INFLUENCE OF GRAPHITE NODULES ON FATIGUE LIMIT OF NODULAR CAST IRON

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ABSTRACT: This paper describes the fatigue behaviour of a nodular cast iron dispersed within martensitic matrix microstructure. Cyclic fatigue tests have been performed on nodular cast irons. The effects of both the microstructure and the graphite nodules geometrical features such as shape and size, on the fatigue behaviour of nodular cast iron were studied. The rule of size and position of graphite nodules on the fatigue limit has been established. On this study is verified if the $\sqrt{area_{\max}}$ (square root of the maximum graphite nodule area projected onto the principal stress plane) parameter model proposed by Murakami, quantitatively predicts with accuracy the fatigue life of the nodular cast iron.

In this paper, a high strength nodular cast iron, with rupture strength of about 1.300 MPa and Young modulus of about 165 GPa has been used. Comparison between experimental results and $\sqrt{area_{\max}}$ parameter model has been assessed.

Keywords: Nodular cast iron, Fatigue strength, defects geometry, automotive**.**

RESUMO: Este artigo descreve o comportamento á fadiga do ferro fundido nodular com matriz martensitica. Testes de fadiga foram realizados em amostras de ferro fundido nodular. Foi estudado o efeito da microestrutura e dos nódulos de grafite (forma e tamanho), no comportamento á fadiga do ferro fundido nodular. Uma relação entre tensão limite de fadiga, tamanho e posição dos nódulos de grafite foi estabelecida. Neste estudo foi verificado se o modelo proposto por Murakami, $\sqrt{area_{\max}}$ (raiz quadrada da máxima área projectada dos nódulos de grafite no principal plano de tensão) prevê com exactidão a tensão limite de fadiga.
Neste artigo foi utilizado um ferro fundido nodular com tensão limite de rotura de 1.300 MPa e modulo de elasticidade de 165 GPa. Uma comparação entre resultados experimentais e o modelo proposto por Murakami, $\sqrt{area_{\max}}$, foi efectuada.

Palavras chave: Ferro fundido nodular, resistência á fadiga, defeitos geométricos, automóvel.

1. INTRODUCTION

Recently, with the high performance and efficiency of machine, there have been required the multi-functions in various machine parts, such as the heat resistance, the abrasion resistance and the stress resistance as well as the strength. The usage of nodular cast iron has been extended for use of structural material. Nodular graphite cast iron is much superior to the other materials in its abrasion resistance, damping property, low temperature shock property, economy and workability, and thus it is extensively used in cylinder block, cylinder head, connecting rod, piston rings and brake parts of automobile assemblies. The attractive properties of the Martensitic Nodular Cast Iron are related to its unique microstructure. Because of its excellent mechanical properties, the Martensitic Nodular Cast Iron is now finding more and more structural applications in automotive components, defense, agricultural, mining and construction equipment.

As considered as the main cause of failure in industrial components, fatigue remains the main source of unexpected failure in mechanical components as the majority of structures are subjected to cyclic, alternating stress. Fatigue limit of cast materials is mainly controlled by the presence of casting defects such as microshrinkages or dross defects. It is therefore of primary importance to consider such defect features as input parameters in fatigue limit assessment.

There exist many approaches of fatigue resistance evaluation for defect containing materials [1–10] and of microstructure [1, 3, 6] on the fatigue strength of nodular cast iron. Fatigue life and fatigue limit are therefore assumed to be controlled by the crack propagation law and by the threshold stress intensity factor, respectively.

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. 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) [1].

Murakami, carried out detailed and systematic experiments, and proposed a simple equation function of the hardness, Hv, and the square root of the maximum projected area onto the principal stress plane of the defect, $\sqrt{area}$ [1]. As been thought that the strength of a graphite nodule itself could be considered as a defect, because the graphite nodules it is weak, as compared with the microstructure, and therefore mechanically equivalent to a stress hole or notch [9]. Endo [10,11], carried out experiments, where he compared the fatigue strength of nodular cast iron specimens containing nodules with electropolished cast iron specimens without graphite nodules at surface. Thus, the nodules of the latter specimens became stress free vacant pores. Comparison of the fatigue strength of these two types of specimens did not show difference 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 a defect [10, 11]. Murakami has done numerical analysis [12] that shows the interaction effect between two cracks.

In this study it will be made a comparison between some of the different 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. Based on the present work it will be possible to understand the scatter of the fatigue life and correlate with intrinsic properties as well as with other geometrical features and with defects.

2. MATERIALS AND EXPERIMENTAL DETAILS

The present study has been conducted with twenty piston rings. The bulk material is a nodular cast iron constituted by a martensitic matrix. The fatigue samples were prepared by MAHLE – Componentes de Motores, S.A.. The mechanical properties of the material are listed in table 1. The bulk material of the different piston rings exhibits graphite nodules with very different mean diameter as shown in Fig. 1 a), and b). Two holes were done on the piston rings in order to assembly it on the fatigue test machine, as shown on (Fig. 2 a)) (where the load and the restraint were applied). Fig. 2 b), shows the stress distribution on the piston ring. The maximum stress is at 180º of the gap. With a strain gage judiciously placed on the area where the stress is maximum strain was measured and the maximum and minimum stress applied on the piston ring were calculated with the elastic modulus, ($\sigma = \varepsilon * E$).

The tests were conducted in air at room temperature on samples with rectangular cross section, using a sinusoidal signal with a frequency of 25Hz and load ratio R=0,3.

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

Material	Class	Subclass	Young Modulus E [GPa]	Tensile strength σ_u [MPa]
Nodular Cast iron	50	MC53	160	1.300

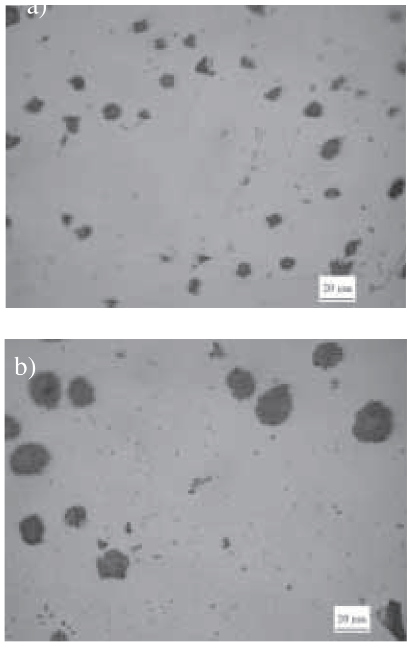


Fig. 1. Nodular cast iron, bulk microstructure; a) mean average diameter 10 μm; b) mean average diameter 21 μm;

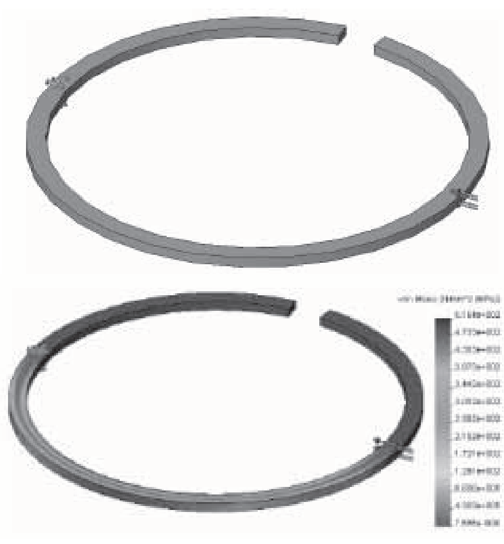


Fig. 2. a) Piston ring (applied load and restrains); b) Stress distribution on a piston ring

All defects found on specimens (see Fig. 3) were measured and taken into consideration along with the graphite nodules since all are considered defects in this study. The tested samples at the stress level $\sigma_{max} = 800$MPa and $\sigma_{max} = 716$MPa, were observed on the optical microscopic according with the scheme shown on Fig. 5. On Fig. 5 is also represented the stress distribution under bending. An area of about 0,6mm x 1mm, near the surface which includes stress levels above 35% of maximum stress was used for geometrical nodule analysis.

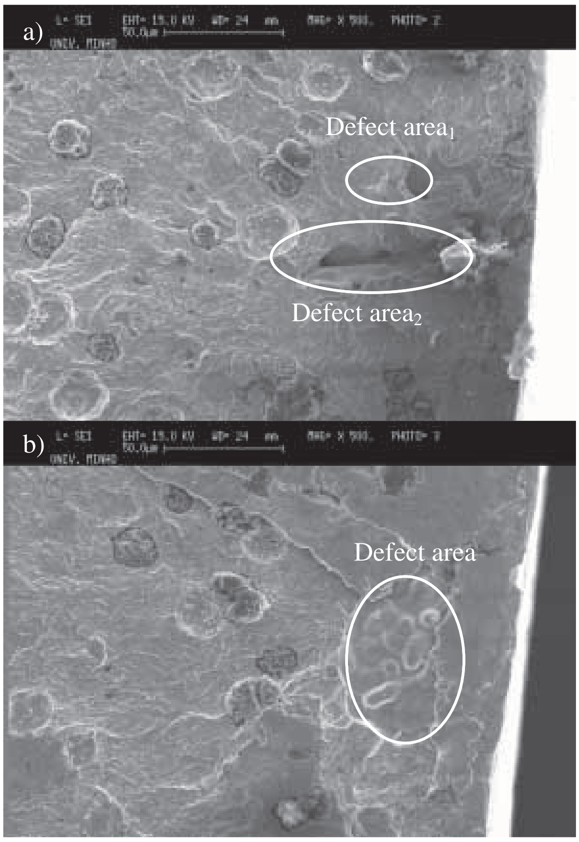


Fig. 3. a) fracture surface of sample 4 (defect area$_1$=543 μm^2; defect area$_2$=1.300 μm^2); b) fracture surface sample of sample 6(defect area = 2.684 μm^2)

The hardness was measured on all samples. The hardness values are the average of five measurements in each sample.

3. RESULTS AND DISCUSSION

3.1 S-N curve

Fatigue test results are presented in Fig. 4, where the number of cycles to failure is plotted vs. the maximum 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 on Fig. 4, that the total life of the specimens tested at $\sigma_{max} = 800$MPa changes from 54.000 cycles to 197.000 cycles, while the specimens tested at $\sigma_{max} = 716$MPa changes from 52.000 cycles to 2.600.000 cycles. Because of this high scatter, two stress levels were selected ($\sigma_{max} = 800$MPa and $\sigma_{max} = 716$MPa) to be studied. 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.

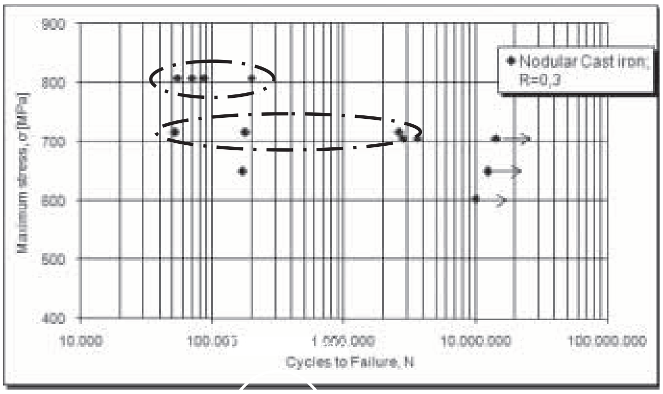


Fig. 4. Martensitic nodular cast iron S-N curve

On 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.

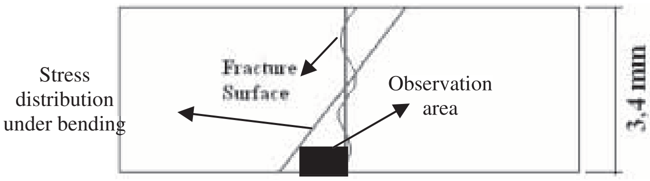


Fig. 5. Scheme of the area used for optical observation (A=0,6mm x 1mm)

3.2 Hardness of the matrix

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

An 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 0º to 90º where 0º means that both graphite nodules are collinear with the load direction (Fig. 6 a)) while 90º represents the case where the nodules are perpendicular to the load direction (Fig. 6 e)). The distance between the two graphite nodules changes from 0,25**d* to 4**d*, where *d* is the smaller diameter of the graphite nodule, *D* is the higher diameter of the graphite nodule, and *a* is the distance between the two graphite nodules.

Table 2 - Mechanical and geometrical properties of the graphite nodules

Sample number	Max Stress [MPa]	Hardness		Total Life [cycles]	Graphite nodules		
		[Hv]	STD		Minimum Diameter [µm]	Maximum Diameter [µm]	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

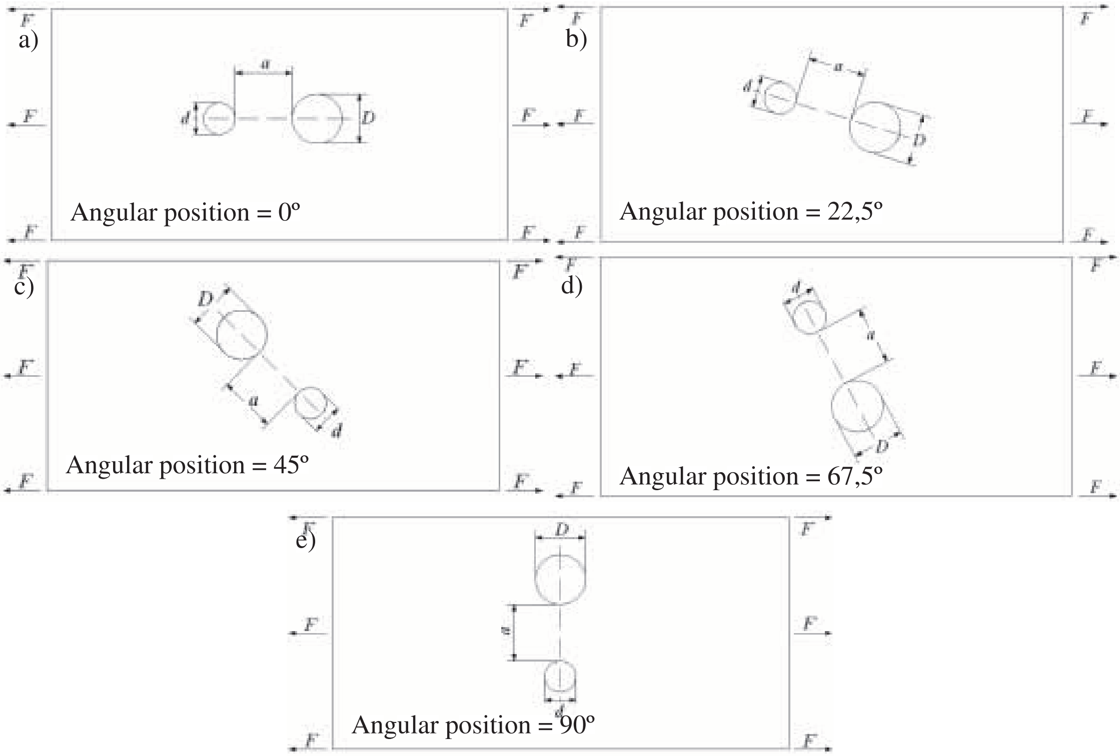


Fig. 6. Interaction effect between adjacent graphite nodules (relative position change from 0º to 90º) on local stress level

Fig. 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 0º or 22,5º 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 between nodules decreases. It is also evident that the relative position has a substantial influence on local stress level only for values of distance between nodules less then *1*d.* This means that the critical situation is when the relative position is between 45º and 90º and the distance is less than 1**d* (see Fig. 7).

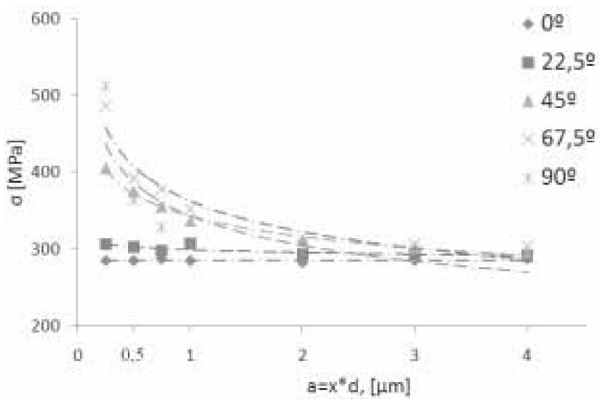


Fig. 7. Influence of relative position between two graphite nodules (distance and angular position) on the stress level

On section 3.1 was shown that there is a very high scattering on the fatigue life of nodular cast iron samples. On section 3.3 was shown that the relative position and distance between graphite nodules have influence on the local stress level.

In the next sections (3.4 and 3.5) will be established a correlation between these geometrical features and the fatigue life scattering. It will be analyzed the correlation between Murakami's model and the experimental results. It will also be presented a modification to the Murakami's model. At last (on section 3.6) it will be presented a factor, ψ, that gives an improved sensibility between fatigue life and graphite nodules geometrical features.

3.4 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 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 so near to each other, then the stress intensity factor increases significantly, and the cracks are likely to coalesce by fatigue crack growth in a small number of cycles.
This was demonstrated on the finite element analysis on section 3.3. Murakami [9] has done numerical analysis that 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. On Fig. 8 is possible to observe a scheme of this rule.

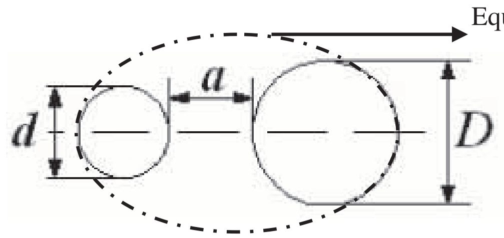


Fig. 8. Interaction between adjacent cracks

Murakami [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 microstructure hardness, Hv.
As shown on table 2, the microstructure Vickers hardness, Hv, 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 analyses were done according to the scheme on Fig. 5.

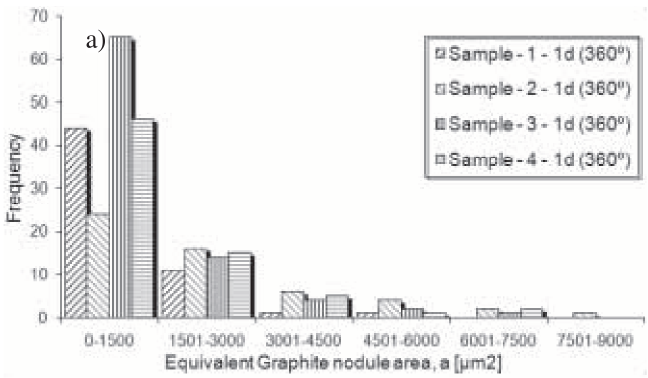
Fig. 9 a) shows a distribution of the equivalent graphite nodules area, $area_{eq.}$, for the samples tested at 800MPa. On the histogram is possible to verify that sample 2 has the higher value for the equivalent graphite nodule area. Sample 1 has the minimum value for the equivalent graphite nodule diameter followed by sample 3 and sample 4. Fig. 9 b) shows the behaviour of the samples tested at 716MPa. 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} = 800MPa

A correlation between equivalent area, $area_{eq.}$, and fatigue life was not found for this stress level. Analyzing Fig. 9 a), is possible to observe that the behaviour in terms of fatigue life of the four samples (if is considerate that as high is the maximum equivalent area, $area_{eq.}$, lower is 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} = 716MPa

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



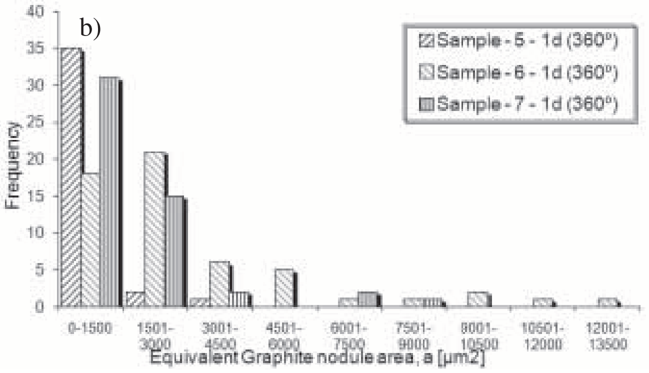


Fig. 9. *Histogram of equivalent graphite nodule area (for a ≤ 1*d, independently of relative position) for samples tested at two different stage levels; a)* σ_{max} = 800MPa; *b)* σ_{max} = 716MPa

From the analysis of section 3.4 is possible to conclude that Murakami's model 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 this model was established for the fatigue limit it can be considered that it has a good correlation with experimental results.

Taking into consideration the rule used by Murakami (interaction between adjacent cracks) and the numerical analysis in section 3.3, in sections 3.5 and 3.6 will be discussed the accuracy of the Murakami rule, and a possible modification to it.

3.5 Others interactions between adjacent graphite nodules

According to [13], for better mechanical properties the nodular cast iron should have the lower frequency of graphite nodules and lower equivalent area. The lower equivalent area means that there are no adjacent graphite nodules *(a ≤ 1*d)*. Taking this aspect in consideration a factor ψ will be defined. The factor ψ defines the frequency of graphite nodules and its equivalent area. The factor ψ is calculated based on values of intersection points between the tendency line and both axes, *x* and *y*. So, the factor ψ could be calculated by the next equation:

$$\psi = x * y \qquad \text{Eq. 1}$$

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.
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On section 3.5.1 and 3.5.2 will be presented the histograms where it is possible to observe the tendency lines for all the samples, from where factor Ψ was determined.

3.5.1 Interaction between adjacent graphite nodules (a ≤ 1*d) independently of relative position

Fig. 10 a), and b) show the histograms with tendency lines where is plotted frequency versus equivalent *graphite nodule area (for a ≤ 1*d, independently of relative position)*, as used by Murakami.

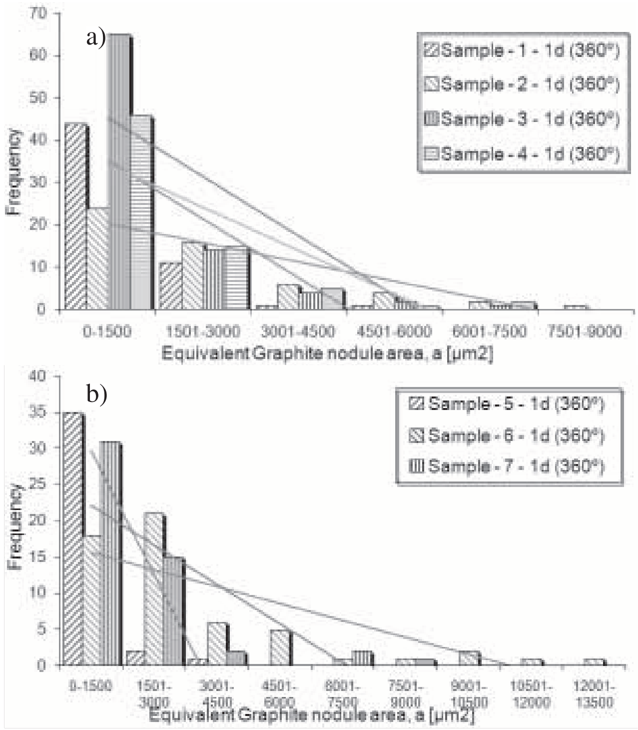

Fig. 10. Histogram of equivalent graphite nodule area (for a ≤ 1*d, independently of relative position) for samples tested at two different stage levels; a) σ_{max} = 800MPa; b) σ_{max} = 716MPa

The factor Ψ, as obtained by histograms on Fig. 10 b) are plotted on Fig. 14 along with other values obtained with other interaction between adjacent graphite nodules.

3.5.2 Interaction between adjacent graphite nodules (a ≤ 1*d) and for graphite nodules relative position between 45º and 90º in relation to the load direction

The method followed in this case was similar to the first one (section 3.4), but in this case only the graphite nodule with angular position between 45º and 90º were taken into consideration. When the position between two or more graphite nodules has a distance *a ≤ 1*d* and an angle between them of 45º to 90º, as shown on Fig. 11, a new equivalent area, $area_{eq}$ was calculated.

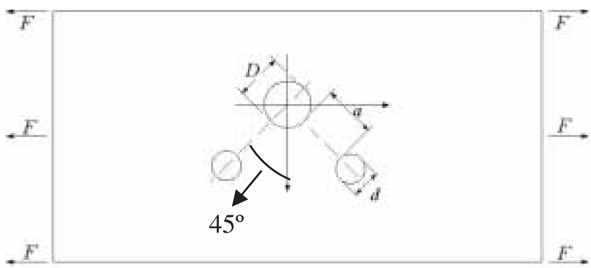

Fig. 11. Graphite nodules relative position between 45º and 90º

Fig. 12 a) shows a distribution of the equivalent graphite nodule area, for the samples tested at 800MPa. On the histogram is possible to verify that sample 2 and sample 3 have the higher value for the equivalent graphite nodule area. It is also possible to observe that sample 1 has the minimum value for the equivalent graphite nodule area followed by sample 4. Fig. 12 b) shows the behaviour of the samples tested at 716MPa. It is possible to observe that sample 7 has the higher equivalent graphite nodule area, while sample 5 has the lower value for the equivalent graphite nodule area.

- Stress level – σ_{max} = 800MPa

As on the previous results, also in this case a correlation between equivalent area, $area_{eq.}$, and fatigue life was not found. Analyzing Fig. 12 a), is possible to observe that the behaviour in terms of fatigue life of the four samples (if is considerate that as high is the maximum equivalent area, $area_{eq.}$, lower is 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} = 716MPa

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

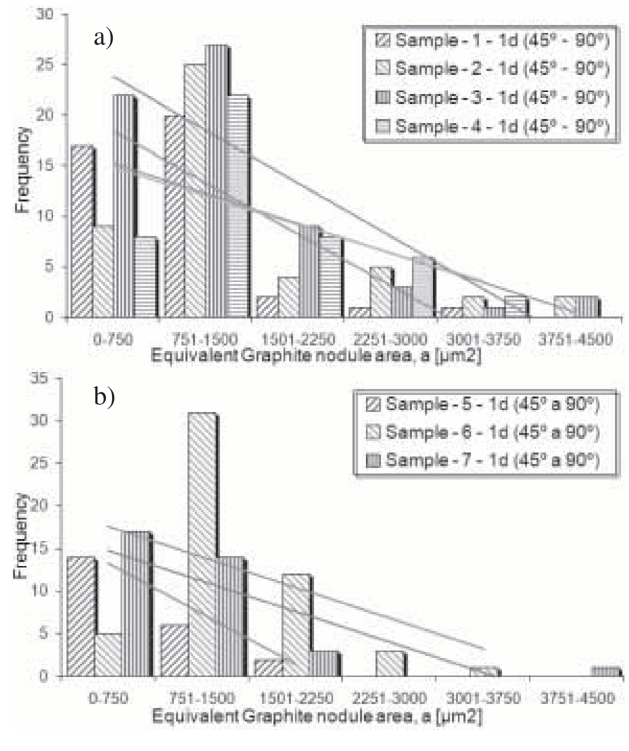

Fig. 12. Histogram of equivalent graphite nodule area (for a ≤ 1*d, and for graphite nodules relative position between 45º and 90º in relation to the load direction) for samples tested at two different stage levels; a) σ_{max} = 800MPa; b) σ_{max} = 716MPa

Although it was not established a correlation between the maximum equivalent area and fatigue life it will be shown on section 3.6 that if factor Ψ (frequency also included in analysis) is considered there exists a good correlation.
The factor Ψ, as obtained by histograms on Fig. 12 b) are plotted on Fig. 14 along with other values obtained with other interaction between adjacent graphite nodules.

3.6 Factor ψ

Fig. 13 shows an equivalent stress value for each tested sample. The equivalent stress value was obtained through the *S-N* regression curve of the nodular cast iron (see Fig. 4). For each sample, according to its fatigue life, was calculated the equivalent stress level, as shown on Fig. 13. So, the equivalent stress levels for all the samples are:

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

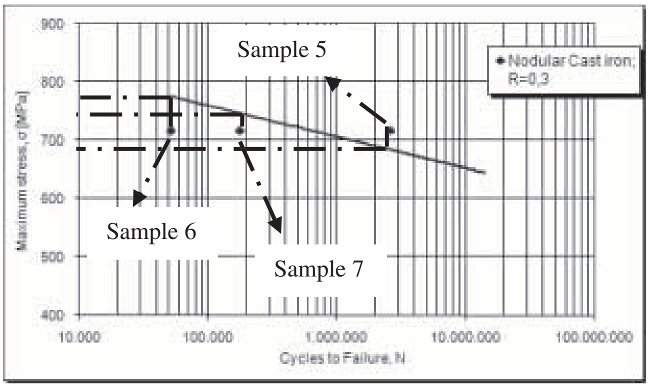

Fig. 13. Equivalent stress for each sample life

Using Eq. 1, is possible to calculate the factor Ψ for each sample. The normalized factor Ψ is calculated through the ratio between each factor Ψ and the minimum factor Ψ of all samples, and can be expressed by the following equation.

$$\text{Normalized factor } \Psi_i = \frac{\Psi_i}{\Psi_{min}} \qquad \text{Eq. 2}$$

Fig. 14 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. 14 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 ≤ 1*d and the angular position is between 45º and 90º, the sensibility also increases in relation to the Murakami model.

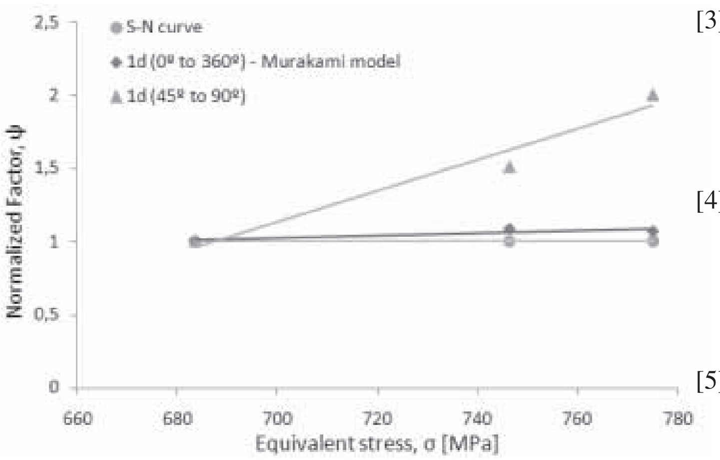

Fig. 14. Normalized factor ψ

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

4. CONCLUSIONS

Murakami [1] model 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 analysis is made:

- The relative position for the distance between two graphite nodules is a≤1*d (similar to Murakami), but taking into account the angular positions effect on stress state (between 45º and 90º in relation to the load direction);

Murakami's models have a lower sensibility and then make fatigue life predictions to have lower accuracy than the other model: *equivalent graphite nodule area (for a≤1*d, and for graphite nodules relative position between 45º and 90º in relation to the load direction).*

ACKNOWLEDGEMENTS

This work has been 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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