\psi_i}{\psi_{\min}} \qquad \text{(Eq 2)}$$

Figure 17 shows the normalized factor ψ vs. the equivalent stress level. The normalized factor ψ represents the sensibility of the graphite nodules' geometrical features on the fatigue life. Starting from actual *S-N* curve as a baseline (horizontal line), Fig. 17 shows that Murakami's analysis, based on an equivalent area, improves the sensibility of the normalized factor ψ (increased slope). However, it is possible to further improve the sensibility of the graphite nodules on fatigue life. It is possible to observe that when the distance between the graphite nodules is $a \leq 0.25{*}d$, the sensibility increases in relation to the Murakami's analysis. Also, when the distance between the graphite nodules is $a \leq 1{*}d$ and the angular position is between 45° and 90°, the sensibility also increases in relation to the Murakami's model. As expected, when both previous modifications (the reduction of the distance between graphite nodules to 0.25**d*, and the angular position of graphite nodules between 45° and 90°) are simultaneously considered the sensibility has a high increase.

Relating to Sofue's model it can be seen that the slope of the curve is small (small sensibility), and gives a negative sensibility, e.g., gives an opposite relation between normalized factor and equivalent stress. This means that although a relation was found between the average graphite nodules diameter and fatigue life (see Fig. 8), if the number and location of the same nodules are incorporated in the relation (as the normalized factor, ψ, does) that relation is lost. Furthermore, it is clear that the sensibility, when compared to the one given by the normalized factor (0.25**d*, and the angular position of graphite nodules between 45° and 90°) is small.

Thus, by the results of this study it seems that it is possible to obtain more accurate predictions than those of Murakami's model if more detailed analyses are performed.

4. Conclusions

Sofue (Ref 2, 3) and Murakami (Ref 1) models seem to establish a good correlation for fatigue life for stress levels near the fatigue limit.

However, it is possible to substantially improve the accuracy of fatigue life prediction if the following procedure is followed:

- The distance between two graphite nodules is $a \leq 1{*}d$ (similar to Murakami), but taking into account the angular positions effect on stress state (between 45° and 90° in relation to the load direction);
- An equivalent area is obtained based on the graphite nodules distance smaller than 0.25**d* for any relative graphite nodules position;
- Both the distance between graphite nodules is smaller than 0.25**d* and the angular position is between 45° and 90° in relation to the load direction. This last option gives the best accuracy.

Sofue's model seems to be scientifically too simple and does not work if a deeper analysis is incorporated in the relation (number and location of the same nodules).

Murakami's model has a lower sensibility and then makes fatigue life predictions to have lower accuracy than any of the other three models: *equivalent graphite nodules area (for* $a \leq 0.25{*}d$*, for every relative position), equivalent graphite nodules area (for* $a \leq 1{*}d$*, and for graphite nodules relative position between* 45° *and* 90° *in relation to the load direction),* and *equivalent graphite nodules area (for* $a \leq 0.25{*}d$*, and for graphite nodules relative position between* 45° *and* 90° *in relation to the load direction).*

Acknowledgments

This work was supported by a BDE—Bolsa de Doutoramento em Empresa (PhD Grant between FCT "Fundação para a Ciência e a Tecnologia" and Mahle Company) with the reference SFRH/BDE/15556/2005.

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