FATIGUE DESIGN OF METALLIC COMPONENTS CONTAINING SURFACE OR INTERNAL DEFECTS

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Abstract

The objective of this paper is to present a fatigue life criterion able to take account for surface or internal defects causing the formation of a crack in structural components. In the first part the importance of the crack initiation site location, at the surface or within the material bulk, on fatigue lifetime or fatigue limit is illustrated. With this aim, results obtained on two metallic materials containing microstructure or elaboration defects which in both cases lead either to surface or internal crack formation are presented. It is shown that internal defects are less damaging than surface ones due to environmental free conditions (vacuum). In the second part, a multiaxial fatigue criterion is proposed to take account for the influence of the defect size on the fatigue life. The last part is devoted to the validation of this criterion. A full scale structural test is presented on a spring containing a defect.

1 Introduction and experimental observations

Defects such inclusions, shrinkages or pores can be at the origin of fatigue failure of components. In order to propose a methodology for designing such components against fatigue, the behavior of defective materials has been addressed. Firstly, differences in fatigue lifetime or fatigue limit, depending on crack initiation conditions, at the surface or in the interior, are illustrated for a titanium Ti6246 alloy. Then, a quantitative analysis of the influence of the location and size of defects leading to the fatal crack initiation in a nodular cast iron are considered.

Fig. 1 presents the fatigue S-N curve obtained on a Ti 6246 cycled at 300°C in air or in a high vacuum. Tests were performed up to failure using 0.25 graded diamond paste polished specimens cycled under constant stress amplitude in fully reversed tension-compression conditions. Fracture surfaces are then carefully observed by SEM in order to reveal the location of the initiation site at the origin of the failure. For most of the stress levels investigated, the fatigue life under vacuum is higher than in air. This behavior is in agreement with results obtained for number of metallic materials: the effect of environment increasing when the applied stress amplitude decreases. However such a difference disappears for the lowest applied stress level at which the fatigue life in air and in vacuum are nearly equivalent. In this case, as it can be seen on the fracture surface, the weakest grain, at the origin of the fatal crack in the air tested specimen, is located within the bulk of the sample far from the surface (see Fig. 2). The other results in the air curve correspond to a classical surface initiation. It can therefore be concluded that when fatigue cracks are initiated within the bulk, most of the fatigue damage stages (initiation and crack propagation) are not affected by the air (oxygen and water vapor) environment. Fatigue life is then near the same than for a test conducted in vacuum. In the active environment the transition from a surface to an internal initiation produces a drastic increase of the fatigue life (by two orders of magnitude). As in air, the fatal crack initiation in vacuum occurs, from a surface site at high stress level and from internal sites at low stress levels. Nevertheless, there is no any change in the slope of the S-N curve since the crack is never assisted by the environment.

From this experimental work on a Ti 6246 it can be concluded that the location of the initiation site can depend on the stress level and that fatigue life associated with an internal failure can be compared to the one obtained under vacuum.

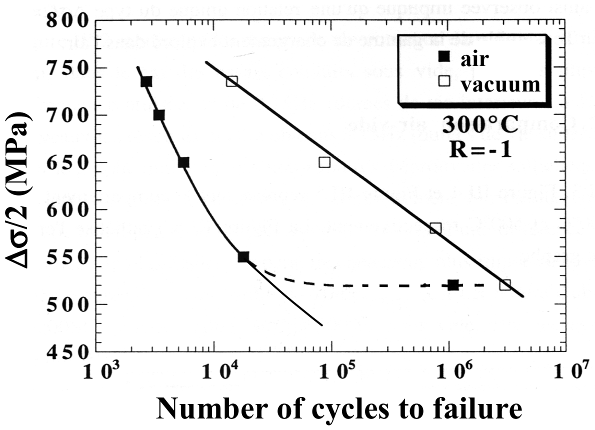

Fig. 1 *S-N curve, Titanium Ti 6246 alloy at 300°C, load ratio R = -1, under vacuum and air environment.*

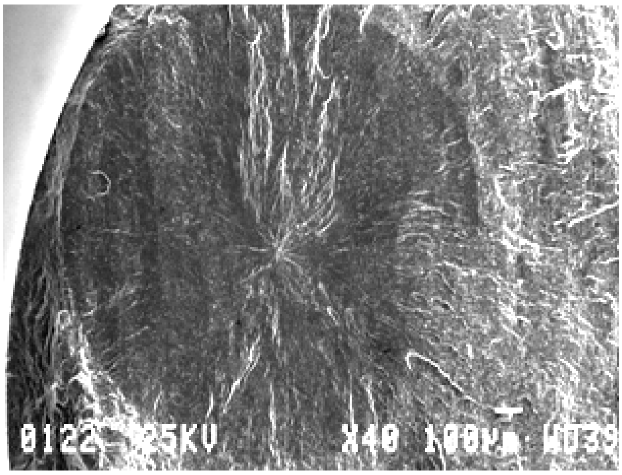

Fig. 2 *Fracture surface (SEM observation) of Ti 6246 : internal initiation.*

Other results can be shown to illustrate the role of internal or surface defect on fatigue damage from investigations conducted on a nodular cast iron containing shrinkages. Fig. 3 presents a failure initiated from a micro shrinkage located in the bulk. In order to compare the fatigue behavior from surface an internal defect, many tests have been conducted in order to obtain the Fig. 4 where the fatigue limit is plotted versus the defect size. There is a clear evidence that the fatigue limit for a given defect size depends upon the position of the defect. The defect size is measured on the fracture surface by the mean of Murakami's parameter [1]. Another clear evidence of the influence of the defect size is shown on Fig. 5. Further details are presented in ref. [2] where comparison between fracture surfaces under vacuum and fracture surface for internal defects are shown to be very similar. It is therefore concluded that environmental free conditions is a major factor that govern fatigue damage mechanisms in internal initiation conditions.

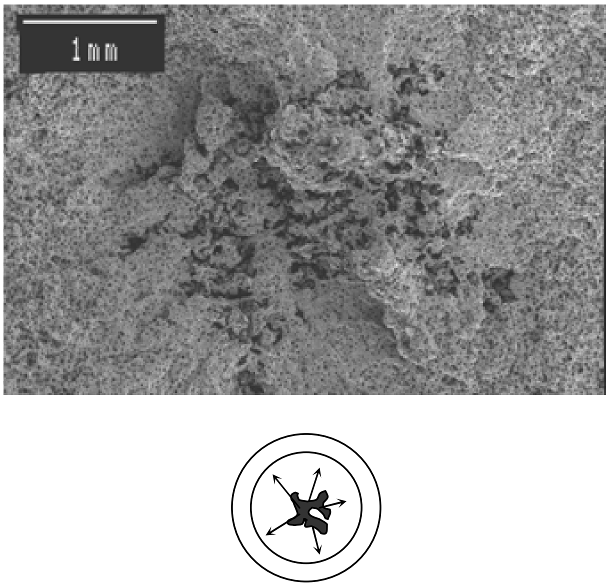

Fig. 3 *Fracture surface (SEM observation) of nodular cast iron: internal initiation.*

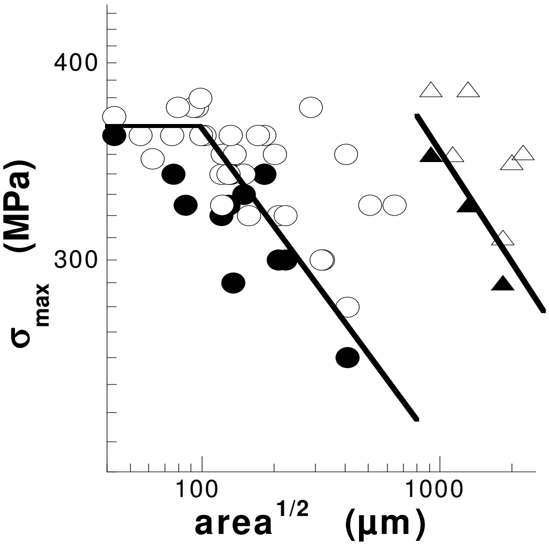

Fig. 4 *Evolution of the fatigue limit with defect size for both surface an internal defect, R = 0.1*

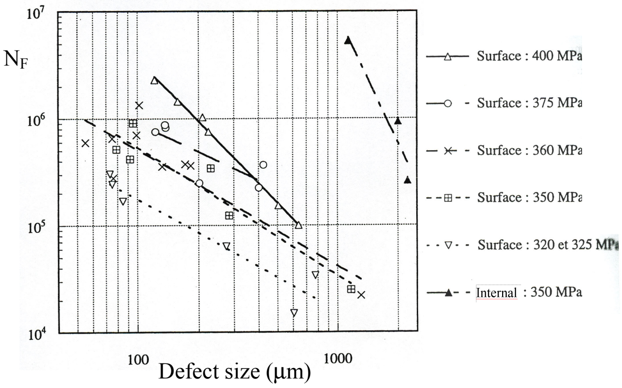

Fig. 5 *Evolution of the number of cycles to failure for different stresses versus defect size, R = 0.1*

From this experimental part, we can conclude that the position of the initiation site is important and strongly related to environmental effects. It is therefore necessary to propose a fatigue criterion that can take into account for the defect size but also for it's location from the surface. The second part is devoted to the presentation of the criterion.

2 Multiaxial fatigue criterion

To study crack initiation mechanisms in defect containing materials, Billaudeau [3] introduced artificial defects at the surface of fatigue samples and observed cracks on these samples after fatigue tests under tension and torsion loading close to the fatigue limit. The first stage of crack nucleation at the tip of the defect occurs in the maximum shear plane and in the maximum loaded part of the defect under both tension and torsion loading. The stress distribution around defects given by FE simulations gives rise to a high stressed volume located in the plane perpendicularly to the direction of the maximum principal stress. Consequently, the macroscopic crack that leads to failure of the sample propagates in that plane in mode I. Nevertheless, the authors conclude that it seems appropriate to use a multi-axial fatigue criterion based on both normal and shear stress to describe the fatigue limit of a defect material.

Based on the previous experimental observations, a second paper by Nadot and Billaudeau [4] propose a multi-axial fatigue criterion for defective materials.

$$\sigma^*_{cr} = \sqrt{J_{2,a}} + \alpha J^*_{1\max} \leq \gamma \qquad (1)$$

$$J^*_{1\max} = J_{1\max}\left(1 - a\frac{G}{J_{1\max}}\right) \qquad (2)$$

$$G = \frac{J_{1\max}(\text{point}\,A) - J_{1\max}\left(\sqrt{area}\right)}{\sqrt{area}} \qquad (3)$$

$J_{2,a}$: Amplitude of the second invariant of the stress tensor (MPa^2). $J_{1\max}$: Maximum value of the hydrostatic stress (MPa). α. and β are material parameters in Crosland's criterion [5]. *a* is a material parameter describing defect influence (µm). *G* is the gradient of hydrostatic stress $J_{1\max}$ based on Papadopoulos work [6]. As shown in equation (3), the gradient is calculated over the size of the defect (in the sense of Murakami : area).

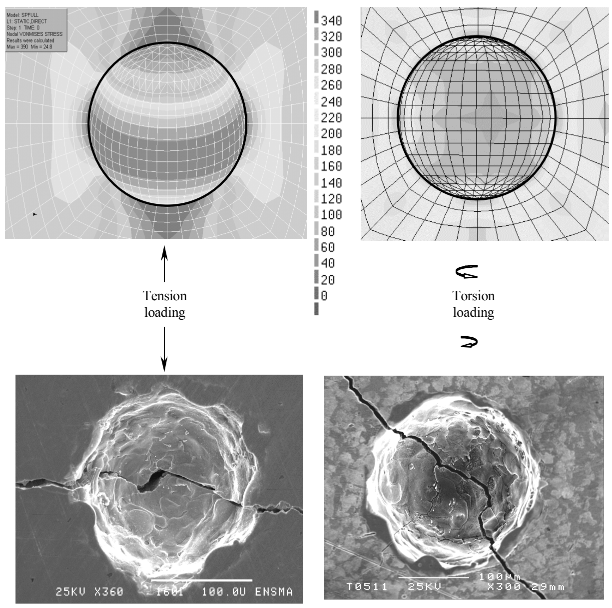

Fig. 6. *Stress state (von Mises equivalent stress) around a spherical defect under tension and torsion and corresponding crack path from SEM pictures.*

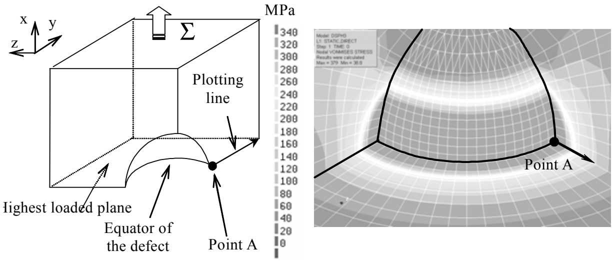

Fig. 7. *Details of the geometry and the mesh under tension*

The identification procedure depends on the type of experimental data available.

The defect free material exists

It is the case for impacted materials, for in service defect creation (corrosion, damage...) and generally for materials where it is possible to test samples with or without defects (machining surfaces of cast materials). In this case the identification of α . and β needs alternating fatigue limit under tension and torsion for the defect free material. The identification of *a* needs one alternating fatigue limit under tension for a given defect size.

The defect free material does not exists

It is the case of most of industrial casting materials, the identification of α. and β needs alternating fatigue limit under tension and torsion for one given size. The identification of *a* needs one alternating fatigue limit under tension for another given defect size.

The other material data needed is the elastic-plastic cyclic behaviour. A non-linear kinematic hardening law is necessary to describe cyclic plasticity at the mesoscopic scale and particularly relaxation of the mean stress. We use standard Chaboche model [7] in Abaqus software.

The parameter 'a' of the criterion should be identified using a fatigue test with a given type of defect. This means that 'a' is not the same for a void, shrinkage or inclusion. This reflects the fact that fatigue mechanisms are dependent on the type of defect. In order to describe the influence of the position of the defect, we propose to change α and β in order to represent the sensibility of the material to environmental effects. In fact, as shown in the first part, we must consider that internal defects are under vacuum and surface ones in air. Therefore, the application of the criterion for a material containing both surface and internal ones needs two sets of parameters because experimental results for a given size are not the same for surface an internal defects.

3 Application to structural components containing surface defect

The objective of the criterion is to determine the fatigue life for a given defect or the defect size for a given fatigue life. The industrial application has been performed on a high strength steel spring.

The criterion has been identified for a high strength steel used for the component: α, β, and *a* as well as the hardening law are identified on experimental results.

The component is re-enforced against fatigue by shoot penning so that we have to take into account for this in the methodology. The computation is performed as follow in the case of a defect at a given position and constant amplitude loading (see Fig. 8):

- At the macroscopic scale, the component is meshed and boundary conditions are applied, material remains elastic.
- The stress tensor at the position of the defect is determined for the maximum and the minimum of the loading applied to the structure.
- Residual stresses are added at this macroscopic level by the mean of a given value of the hydrostatic stress. This value represent the residual stresses after stabilization due to cyclic loading.
- The stress tensor determined at the maximum and the minimum is applied as boundary condition on the cube representative of the mesoscopic scale. At this scale, the load is applied cyclically up to reach the stabilised value of the stresses at the tip of the defect and material hardening law is considered.
- Finally, the stress tensor is calculated after stabilisation at the tip of the defect and in the

bulk at a given distance in order to compute the stress gradient. The equivalent stress including gradient effect is calculated so that a number of cycle to failure can be given and compared to experimental result.

In the case of this component the result is quite good but needs to be confirmed by other tests to be validated.

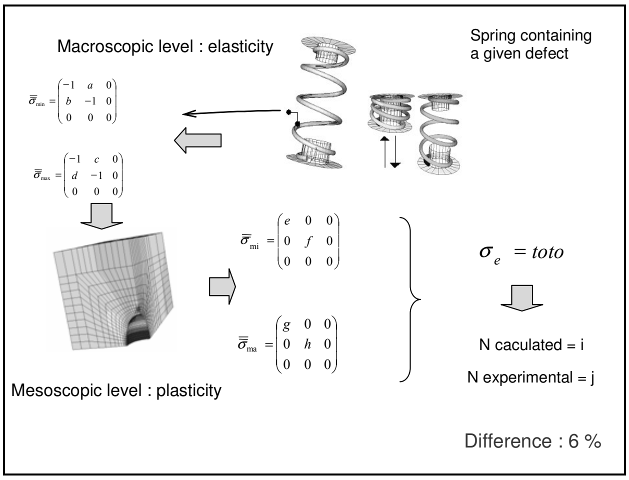

Fig. 8. *Application of the criterion to suspension spring containing a surface defect*

4 Conclusions

From this study the following concluding remarks can be done:

- The fatigue behavior of defective material is dependant on the position of the defect. For a given size, an internal defect is less damaging than a surface one. This is mainly due to environmental effect.

- A multiaxial fatigue criterion for defective material is proposed. The type of defect is characterised by one parameter identified with a fatigue limit for a given defect. Two other parameters are necessary to identify the multiaxial behavior in air for surface defect. In order to characterise the behaviour for internal defect, tests under vacuum are necessary.

- The application of the proposed method on a high strength steel springs containing surface defects give interesting results.

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