INTEGRITY OF CAST COMPONENTS CONTAINING INHOMOGENEITIES

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ABSTRACT

The high cycle fatigue behaviour of cast components is highly influenced by the presence of inhomogeneities dues to casting process. The purpose of this paper is to discuss a method that takes into account the presence of these defects in the fatigue assessment of automotive components submitted to multiaxial loading. We will first analyse fracture surfaces of suspension arms which have been cycled up to failure at high stress levels in order to reveal the type of defects involved in crack initiation; it is shown that both size and position of defects influence the fatigue resistance of the material. Secondly, fatigue test results obtained on laboratory samples are presented in order to point out the factors that have to be considered when assessing fatigue behaviour of defect materials. The fatigue limit evolution is given in tension and torsion as a function of defect size: this permits to establish the relationship between failure probability and defect size. The fatigue assessment proposed is based on Dang Van's fatigue criterion which includes the defect size parameter. Finally, an application is done in the case of suspension arms submitted to bi-axial fatigue. Results are in good agreement with available experiments.

INTRODUCTION AND INDUSTRIAL CONTEXT

Nodular cast iron is a material commonly used in the automotive industry for manufacturing engine and safety components such as crankshafts or suspension arms. This type of material contains microstructure heterogeneities, e.g. microshrinkages or dross defects, which are inherent in casting processes. The role of such heterogeneities in the fatigue resistance of the material must be assessed in order to ensure the optimisation of the component's design against fatigue. Accurate safety analysis requires to characterise the cyclic stress and strain state in the component and to analyse the influence of casting defect morphology on the successive fatigue damage process. It also necessitates the use of realistic fatigue damage laws representative of the influence of intrinsic or extrinsic factors governing crack initiation and growth. The most common method used to evaluate the fatigue limit of a material containing defects consists in assimilating the defect to a pre-existent crack. However, different questions arise about this approach with regard to the accuracy of the calculation of the stress intensity factor for small cracks or the validity of the crack growth data (ΔK threshold, crack growth law) classically established for long cracks. Moreover, the difference in behaviour of internal and surface defects have to be considered in particular with regard to environment-damage interactions which can be highly dependent on the location of the defects initiating the fatal crack: at the surface of the material or within the bulk.
In this paper, we will focus our attention on the fatigue behaviour of suspension arms (see figure 1). These

components are shoot penned in order to intoduce compressive residual stresses on the layer surface, they are made with a nodular cast iron and used as cast without any heat treatment. These components are submitted to high cycle fatigue loading and multiaxial loading has to be considered. The defect size is the other parameter that has to be integrated in the calculation process: as shown on figure 1, two types of defects can initiate the fatal crack. The first type of defect is located at the surface of the component and can be until 1 to 3 mm below the surface; they consist in oxides (see figure 1, suspension n°79, 81 and 91). The second type of defect is located in the bulk material, these microshrinkages are formed during the solidification process and are located close to the geometric centre of the component (see figure 1, suspension n°98).

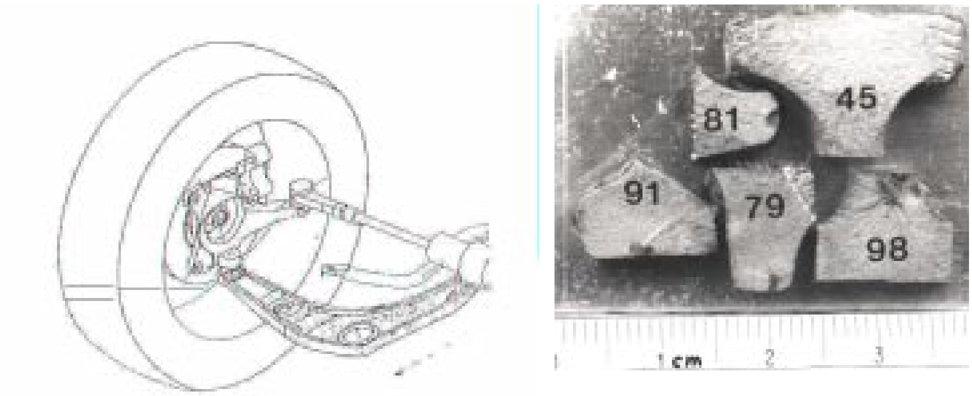

Figure 1: Suspension arm and defects on the fracture surface
(suspension arms broken at high stress level during laboratory tests)

Many parameters influence the fatigue resistance of such components: casting skin, heterogeneous microstructure, defect size, residual stresses... In order to get a clear insight on the influence of defects on the fatigue limit, the study has been separate in two parts:

- in the first part, results obtained on laboratory samples for two kinds of loading are presented. This permit to establish the proposed method that introduces the size of the surface defect in a multiaxial criterion. Furthermore, this allows to establish the relationship between failure probability and a defect size.

- The second part of the paper is devoted to a validation of the proposed method on fatigue tests which were conducted on suspension arms.

FATIGUE RESULTS ON LABORATORY SAMPLES

This part of the paper will present results obtained on nodular cast iron taken off from a casting block containing only microshrinkages. This avoids the presence of the casting skin which exhibits a very complex microstructure. Different size of microshrinkages are studied depending on the location of the sample in the casting block.

RENAULT has provided nodular cast iron used in the present study. The fully ferrite matrix is elaborated as cast without any heat treatment. The volume fraction of nodules is 10% with a mean size of 15 μm and a ferrite grain size of 50 μm. The bulk matrix exhibits a homogeneous distribution of nodules in the ferrite matrix. Samples are taken off the bulk of a casting block in order to avoid surface dross defects and to avoid a heterogeneous microstructure on the casting surface. The only defects expected in a sample are microshrinkages of size varying from 50 to 2200 μm. Mechanical properties are : E = 180 GPa, $R_{P0.2}$ = 380 MPa and R_m = 510 MPa. Fatigue life tests are conducted on smooth cylindrical samples polished up to 4000 paper.

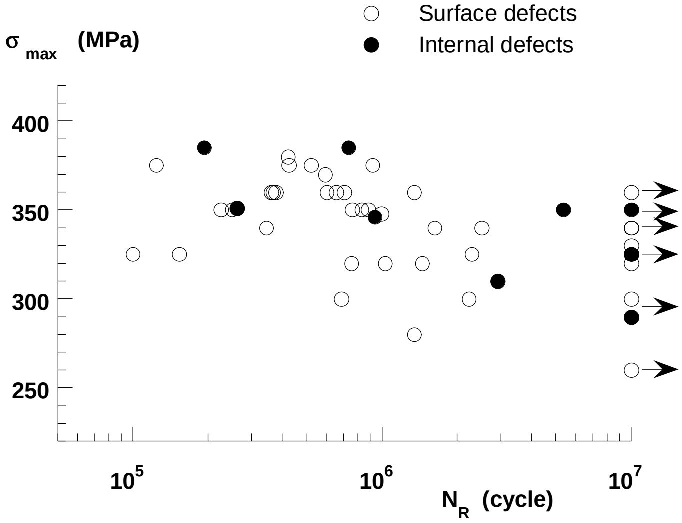

Figure 2: S-N curve, load ratio R = 0.1

Figure 2 presents the SN curve for tests conducted at a load ratio R = 0.1. All the samples were observed after failure. The behaviour of defect materials is usually analysed by assuming the initial defect as a pre-existent crack. The figure 3 gives some elements to discuss this assumption: a fatigue life assessment has been done on the basis of the integration of the crack growth law [1]. Results are reported on figure 3 where initiation stage (number of cycles to failure compared to calculated propagation life: initiation stage (%) =$(N_F-N_p)/N_R$) is plotted against fatigue life. This curve clearly shows that initiation stage is very important in the high cycle regime ($N > 10^6$ cycles). For lower fatigue lifes, the initiation stage is very sensible to defect size but can be very small so that it is good approximation to consider a defect as a pre-existent crack for short fatigue life regime ($N < 10^6$ cycles).

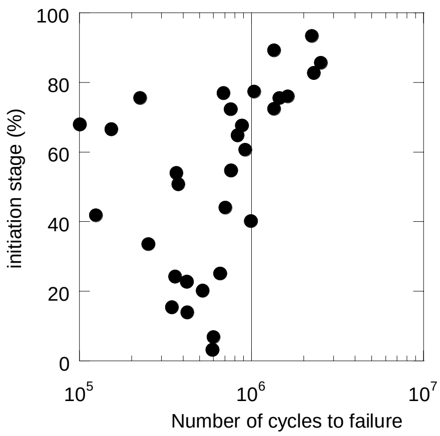

Figure 3: Evolution of the initiation stage against experimental fatigue life (surface defects only)

These observations lead to the conclusion that initiation stage is important in the high cycle regime: a realistic fatigue life assessment should take into account this phenomenon. Further more, the calculation of the fatigue limit can not be done using the threshold stress intensity factor because defect can not be assumed to be a crack in the high cycle regime. The point is now to determine how to evaluate the influence of defect on fatigue limit. On the basis of Murakami's defect size parameter ($area^{1/2}$) [2], an experimental determination of the evolution of the fatigue limit with defect size has been done; results are presented on figure 4. Experimental details are given in reference [3].

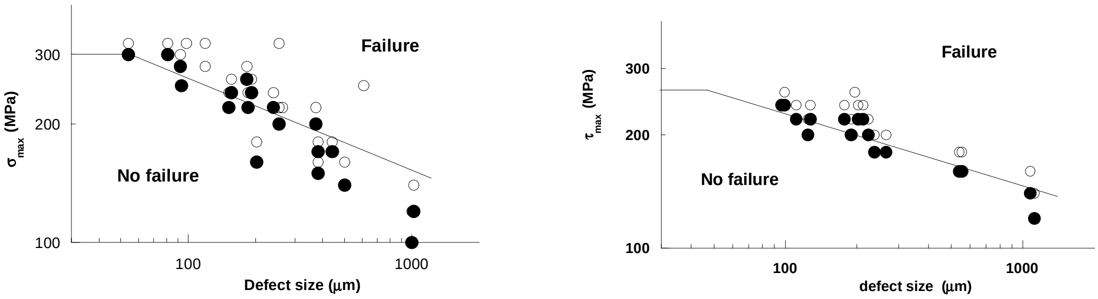

Figure 4: fatigue limit evolution with defect size: tension R = -1 and torsion R = -1

Those results permit to establish the experimental relation between the fatigue limit and the defect size (we suppose that a defect smaller than 50 µm does not influence fatigue limit). Furthermore, using this relation, it is possible to link a failure probability at the endurance limit to a defect size.

Fatigue limit, tension-compression (R = -1):

Defect < 50 µm : $\sigma_D = 300$ MPa (1)

Defect > 50 µm : $$\sigma_D = \frac{575}{\sqrt{aire}^{1/6}}$$

Fatigue limit, torsion (R = -1):

Defect < 50 µm $\tau_D = 250$ MPa (2)

Defect > 50 µm $$\tau_D = \frac{480}{\sqrt{aire}^{1/6}}$$

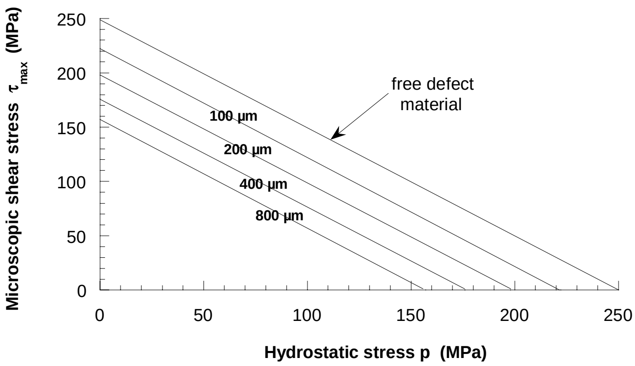

Figure 5: Threshold line from Dang Van criterion including defect size parameter

As shown on figure 5, thoses results can be used to establish the Dang Van's multiaxial criterion [4]. The threshold line is calculated using two fatigue limit (tension and torsion). Using formula (3) it is therefore possible to determine the fatigue limit of a component submitted to every kind of constant amplitude loading and containing a surface defect. Threshold line on Dang Van's criterion, including defect size, is determined by equation 3:

$$\tau + p = \frac{480}{\sqrt{aire}^{1/6}} \tag{3}$$

INDUSTRIAL APPLICATION ON CAST SUSPENSION ARMS

The purpose of this part is to present an industrial application of the calculation method proposed in the first part. This has been done on suspension arms as used on the car but submitted to very high stress level in order to fail the component. The suspensions were shoot penned and used as cast without any heat treatment. Figure 6 presents S-N curves for two different loading cases (experimental details are presented in reference [5]).

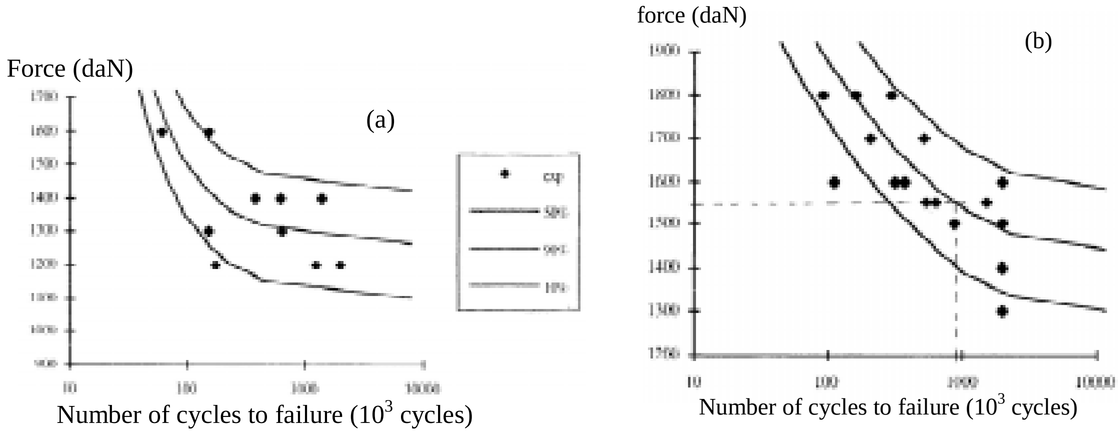

Figure 6: S-N curve on suspension arms for two kind of bi-axial loading

Suspensions are observed after failure and the defect at the origin of the failure is measured using the area$^{1/2}$ parameter. The S-N curve at 50 % is then associated to a defect size that permit to establish the loading path for a given defect size for both loading conditions in the Dang Van diagram (see figure 7). To establish Dang Van's threshold line, fatigue limit has been determined in tension and torsion for different surface defect size. This has been done on sample representative of the suspension arm: as cast samples, shot penned and same type of defect (surface oxides). The equation of the Dang Van line is:

$$\tau + 1{,}197\, p = \frac{597}{\sqrt{aire}^{\,1/6}} \tag{4}$$

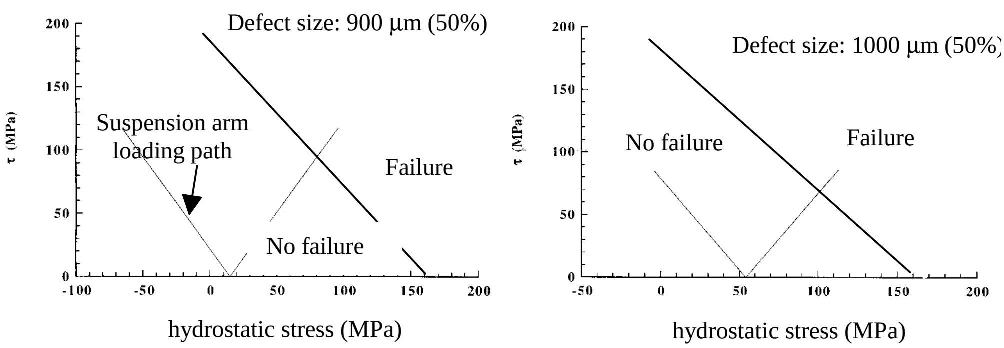

Figure 7: comparison between loading path and threshold line for two loading case

Figure 7 shows the comparison between the loading path (corresponding to a failure probability of 50 %) on the critical zone of the suspension arm and the threshold line. This is done for the two different loading conditions. In both case the loading path on the suspension cross the threshold line. A perfect prediction should put the end of the loading path on the threshold line. Nevertheless, error is not very important: 20 % so that we can conclude that the method is interesting. Furthermore, the main point is that it seems realistic to introduce the defect parameter in a multiaxial criterion as soon as we can determine a threshold line and it's dependence to defect size.

CONCLUSION

From the present study, the following conclusion can be drawn:

- defects are at the origin of the failure of cast suspension arms submitted to bi-axial fatigue so that defect size parameter have to be taken into account for the fatigue strength calculation of cast components.
- The initiation stage becomes very important in the high cycle fatigue range even for defect material, it seems therefore inapropriate to use crack threshold to calculate fatigue limit evolution with defect size. The calculation of the fatigue limit is based on empirical results using Murakami's parameter both in tension and torsion.
- We propose to introduce defect size parameter in Dang Van's multiaxial criterion. The method is applied to cast suspension arms and gives interesting results.

ACKNOWLEDGEMENTS

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