Mechanism of Fish-eye Formation in the Gigacycle Fatigue

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ABSTRACT. *In gigacycle fatigue regime (Very High Cycle Regime, $N_f > 10^7$cycles), the cracks can nucleate on inclusions, "supergrains", pores …which leads to a fish-eye propagation around the defect. The initiation from an inclusion or other defect is closed to the total life, perhaps much more than 99% of the life in many cases. The integration of the Paris law allows one to predict the number of cycles at crack initiation. As the crack initiation appears, a short crack around the defect propagates followed by a long crack. In all cases, a cyclic plastic zone around the crack exists, and the recording of the surface temperature of the sample during the test must allow to follow the crack propagation and to determine the number of cycles at the crack initiation. A thermo-mechanical model was developed. It allows the determination of the temperature field evolution in the specimen and shows a good correlation with the experiments.*
In this study, several fish-eyes from various materials (normalized steels, quenched and tempered steels, aluminium alloys) are observed by Scanning Electron Microscope, and the fractographic results are analyzed in accordance with the mechanical and thermo-mechanical model. These analysis suggest a mechanism for fisheyes formation.

INTRODUCTION

In fatigue tests, according to the strain or stress level, three domains exist: the Low Cycle Fatigue domain ($N_f < 10^4$ cycles or "oligocycle" domain), the High Cycle Fatigue domain ($10^4 < N_f < 10^7$ cycles, megacycle domain) and the Very High Cycle Fatigue domain ($N_f > 10^7$ cycles, gigacycle domain). The latter is now investigated [1] with the development of devices (piezoelectric fatigue machines) working at high frequency (20 or 30 kHz), allowing to obtain 10^8 or more cycles in reasonable testing time. These tests have shown that fracture can occur at 10^9 or more cycles which is problematic since many components and structures in several industries require design fatigue life often superior to 10^8 cycles.
According to the fatigue domain, different types of crack initiation occur. In gigacycle fatigue domain, the initiation site may be located in an internal zone or at the surface. When the crack initiation site is interior, this leads to the formation of a "fish-eye" on the fracture surface, and the origin of the fatigue crack is an inclusion, a "supergrain" (microstructural inhomogeneity), or a porosity. At the macroscopic scale, under the optical microscope (or naked eye), the fish-eye area looks white, whereas the region outside of the fish-eye looks grey. In almost all cases,

this fish-eye appears circular, with a dark area in the center, inside which the crack initiation site is located. Controversies exist on the origin of this dark area, which gives, among the authors, different expressions to name it : “Optically Dark Area (ODA)” by Y.Murakami [2], “Fine Granular Area (FGA)” by T. Sakai [3], “Granular Bright Facet (GBF) by Shiozawa [4]...). For Y. Murakami et al., the mechanism of formation of ODAs is presumed to be micro-scale fatigue fracture caused by cyclic stress coupled with internal hydrogen trapped by nonmetallic inclusions. It is presumed, that when the size of an ODA exceeds the critical size for the intrinsic material fatigue limit in the absence of hydrogen, the fatigue grows without the assistance of hydrogen, and the crack cannot become non-propagating. For T. Sakai et al., the mechanism of formation of FGAs is caused by intensive polygonisation induced around the interior inclusion, followed by micro-debondings which can coalesce to one other leading this fine granular area. For Shiozawa et al., the mechanism of formation of GBFs is due to the separation of boundaries between carbides particles and matrix. At the microscopic level, Mugrahbi et al. [5] show that the initiation of fatigue crack in the gigacycle fatigue regime can be described in terms of microstructurally irreversible portion of the cumulative cycle strain.
As this ODA, FGA,GBF... is formed around the inclusion..., related with the persistant slip bands formation, all authors agree to say that the crack growth is governed by the Paris’law.
To predict the number of cycles to initiate a fatigue crack from an inclusion, several models are used more or less successfully [1]. In the gigacycle fatigue range, the integration of Paris’ law [6] allows one to predict the number of cycles in the fish eye growth and to obtain the number of cycles at crack initiation. The number of cycles for the crack propagation in the fish-eye calculated by the model is very small compared with the total fatigue life.
In an internal initiation, it is difficult to determine the number of cycles at initiation. By a thermomechanical approach, Wagner, Ranc et al. [7,8] have determined the number of cycles at initiation (even in an internal initiation) by the recording of the surface temperature of the sample during the test which allows to follow the crack propagation and to determine the number of cycles at the crack initiation. These results confirm that in the gigacycle domain, more than 90% of the total life is devoted to the initiation of the crack.
The purpose of this study is to complete the mechanical and thermomechanical approach by fractographic observations when the crack initiates in internal defect and leads to the formation of a fish-eye on the fracture surface. These observations are conducted on steels (quenched and tempered low alloyed chromium steel and normalized carbon-manganese steel) and an aluminium-silicium-copper alloy.

MECHANICAL APPROACH

The model of Paris et al. for crack growth in the fish-eye is based on the integration of the Paris’law as in Figs 1 and 2. Reviews on crack growth and threshold allow to predict the threshold corner at $da/dN = b$ and $\Delta K_{eff} / E\sqrt{b} = 1$, where b is the Burger’s vector and E is elastic modulus.
The total crack growth lifetime for an internal failure can be estimated by the addition of following lifetimes :

- below threshold from an initial crack size a_{int} to a_o
- small crack from an initial crack size a_o to a_i
- large crack from transition small to large crack point a_i to a.

Fig. 1: Modelling of relevant crack sizes

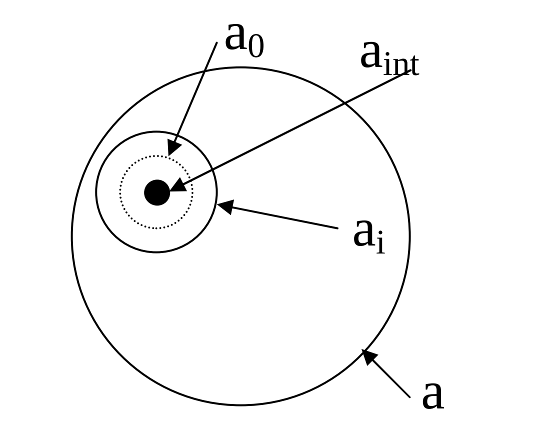
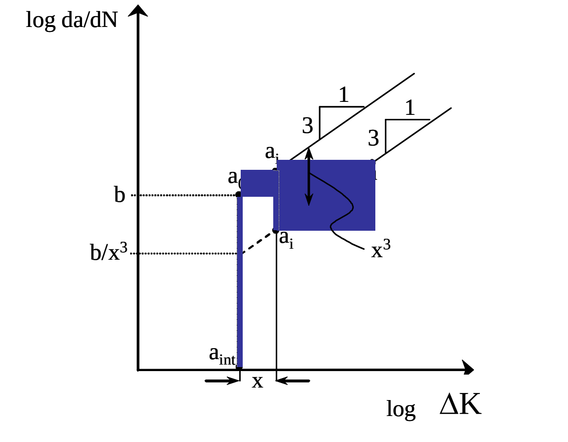


Fig. 2: Modelling of crack growth in fish-eye



THERMOMECHANICAL APPROACH

Previous studies [7,8] have investigated the temperature evolution on surface specimens during tests in the gigacycle fatigue domain. Two recordings are given Figs 3 and 4 for a low alloyed chromium steel. Figure 3 is the entire recording from the beginning of the test. At first time, the temperature increases rapidly, followed by a stabilization. The temperature variation depends on the material and its microstructure and on the stress amplitude level (Δσ);the higher the stress, the higher the temperature reached. At the end of the test, the temperature increases rapidly. Figure 4 is an enlargement (coming from an other specimen of low alloyed chromium steel) of the test end . In fig. 3 the sample was refreshed during the test, whereas it is not the case for the test of fig. 4.

Fig. 3: Temperature evolution on the surface sample

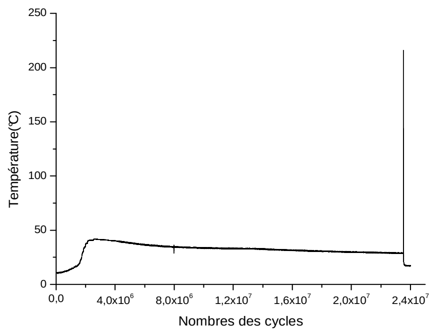
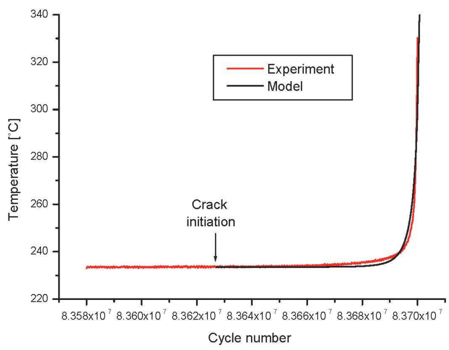


Fig. 4: Temperature evolution at the test end.



In order to better understand these thermal effects and to make a connection with the crack initiation and propagation, a thermo-mechanical model was developped [8]. The numerical resolution of the thermal problem allows the determination of the temperature field evolution with time in the specimen. The comparison between test and model shows a good correlation (fig. 4). So, the fast increase of the temperature at the end of the test corresponds to the fracture initiation and the number of cycles at initiation can be determined accurately.

FRACTOGRAPHIC APPROACH

Firstly, at the macroscopic scale, the appearence of the fish-eye is not the same in optical microscope (OM) and scanning electron microscope (SEM). Figures 5 and 6 show the observations with optical microscope and SEM for a same sample. These results are obtained on a low alloyed chromium steel whose testing specimens were carburized. The microstructure is martensite with retained austenite. In the optical observation the crack initiation site appears as a dark point (well named ODA), whereas in SEM observation, it appears not so clear at low magnification. For this sample, the crack initiation site is a "supergrain" (probably a soft large retained austenite grain). As reported by Murakami and Sakai, at high magnification (Fig.7 and 8) in SEM observation, the dark area appears like a granular layer (well named FGA).

Fig.5: Observation with optical microscope

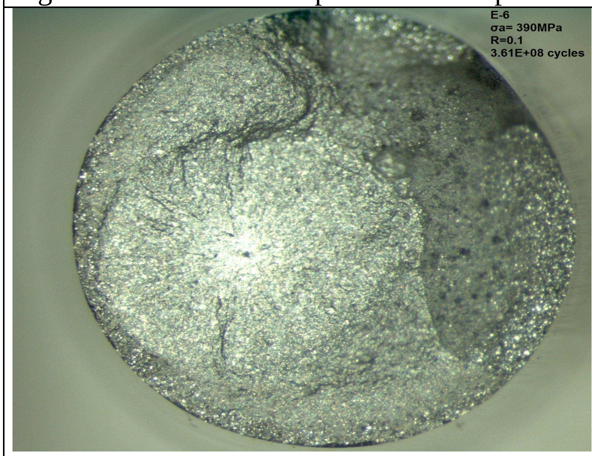


Fig. 6: Observation with SEM

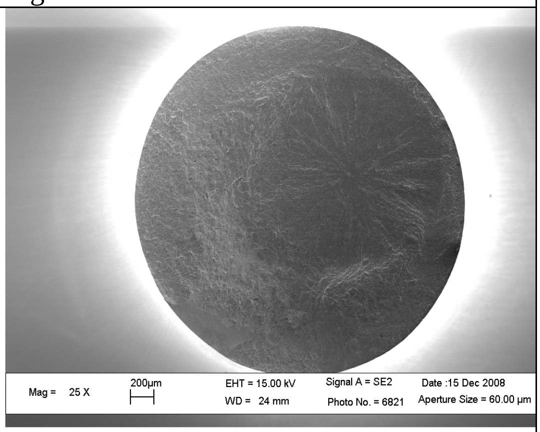


Fig.7: Initiation site of the above sample

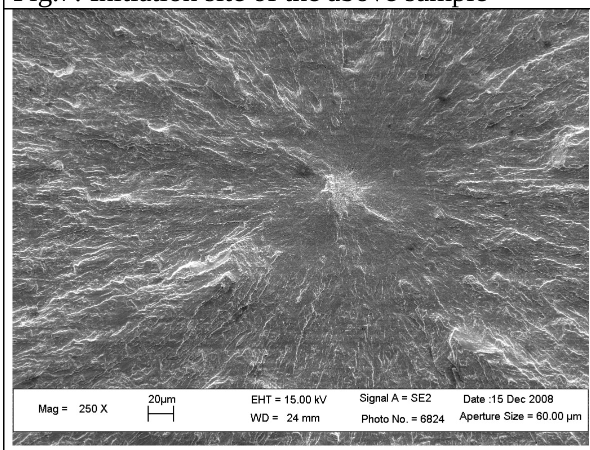
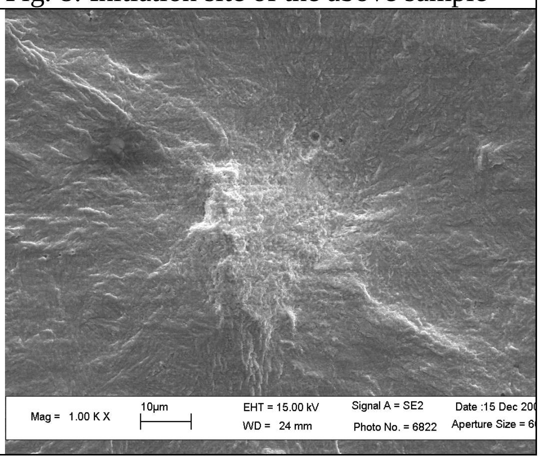


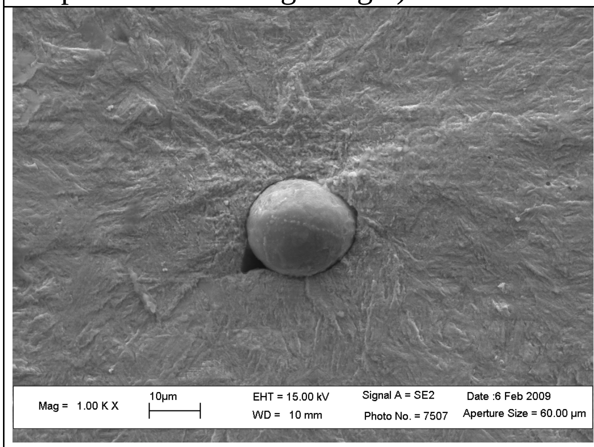
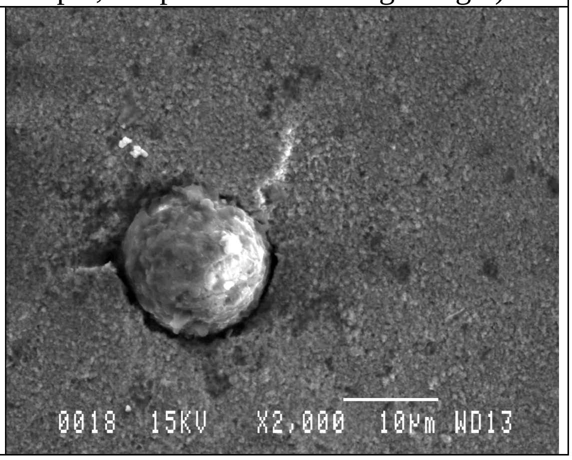
Fig. 8: Initiation site of the above sample



Around the dark point, a white zone is present in optical observation. In SEM observation, this zone is rather flat (Fig.7) and circular (penny-shape). Outside this white zone, we can see in optical and SEM observations a wide fracture surface having radial ridge pattern.

Dark area observations

As mentionned in the thermomechanical approach, the temperature recording on the surface specimen during the gigacycle fatigue tests were performed with or without cooling of the sample. Figures 9 and 10 show for the low alloyed chromium steel the crack initiation site on inclusions (non metallic inclusions) in a sample cooled during the test (fig.9) and in a sample not cooled strongly (fig.10). In the latter case, the Fine Granular Area spread over the all center of the fish-eye. For this sample, the temperature during the fish-eye propagation (fig. 4) is comprised between 240°C (513K) (at the crack initiation) and 330°C (603K) (at the failure).Y. Murakami [2] reported the work of Takai et al. [9] which verified directly the presence of hydrogen trapped at the interface of inclusions by Secondary Ion mass Spectrometry. Takai et al. showed that non metallic inclusions trapped hydrogen more strongly than other sites such as dislocations, grain boundaries and microstructural textures. The hydrogen trapped by non metallic inclusions could be desorbed only by heating the sample to more than ~573K. When the sample is not cooled, the important dark area observed can be explained by the reached temperature; higher the reached temperature, greater the dark area extension (surface and thickness)

<table>
<tr><td>Fig. 9: Crack initiation site (cooled sample, temperature recording in fig.3)</td><td>Fig.10: Crack initiation site (not cooled sample, temperature recording in fig.4)</td></tr>
<tr><td>
</td><td>
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"Penny-shape area" observations

Whatever the crack initiation site (spherical inclusion, elongated inclusion, supergrain, porosity), the fracture surface becomes circular ("penny-shape") around the initiation site. Figures 11 to 14 give examples of such behaviours:

- Figs.11/12 : this figure is a fish-eye obtained in a ferrite-perlite carbon-manganese steel with a high sulfur content (0.030%). The longitudinal axis of the test sample was perpendicular to the rolling direction. The origin of the crack initiation is a manganese sulfide failed in its longest direction. Figure 11 is an optical microscope observation and figure 12 a SEM observation.

- Fig.13: this figure is a fish-eye obtained in a cast aluminium-silicium-copper alloy. The origin of the crak initiation is a porosity.
- Fig.14: this figure is a part (high magnification) of the figures 7/8, obtained on a low alloyed chromium steel. This figure is interesting because besides the dark area zone, the lath martensitic microstructure appearence is visible.

Fig. 11: OM observation in a C-Mn steel

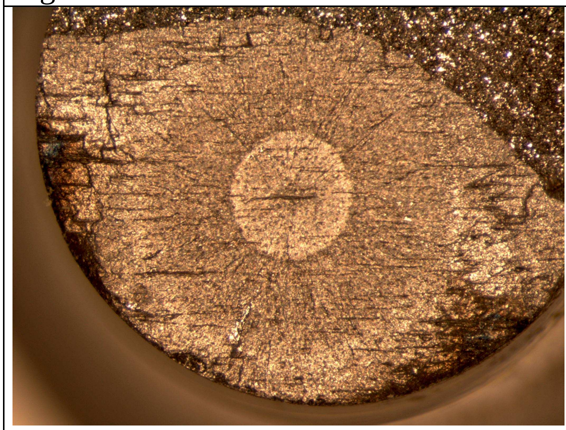


Fig. 12: SEM observation in a C-Mn steel

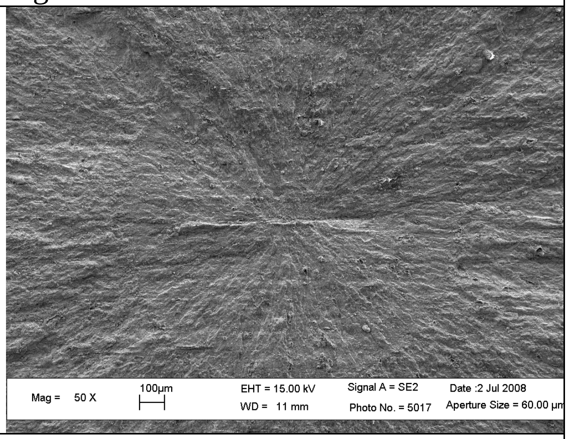


Fig.13: SEM observation in a Al-Si-Cu alloy

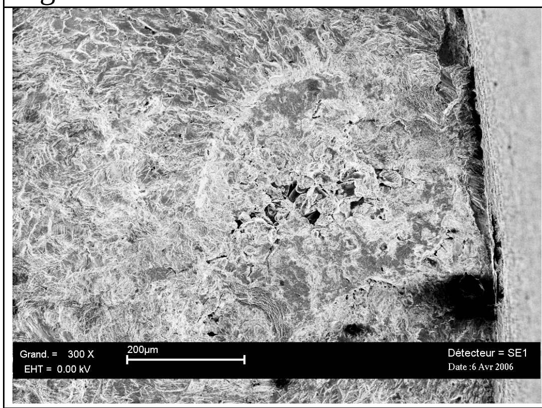
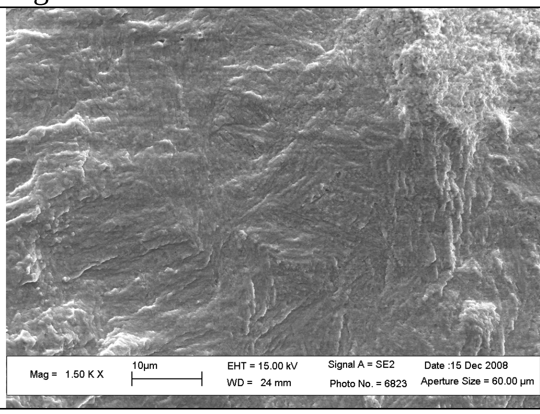


Fig.14: SEM observation in Cr steel



At the end of this “penny- shape” zone, small radial ridges appear. Theoritically, it is in this zone, that the transition short crack-long crack happens.

Fracture surface with large radial ridges

In this zone, high magnification SEM observations show striations (Figs 15 to 18). All the observations and measurements were made on the low alloyed chromium steel on many specimens. For each picture at high magnification (x5000), was associated immediately a picture at minor magnification (x100) showing the location of the striations with regard to the crack initiation site.

Fig.15: Striations in the ridged zone	Fig.16: Striations location

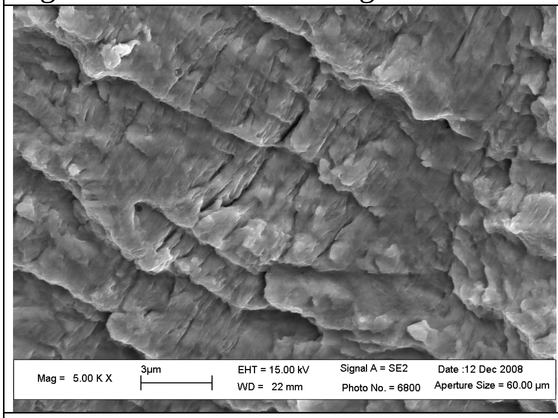
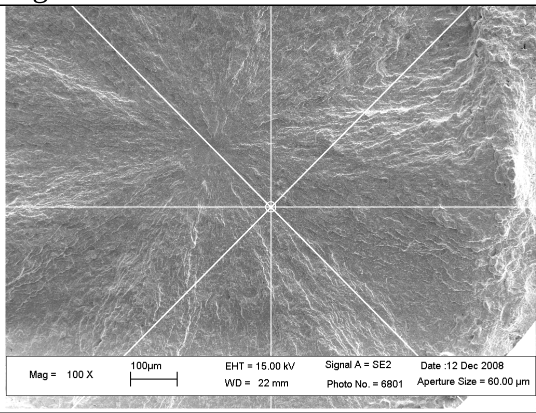
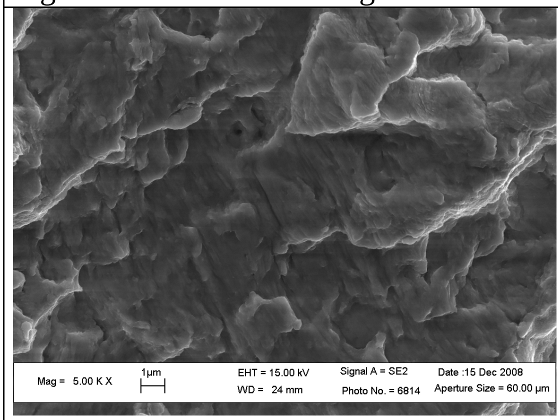
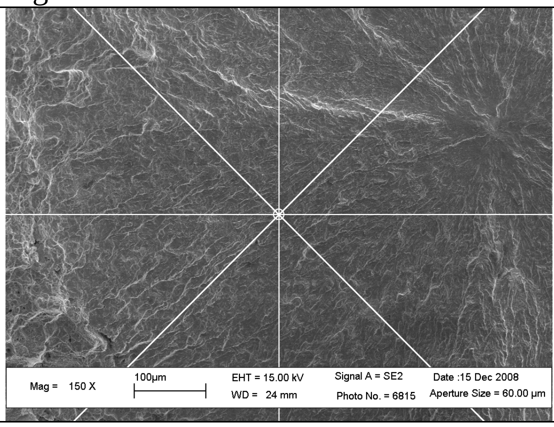

	

Fig.17: Striations in the ridged zone	Fig.18: Striations location
	

A review of the environment effect by J. Petit and C. Sarrazin-Baudoux [10] relates that striations in vacuum are possible but less clearly defined. The number of cycles per striation is more important in vacuum than in air. Moreover, if hydrogen is desorbed from non metallic inclusions (at the initiation site, or inclusions on the crack path during the propagation), the environment is not exactly vacuum.

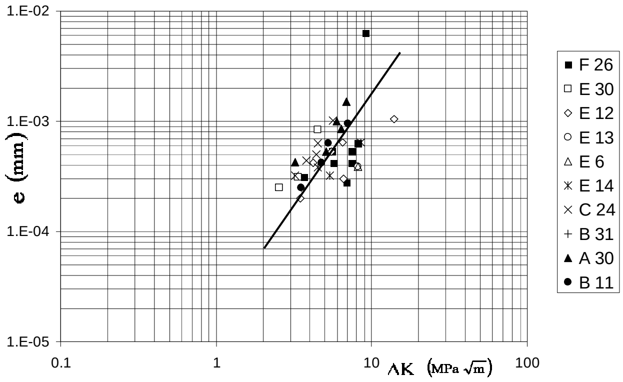


Fig 19: Striation spacing e versus ΔK

For each studied zone with striation, the mean distance between two striations was measured and the associated ΔK was calculated. Figure 19 gives the evolution of the striation spacing Log(e) versus Log(ΔK). The equation of the straight line is Log = 2LogΔK – 10.97. This is in good agreement with what is expected, considering that the striation spacing is a function of ΔK^2.

CONCLUSION

The different zones of a fish-eye in the gigacycle fatigue domain have been observed with optical and scanning microscope. The fractographic results show three main zones in agreement with the mechanical model:

- a dark area zone (a_{int} to a_o) due to the formation of irreversible portion of PSB.The dark area extent (area and thickness layer) seems depend on the reached temperature during the test and the environment (hydrogen?, oxygen? trapped during the elaboration process).
- A penny-shape zone (a_o to a_i, crack growth in stade I).Whatever the crack iniation site (spherical or elongated inclusion, supergrain, pore), the fracture surface becomes circular (penny-shape) around the initiation site. In this zone, it is confined that short crack-long crack transition happens.
- A zone with large radial ridges (a_i to a, crack growth in stade II). In this zone, the fatigue crack propagation produces striations which mean distance between striation is a fonction of ΔK^2, that is to say in good agreement with the CTOD.

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