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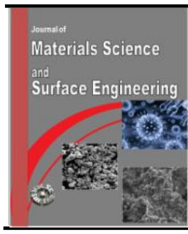

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Improving Fatigue Strength of Ductile Iron Components Meant for Automotive Applications through Foundry Processes

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Abstract

Fatigue strength is an important characteristic of the components which decides the life of the product. Since fatigue failures of the components are happening during running of the vehicle or the machine the consequences of failures are relatively severe than the other type of failures. Ductile iron is mostly used for automotive applications because of its good fatigue resistance. Ductile Iron is also known as S. G. Iron or Nodular Iron. Nodular shaped graphite acts as a stress arrester which leads for this good fatigue resistance characteristic of this material. But design of the component and the foundry processes are much focused because these two factors play a vital role in deciding the fatigue strength of the component.. In this paper it has been discussed the ways and means to enhance the fatigue resistance of the component through foundry processes.

The work had been presented *at an* international conference ***Fatigue Durability India 2015****, 28-30th May 2015, JN TATA AUDITORIUM, Indian Institute of Science, Bangalore.*

Introduction

Ductile iron is used mostly for engine and transmission components nowadays because of the following reasons

a) Good strength to weight ratio
b) Good fatigue strength
c) Good manufacturability
d) Relatively less manufacturing cost
e) Excellent machinability

Normally automotive components especially components for transmission, engine and brake applications are subjected to fatigue or endurance test to about 10 million cycles with variable load for validating the component design and foundry processes before put into serial production. While designing the component the standard properties of the material are taken for guidance but it should be remembered that these properties are derived based on the fact that the material is with homogenous microstructure with no internal defects. But in reality no material is having homogeneous microstructure and without flaw. Though factor of safety is included to compensate this, sometimes component will fail miserably in a minimum number cycles due to various factors which are discussed in this paper.

Component design and foundry processes are both complementary to each other in achieving the desired fatigue properties of the component. Producing casting to meet the general dimensional requirement and metallurgical are easy but to pass the fatigue or endurance tests foundry need to work more on finer metallurgical parameters which can be achieved through good process control and good foundry practices

Usually a ductile iron casting with desired microstructure and good integrity exhibits good fatigue resistance. The followings factors are affecting the fatigue strength of the casting

Macro Level Factors

a) Casting geometry by design.
b) Presence of shrinkage defects in the casting.
c) Presence of surface and subsurface defects.
d) Surface irregularities and presence of cracks due to poor fettling processes.
e) Surface finish of the casting.

Micro Level Factors

a) Less material strength (Tensile and yield strength).
b) Presence of micro porosities and drosses in the casting.
c) Presence of carbides.
d) Bigger nodule sizes (>30 microns).
e) Poor nodularity (<85%).
f) Presence of internal stresses.
g) Bigger grain sizes.

For engine and transmission parts fracture toughness is an important requirement which ultimately decides the fatigue limit of the material. Fracture toughness is the characteristic of the material which shows its ability of absorbing impact loads. Graphite morphology and microstructure of the ductile iron facilitates the enhanced property of fracture toughness. Normally, the presence of any non metallic inclusions in the metal reduces the fatigue strength, but in ductile iron the graphite presence in the form of nodules acts as stress arrester, it absorbs the load and suppresses the intensity of load propagation inside the material further which consequently increases the resistance of crack propagation.

Metallurgical Properties Requirements for Good Fatigue Strength

To improve the fatigue strength of the material apart from the design factors, graphite morphology and microstructure play a vital

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role. Graphite is a non metallic inclusion but fatigue strength depends on its shape, size and number of nodules. When the shape of the graphite is in flake form it shows poor fatigue strength whereas when it is in nodular form, fatigue strength increases dramatically. Graphite form in ductile iron is classified in standards like ISO 945 standard and ASTM A247. According to the standards graphite as form V and VI as per ISO945 and class 1 and 2 as per ASTMA247 indicate good degree of roundness i.e the circumference to diameter ratio is nearing to 3.14. % Nodularity on the other hand represents the number of nodules present with good degree of roundness in percentage. Experimental results shows fatigue strength of the ductile iron increases with increase in nodularity also there is a relationship with nodularity and nodule size. Whenever the nodule size decreases nodularity will increase. Nodule size normally will vary between 10 microns and 50microns. The notable relationship is found between nodule size and count. Nodule count decreases with increase in nodule size. So to get good fatigue strength the following conditions should be satisfied when seeing the microstructure under 100X magnification

Nodularity >90%Nodule count > 300 /mm²

Nodule size - 10 -25 microns

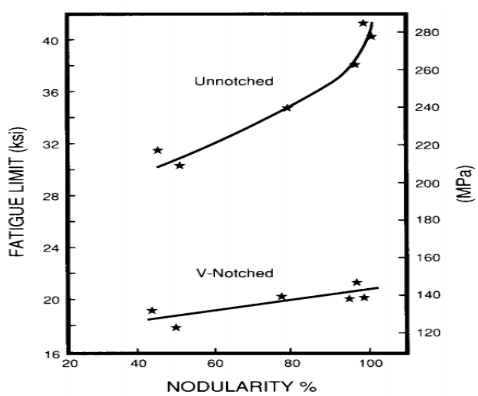
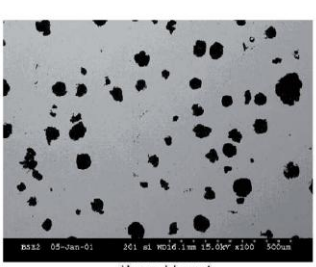


Figure 1: Effect of Nodularity over Fatigue Limit

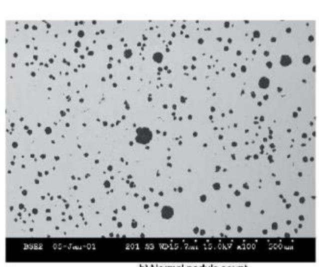
The above graph in figure 1 shows that fatigue limit is directionally proportional to the nodularity.

Achieving the above values is depends on the process control in melting and gating design. The amount of carbon and silicon is taking a vital role in deciding the graphite morphology. Increase in carbon increases the size of the graphite nodules. Similarly silicon acts a graphitizer and increases the nodule size. On the other hand the lower percentage of carbon and silicon induces the chances of creating shrinkage defect in the casting which consequently reduces the strength of the casting drastically. So maintaining the carbon and silicon to the optimum level is very important.



a) Low nodule count

Figure 2: A



b) Normal nodule count

Figure 2:B

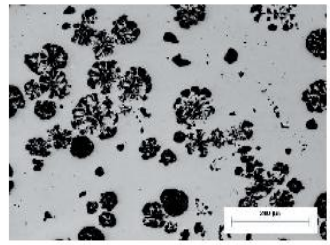


Figure 2:C

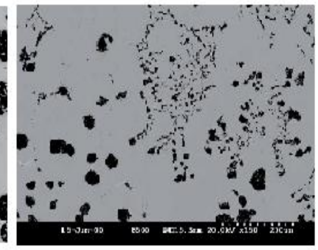


Figure2:D

Figure 2: Nodule microstructures

In the above pictures figure 2: A shows low nodule count <150/mm² with bigger nodules and figure 2:B shows more nodule count >600/mm² with smaller nodules. Figure 2:B is desirable when fatigue application is concerned.

Poor melting practice, high carbon equivalent and presence of tramp elements will deteriorate the graphite nodules resulting exploded graphite (figure 2: C) and spiky graphite (figure 2:D)

Nodule alignment is another phenomena which affects the fatigue strength of the casting considerably. Still the reason for this nodule alignment is not fully understood.Good inoculation practice and optimum carbon and silicon presence in the metal minimizes this defect.

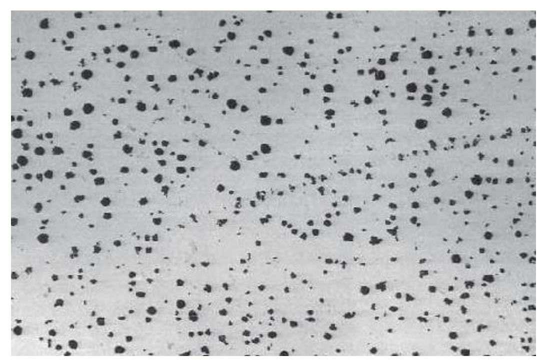


Figure 3: Nodule alignment

Fracture plan will fall on the aligned nodules since this plane exposes as a weaker strength to withstand the external load.

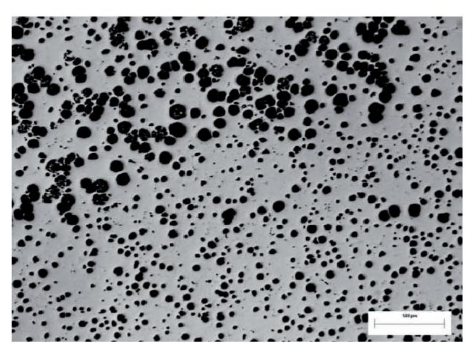


Figure 4: Graphite Floatation

Microstructure shown in Figure 4 is graphite floatation. Typically this type of defect will happen in castings having thick sections when carbon equivalent crosses thermal hyper eutectic values i.e C.E>4.5% . All the floated carbon reaches the surface and subsurface of the casting due to lesser in density and slow cooling of liquid metal due to heavy section thickness.

Table 1: Relationship between Nodule size and Total Life[1].

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

The above table is extracted from Ciência e Tecnologia dos Materiais, Vol. 20, n.º 1/2, 2008 N. Costa et al.[1]

The above table clearly explain the effect of nodule size over life of the component. Nodules with smaller in diameter exhibits more number of life cycles.

For the Ductile Iron Grade 60-40-18 has the highest QI of 64.8 and 29 for grade the 120-90-02. When tensile strength increases at the cost of elongation, QI decreases. Higher the Quality Index yields better fatigue ratio. The combination of UTS and % Elongation is referred in terms of Quality index.

$$QI = (\text{tensile strength ksi})^2 \times (\text{elongation}\%) \div 1000$$

Fatigue strength of the material is depends on ultimate tensile strength (UTS) and endurance ratio. Endurance ratio is the ratio between fatigue limit and tensile strength.

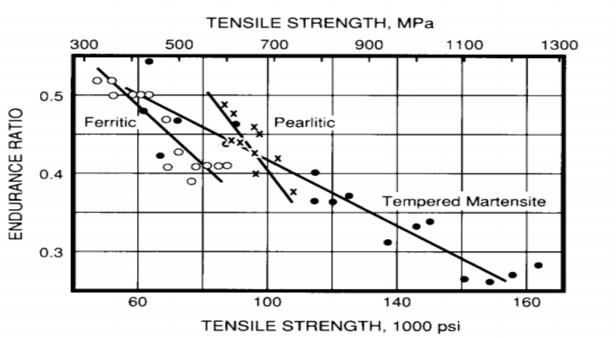


Figure 5: Relationship between Tensile strength and Endurance ratio

Requirements in Melting Practice to Improve Fatigue Strength

Disciplined melting practice is required to have good nucleation potential. The following factors related to melting are affecting the nucleation potential of the metal,

1. Long duration melting and unwanted holding of metal,
2. Super heating of metal
3. Poor quality of melting scraps.
4. Presence of tramp elements like Cd, Bi, As, Pb.
5. Excess amount of elements such as Cr, Mn, V, Sn, P etc present in the metal.
6. Poor quality of inoculants
7. Long pouring duration
8. Very fast melting.
9. Very low oxygen and sulphur levels.
10. Delayed pouring.
11. Un-controlled Magnesium treatment.
12. Low temperature pouring

The above things have to be avoided in melting to enhance the fatigue strength. Pre-conditioning of the metal, i.e removing excess oxygen in the metal will help in reducing the required amount of magnesium which is used to convert flake type graphite into nodule shaped graphite. Excess amount of magnesium will react with sulphur, oxygen and silicon and generates drosses in the metal which reduces the fatigue strength of component drastically.

At low pouring temperature iron is mixed with plenty of dross inclusions which do not separate easily from the melt. As the temperature increases the slag separates from the melt more easily and reduces its oxides of Si, Mn, Mg and Fe to their elemental form and possibility of getting oxide and silicate inclusions in the casting is minimized.

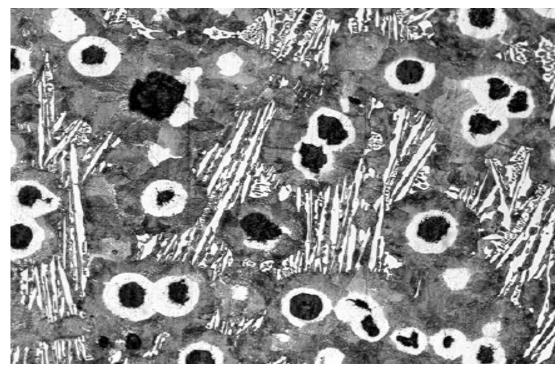


Figure 6: Microstructure contains primary carbides

Poor nucleation potential in the metal due to various factor as mentioned above will promote carbides and shrinkage porosity which affects the fatigue strength of the component significantly.

Excess amount of elements such as Cr, Mn, V, Sn, P etc present in the metal will solidify after Iron combined with carbon and formed its carbides, for example Cr (chromium) will form as chromium carbide and segregate at the grain boundaries weakens the component. The late solidification of these alloys will also produce micro porosities at the grain boundaries weaken the component further.

Thermal analysis software nowadays helps us to predict the metal behaviour and condition of the metal in order to improve the metal condition before pouring into the mould.

Gating and Risering Design

Gating and risering design play a vital role in achieving the desired fatigue strength. The running system is designed in such a way that the metal should not carry any unwanted materials inside the casting cavity. Unwanted materials such as non metallic oxides, sulphides and silicates may be from external source or generated inside the mould. The following things are to be considered while designing the gating system,

a) Long running system to be avoided.
b) Placing metal filters to prevent foreign particles entering into the casting cavity. Filter location must be as close to the casting cavity.
c) Non-pressurized or slightly pressurized gating system is preferable for ductile iron.
d) Velocity of the metal should not exceed 0.8 m/sec while entering into the casting cavity.
e) Right location of the gating system to minimize the impingement velocity.

f) Gate location should promote directional solidification.

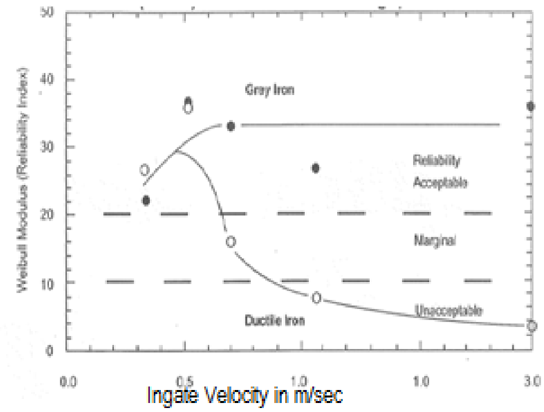


Figure 7: Graph shows the relationship between in-gate velocity and reliability index

Figure 7 indicates that reliability index is reducing with in-gate velocity. If velocity of the metal increases beyond 0.8m/sec it turns into turbulent flow which induces the formation of drosses inside the mould.

Bottom gating system is usually adopted for the castings subjected to fatigue strength. Smooth filling of metal with minimum turbulence is possible when the metal is entered from bottom gate. Because of the more impingement velocity top gating will produce more drosses in the metal.

Figure 8 shows the difference between bottom gating and parting line gating system. In the bottom gating velocity of the entry metal is less than 0.8m/sec where as the velocity in the parting line gating system shows more than 2m/sec which is very prone for producing dross defects.

Figure 8: Simulation shows the velocity of metal

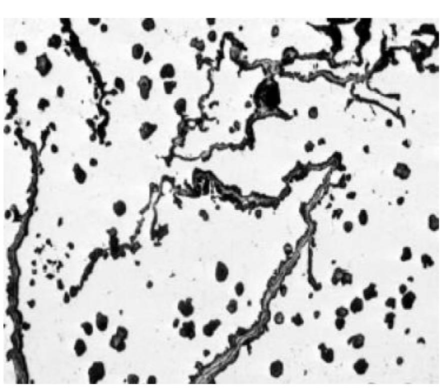


Figure 9 Microstructure shows silicate inclusion

Figure 9 shows silicate inclusion in the metal which affects the strength of the component drastically.

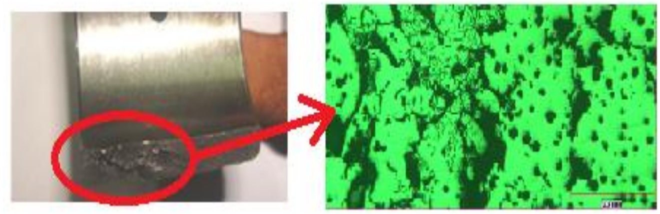


Figure 10: Fracture area of the castings with oxide and sulphide inclusion

Figure 10 indicates the presence of oxide inclusion at the fractured surface. Figure 11 explains the importance of clean metal in achieving the desired strength.

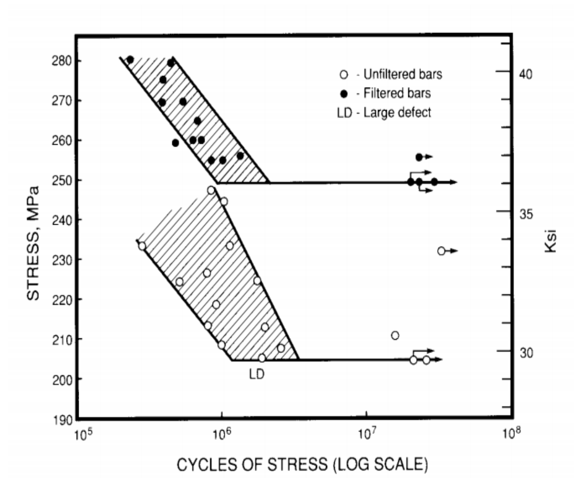


Figure 11: Effect of clean metal on stress and no of stress cycles

Similarly while designing the feeder (riser) the following things are to be considered,

a) Right sized riser based on modulus* of the casting. Under sized riser will create shrinkage porosity in the casting and oversized riser will create undesired graphite morphology.
b) Right location for the riser.
c) Right sized riser contact.

Modulus * - Ratio between volume and surface area of the casting.

Moulding requirements

Metal mould reaction is inevitable when a liquid metal get in touch with the mould. Metal temperature is playing a vital role here. High temperature induces the reactivity of the metal with mould material and produce lot of reaction products mainly magnesium silicates and sulphides.

Presence of sulphur components in the moulding materials react with magnesium in the metal and produces magnesium suphides. Also depletion of magnesium takes place on the surface of the metal which produces flake graphites at the surface of component as shown in figure 12. Presence of non metallic defects and deterioration in the graphite nodules at the surface affecting the fatigue strength of the product drastically since the deteriorated surface of the component is not able to withstand the tensile stress generated on the surface during function of the component and initiates crack on the surfaces.

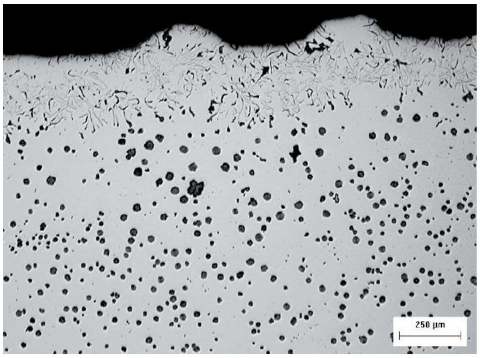


Figure 12: Flake graphite at the surface of the casting

Surface finish of the casting also playing a important role in achieving the fatigue strength. Poor surface finish of the casting, say the cast finish more than 10 RMS is not desirable for the products with fatigue application in the experience of the author. Peaks and valleys on surface of the component acts as stress raiser and initiates crack when loading.

Importance of Heat treatment

Because of the varying cross sectional areas the rate of solidification will vary from place to place even in a single casting. Differing solidification rates develop internal stresses within the component. Formation of microstructure is also depends on rate of heat transfer rate. So due to varying cross sectional areas in the casting the heat transfer also will vary from place to place. So each section in the casting will have different microstructure. To remove the internal residual stresses and to make the microstructure homogenous normalizing followed by stress relieving heat treatment is necessary.

Fettling and Shot Peening

Fettling in casting process refers de-gating, removal of parting line flashes and riser pads. While de-gating care should be taken that any of the de-gating methods should not create crack in the components. It is difficult to check the sub surface cracks sometimes which lead to fatigue failures. Proper methods to be adopted to remove the parting line flashes.

While removing the parting line flashes by using grinding wheels or cut-off wheels casting surface is marked with grinding marks as shown in figure 13B. When the direction of grinding marks is perpendicular to direction of loading plane then the grinding marks will act as a V notches and initiates crack during repeated bending. So the castings subjected to fatigue applications should not have any deep grinding marks on the surface.

Figure 13:A

Figure 13:B:

In the above picture figure 13A shows good surface finish where as figure 13B shows poor surface finish due to deep grinding marks created during removal of parting line flashes with traditional bench grinders.

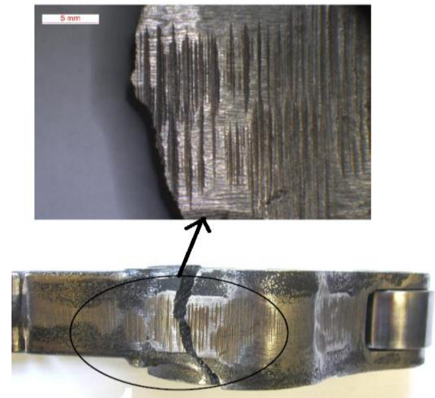


Figure 14: Casting failure due to deep grinding mark

While solidification of casting the surface of the casting starts solidify first due to sudden heat extraction by the mould wall. It produces undesired surface strain on the casting surface. Surface strain in the component will induce the premature fatigue failures when the part is subjected to repeated bending cycle.

Also when the part is subjected to repeated bending, tensile stress is induced on the outer surface layer of the component and compressive stress is induced in the inner surface layer of the component. Tensile stress will try to tear the surface layer when bending as shown in the figure 15 A.

Shot peeing is carried out on the surfaces to introduce compressive stress on the outer surface in order to neutralize the tensile stress and to remove the surface strain by work hardening.

Figure 15A: Before shot peening

Figure 15B: After shot peening

Graph shown in figure 15 depicts the effect of shot peening on fatigue cycle.

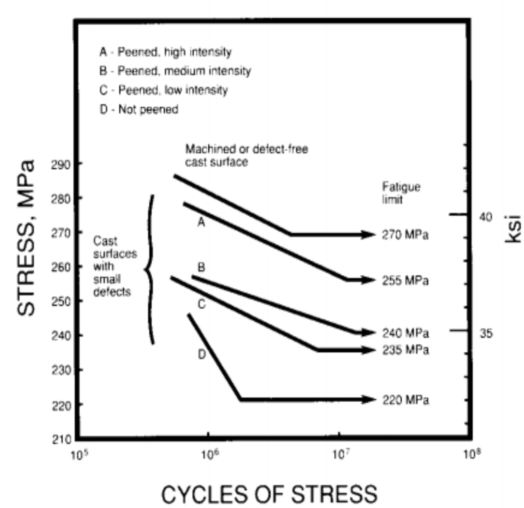


Figure 16: Effect of shot peening over fatigue cycles

Conclusions

Normally castings for transmission parts or engine parts are subjected to endurance test to about 10 million cycles with variable load. Producing castings to meet the requirement of passing 10 million cycles in endurance test are really a challenging task. Meeting the general dimensional requirements and metallurgical requirements are easy as said earlier but to pass the fatigue or endurance test we need to work more on mechanical and metallurgical factors on all the areas of foundry processes starting from pattern shop to fettling shop as discussed in this paper. Gating and risering design simply methoding in a foundry language and melting practice are the vital areas in a foundry which need to concentrate more to achieve the desired fatigue strength and to pass the endurance test.

References

1. Influence Of Graphite Nodules On Fatigue Limit Of Nodular Cast Iron N. Costa 1,2, N. Machado 2 , F. S. SILVA1 1 Universidade do Minho, Departamento de Engenharia Mecânica, Azurém, 4800-058 Guimarães, Portugal. 2 MAHLE Componentes de Motores S.A. Murtede, Portugal. nuno@dem.uminho.pt

2. Ductile Iron.org./ductile iron date.

