Microplasticity , Microdamage, Microcracking in Ultrasonic Fatigue

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Abstract: Depending upon the fatigue domain, different types of crack initiation occur. In low cycle fatigue, the cyclic plastic deformation is critical at the surface but exists also in the bulk of the metal. In high cycle fatigue, the plastic deformation is limited to the surface in plane stress conditions. In very high cycle fatigue, the crack initiates from the interior, starting from a defect in plane strain conditions. This means that the initiation mechanisms in gigacycle fatigue depend not only on upon the stress field but also on the stability of the microstructure.

Keywords : Gigacycle fatigue, fish eye, plasticity, microstructure

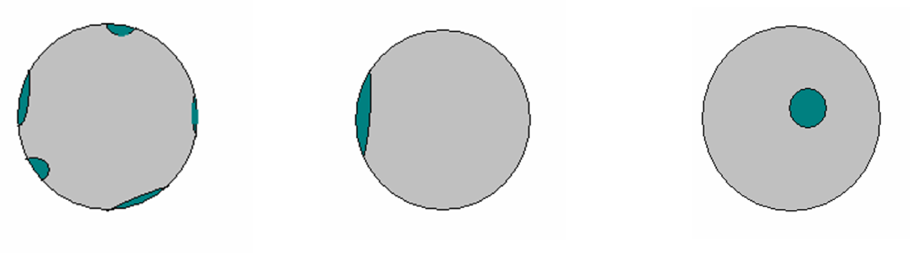
1-Introduction

The initiation of fatigue cracks can be considered differently from physical or mechanical points of view. At the microscopic level, Mughrabi [1] shows that the initiation of fatigue crack in the gigacycle fatigue regime can be described in terms of a microstructurally irreversible portion of the cumulative cycle strain. This means that there is no basic difference between fatigue mechanisms in low, mega, and gigacycle fatigue except for the strain localization. However, specific mechanisms can occur depending on the fatigue life. The fatigue life seems to be a key parameter to determine correctly the fatigue initiation location. In low cycle fatigue, in megacycle fatigue and in gigacycle fatigue different mechanisms can operate at different scales of plasticity. In the low cycle fatigue regime, the cyclic plastic deformation is critical at the surface but exists also in the bulk of the metal. Typically, several cracks nucleate from the surface. When the fatigue life is below 10^5 cycles, general plastic deformation of the specimen bulk governs the initiation. When the fatigue life is between 10^6 and 10^7 cycles the plastic deformation depends on the plane stress surface effect and the presence of flaws which explain the critical location of fatigue initiation. Typically, the initiation starts with one crack only, from the surface. However approaching 10^9 cycles the plastic deformation in plane stress conditions vanishes; the macroscopic behaviour of the metal is elastic except around flaws, metallurgical defects or inclusions. In very high cycle fatigue, the plane stress conditions are not enough for a surface plastic deformation according the Von Mises criteria. The initiation may be located in an internal zone. When the crack initiation site is in the interior, this leads to the formation of one fish eye on the fracture surface, typical of gigacycle fatigue. In this case, the cyclic plastic deformation is related to the stress concentration around a defect: inclusion, porosity, super grain. Since the probability of occurrence of a flaw is greater within an internal volume than at a surface, the typical initiation in Gigacycle fatigue will ~~be~~ most often occur in the bulk of the metal.

To sum up the state of art, it is generally accepted that if the first damage in fatigue is located at the surface the typical feature is persistent slip band (PSB), intrusion or extrusion, all related to a strong planar shear deformation, in plane stress. ~~,~~ On the contrary, if the first damage occurs around an internal defect, typically a cellular dislocation network in 3D is observed for plane strain. According to our own observations and those in the literature [2] [3] two main factors are operating in the Gigacycle regime:

- The stress concentration due to metallurgical microstructure misfit becomes an important parameter when the applied load is low. The inclusions in steels or in nickel base alloys or the porosity in cast aluminium or in powder metallurgy are among the most efficient stress concentrators.

- The stress concentration due to the anisotropy of metals is another parameter. At low deformation,- plasticity can appear only if the grain orientation and the grain size are in suitable for dislocation glide. A large grain can become a critical location for initiation in low carbon steel, austenitic steel or titanium alloy.



$N_i=10^4$ cycles $N_i=10^6$ cycles $N_i=10^9$ cycles

Figure 1 fatigue crack initiation sites

2-Fish eye growth

When the crack initiation site is in the 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 “super grain” (micro structural homogeneity), or 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 virtually circular, with a dark area in the centre, inside of which the crack initiation site is located. Controversies exist on the origin of this dark area, which some authors have variously named: “Optically Dark Area (ODA)” by Y.Murakami [4], “Fine Granular Area (FGA)” by T. Sakai [5], and “Granular Bright Facet (GBF) by Shiozawa [6]...). According to 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 non-metallic 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 crack grows without the assistance of hydrogen. According to T. Sakai et al., the mechanism of formation of FGAs is caused by intensive polygonisation induced around the inclusion, followed by micro-debondings which can coalesce leading to this fine granular area. By the way, no PSB has been reported for fish eye formation.

The fractographic observations show zones (figure 2) in agreement with a mechanical model:

- a dark area zone (so-called ODA) due to the initiation mechanisms. [4]
- a penny-shaped zone (short crack growth). Whatever the crack initiation site (spherical or elongated inclusion, super-grain, pore), the fracture surface becomes circular around the initiation site.
- A zone with small radial ridges corresponding to the short to long crack transition

- A zone with large radial ridges (long crack growth). In this zone, the fatigue crack propagation produces striations for which the mean distance between striations is a function of ΔK^2, in good agreement with the CTOD [7].

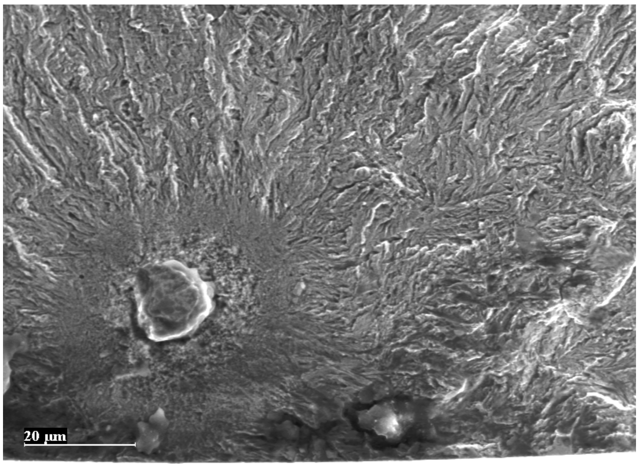


Figure 2 Typical fish eye with initiation and short crack growth.

3-Prediction of fish eye

In order to predict the fish eye propagation, one should refer to a general behaviour pattern of the crack growth rate curve as illustrated by the equations preceding. Estimating the life for a crack of this type beginning just above threshold it is then appropriate to consider the growth law as:

$$\frac{da}{dN} = b\left(\frac{\Delta K_{eff}}{E\sqrt{b}}\right)^3$$

Paris-Hertzberg Law

The figure 3 introduces the Paris-Herzberg model which is presented in detail in [2].At the beginning of the crack growth, a small crack a_o (with no crack closure and corresponding to $\Delta K_{eff} / E\sqrt{b} = 1$) starts from a defect of size a_{int}. This short crack becomes a long crack at a_i (figure 3). The growth rate is higher for small cracks than for long cracks. The transition point from a short crack to a long crack is located at a factor x in terms of the stress intensity factor from the threshold for short cracks (Fig. 2). The factor x has been observed at a maximum around 3 for low load ratios (R=0). The total crack growth lifetime for an internal failure can be estimated by the adding cycles associated with the following regimes:

- $N_{ao \rightarrow ai}$ small crack from an initial crack size a_o to a_i
- $N_{ai \rightarrow a}$ large crack from transition small to large crack point a_i to a (final crack)

The number of cycles related to initiation from an inclusion is:

- $N_{aint \rightarrow ao}$ below threshold from an initial crack size a_{int} to a_o

The time spent initiating from an inclusion or other defect itself must be close to the total life, perhaps much more than 99% of the life in many cases. This is made evident by integrating the fatigue crack growth rates for small cracks to estimate the possible extent of crack growth life. In order to do this one should refer to the general behaviour pattern of the crack growth rate curve. It is well-established that small cracks such as those growing from small inclusions do not exhibit crack closure so these equations in terms of ΔK_{eff} apply fairly well with ΔK_{eff} being replaced by ΔK_{nom}. They form an upper bound on crack growth rates for the small cracks in the “fish eye” range for which crack closure is minimal, see figure 3.

The integration of the Paris Hertzberg law without transition, to determine the crack growth life will begin here with the crack growth rate corner which we shall denote as ΔK_0 corresponding to an initial circular crack of radius, a_0. In first approximation, we obtain [7]:

$$\boxed{N_f = \frac{\pi E^2}{2(\Delta\sigma)^2}}$$

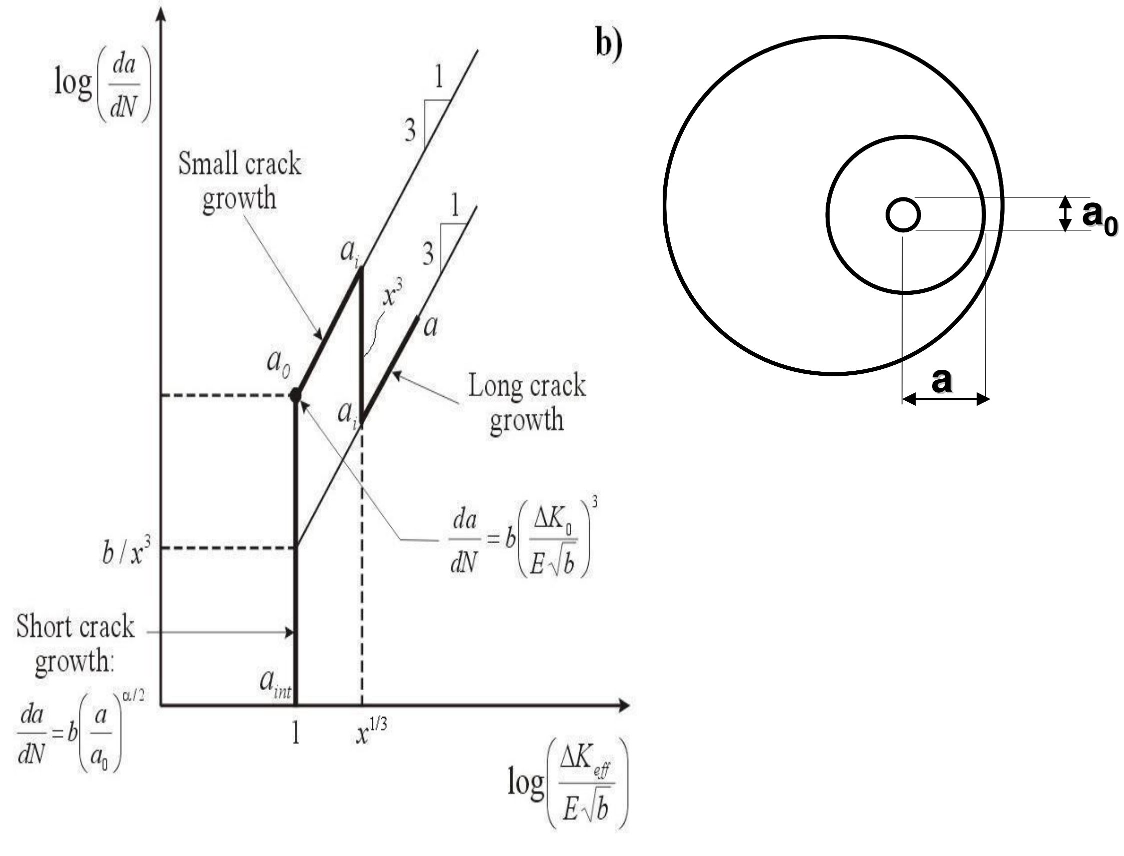


Figure 3 Fish eye scheme from the Paris Hertzberg relation.

This means that the number of cycles for the crack growth inside the fish eye is on the order of 10^5 cycles independent of the actual metal being considered. Initiation of the crack from a defect is the key problem in the gigacycle regime. Essentially we must determine the damage (or plasticity) to initiate a crack at about 10^9 cycles.

4-Micro Plasticity in the gigacycle fatigue

Generally ultrasonic tests are performed with round specimens. From a mechanical viewpoint, it is better to use cylindrical specimens which avoid edge effects.

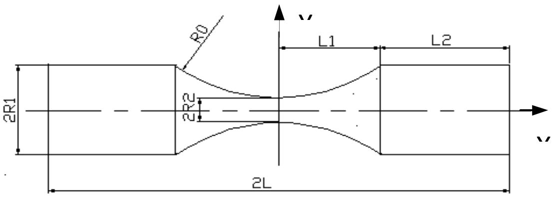


Figure 4 Typical round specimen for ultrasonic fatigue

However for microscopic observation, a flat specimen is more convenient (Fig 4). It must be pointed out that a plane stress field is favoured in a flat specimen of one millimeter thickness or less. In comparison, the plane stress effect is limited to the surface in a round specimen. In this respect, tests have been carried out with both specimens machined in Armco iron or high strength steel. Using flat specimens is more challenging than round specimens and proper testing requires some investigation. A flat specimen,figure 5, is used for ultrasonic frequency fatigue testing, with a special fitting attachment.

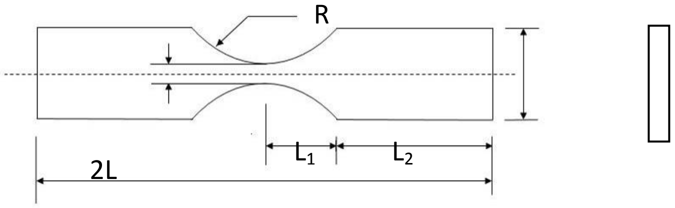


Figure 5. Flat specimen drawing

Working at resonance of 20 kHz frequency, the specimen was designed to have a natural frequency at 20kHz.. According to the longitudinal elastic wave equation on a one-dimensional elastic body and based on the given geometric and material properties, the resonance length and maximum stress in the middle of the specimen can be calculated using Equations 1 2.

$$L_1 = \frac{1}{k}\arctan\{\frac{1}{k}[\beta \coth(\beta L_2) - \alpha]\} \qquad (1)$$

$$\sigma_{\max} = E_d A_0 \beta \frac{\cos(kL_1)\exp(\alpha L_2)}{\sinh(\beta L_2)} \qquad (2)$$

Where:

$$C = \sqrt{E_d/\rho}, \quad k = \frac{2\pi f}{C}, \quad \alpha = \frac{1}{2L_2}\ln(\frac{T_2}{T_1}), \quad \beta = \sqrt{a^2 - k^2}$$

In order to observe the micro plasticity in the gigacycle regime, single phase (α) Armco iron was chosen, for which the UTS is 300 MPa and the yield strength 220 MPa. This is a reference metal with a simple microstructure of ferrite grains, without significant inclusions. This of course suggests comparison with very high strength martensitic steel using the same specimen geometry.

The iron is loaded below the yield point at 70, 85, and 120 MPa in push pull loading at 20kHz, for a failure beyond 10^8 cycles. Figures 6 and 8 show the initiation occurring at the surface of the flat specimen and of the round specimens in iron The damage is starting in stage 1 along more or less one millimetre depth before growing in stage 2. There is not any difference in mechanism between mega and giga cycle fatigue, in this case. During stage 1, it is clear that the microscopic mechanism is related to the formation of quasi-persistent slip bands (PSB). We use the term “quasi persistent slip bands” because they actually differ from what one traditionally considers to be a PSB (i.e. hedge structure with strain being carried by screw dislocations).

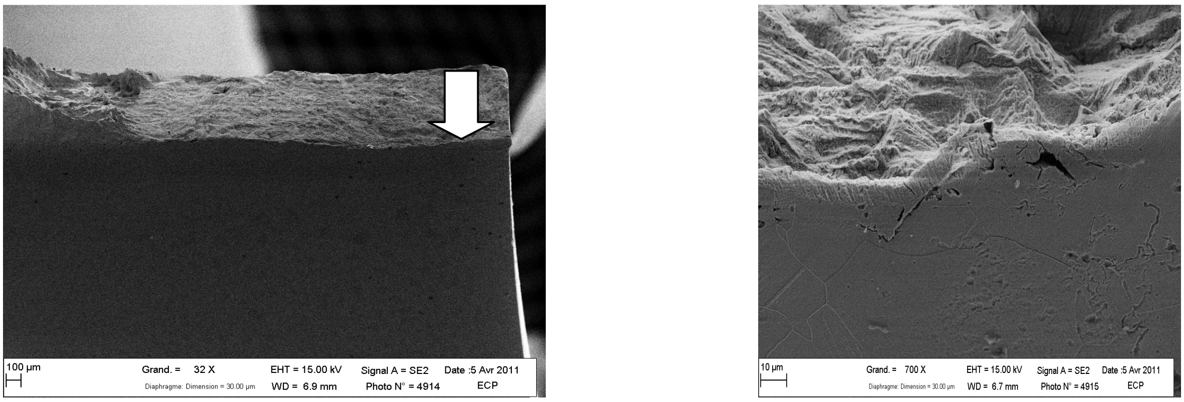


Figure 6 Initiation of a crack in a flat iron specimen. Quasi PSB starting at the surface

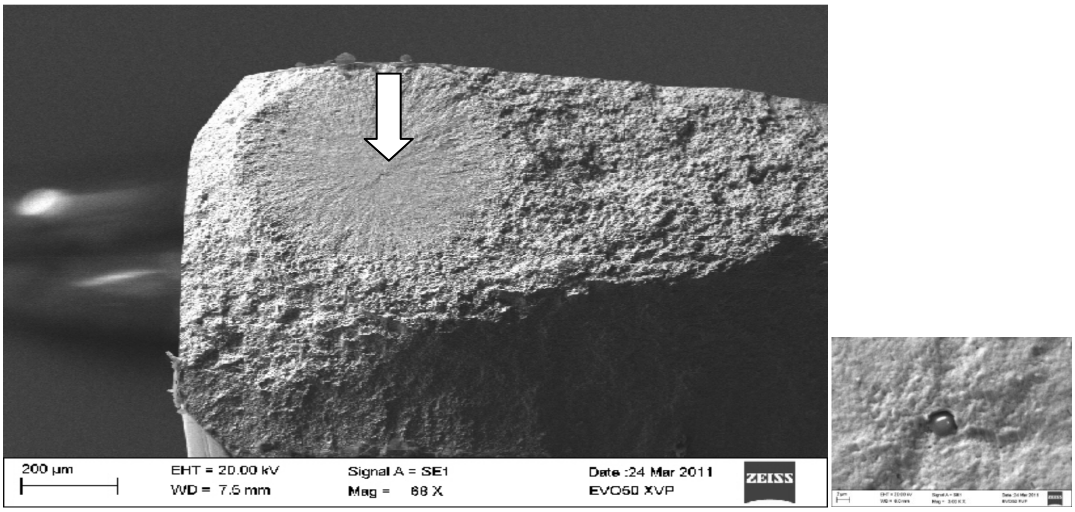


Figure 7 Initiation of a crack in a flat martensitic specimen. Fish eye at the interior.

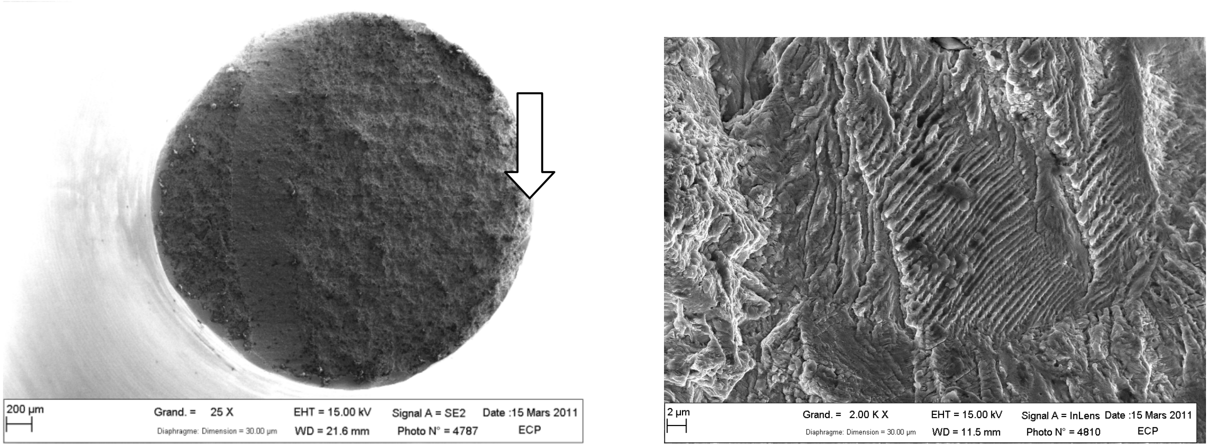


Figure 8 Initiation of a crack in a round iron specimen. Quasi-PSB starting from the surface in iron

Along these lines, Lukas [8] as shown that at least in Cu in the high cycle regime the “persistent slip bands” are composed of localized regions of very high vacancy concentration. It seems that a threshold exists, in iron, for the formation of the quasi-PSB. It is found that below 70 MPa no PSB occurs up to 10^9 cycles. However, the number of PSB increases with the number of cycles, but at present no experimental evidence is available to prove that some PSBs cannot form at 10^{10} cycles or more. No fish eye occurs in these conditions, probably due to the strong effect of the plane stress field and the very small size of the inclusions in a low yield stress Armco iron.

It is of interest to compare iron and martensitic steel, with the same flat specimen (1mm) and the same frequency, in push pull loading at 620 MPa, for a fatigue life beyond 10^8 cycles. Figure 7 shows that the initiation in martensitic steel starts from a fish eye and not from the surface. Reasons for this location must be addressed.

The fish eye occurs in the high strength steel from a small inclusion of oxide, in plane strain conditions, located inside a plastic zone around an inclusion. In this case, the plane stress effect at the surface is not efficient in causing plasticity due to a defect in steel where the UTS is close to 2000 MPa. There is a competition between plane strain plasticity and plane stress plasticity. In this case the micro plasticity is not governed by the Von Mises criteria but by the stress concentration effect. In plane strain plasticity the PSB or quasi PSB are not observed in the fish eye. The mechanism of plasticity seems relevant to polygonisation; grain refining or phase transformation, around the inclusion.

These results show that initiation in gigacycle fatigue is explained by a fish eye formation except when the effect of plane stress occurs in thin sheets or in thick bars when the yield point of the metal is low. In this condition the surface governs initiation. Otherwise in high strength alloys the initiation, in the gigacycle range, is sub-surface and always depends on defects: inclusions, pores, super grains. The surface effect is less important except if the residual stresses are important.

According to these observations more attention must be paid to the microplasticity (or damage accumulation) inside the fish eye in high strength alloys such as martensitic steels.

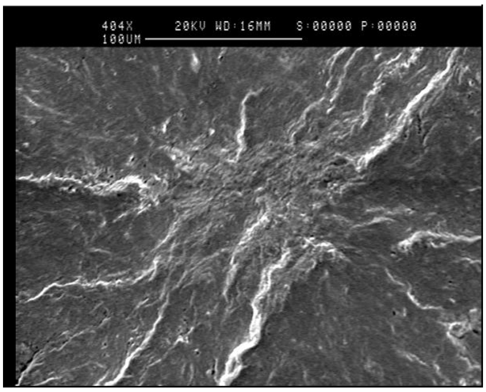
5-Instability of microstructure in VHCF

Our own results and those from the literature it is observed that the micro plasticity in gigacycle fatigue is more than simple dislocation slip. Sometimes phase transformation, refining of the grain, twinning, and instability of the yield point, occur even at low loads for a very high number of cycles. Several observations are enumerated up below:

-In austenitic stainless steels the austenite is not stable in the gigacycle fatigue regime even if the plastic deformation is theoretically very small. There is also a large thermal dissipation [9].

-When the amount of retained austenite approaches 10% in martensitic steels, a large thermal dissipation is observed at the beginning of the test followed by a high temperature rise when the fish eye propagates. [10]

-In low carbon steels the mobility of dislocations is affected by interstitial atoms, depending on the strain rate and the grain size. Several types of instability are observed in monotonic loading such as Luder’s bands, Portevin-Le Chatelier bands or Neumann’s bands, twinning, etc. It seems useful to consider similar effects in ultrasonic fatigue. [11]



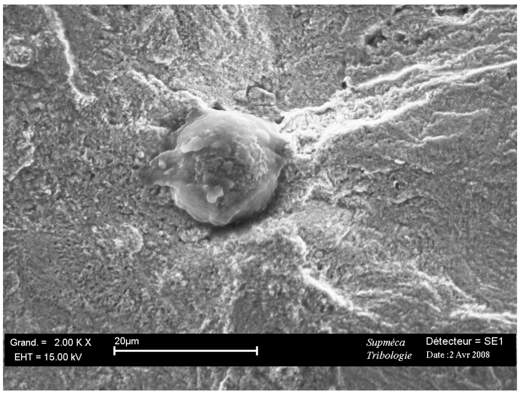


Figure 9 Initiation from a super grain (Pearlite)

Figure 10 Initiation from an oxide inclusion

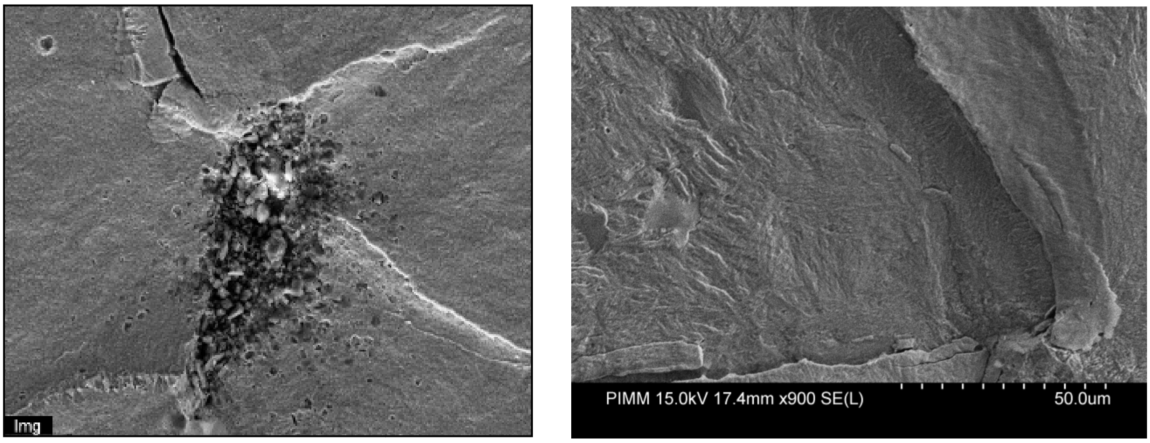


Figure 11 Initiation with phase transformation and grain boundary cracking starting from an oxide.

One of the most interesting behaviours is the instability of martensite or bainite in high strength steels. Depending on the chemical composition, heat treatments and processing, several types of microstructure are observed around the defect in the centre of the fish eye.

Figure 12 Comparison between wings in rolling contact fatigue and push pull gigacycle fatigue in a bearing steel

In a ferrite-pearlite steel (D38), the initiation starts in the centre of a fish eye, from a colony of pearlite, a so-called super-grain, but in a martensitic steel the initiation starts generally from an oxide inclusion, as shown in figures 9 and 10. This is typical of gigacycle plasticity. However, in high strength steel, that is to say when the UTS is higher than 900

MPa the initiation of the crack in the centre of the fish eye is sometimes more complicated as is shown in figure 11.

In high carbon and high strength steels, there is a transformation of the microstructure starting from the inclusion, in relation with the stress concentration and the stress field. It is difficult to understand this transformation which appears at the microscopic scale within a radius of 200 microns around an inclusion! Based on SEM observation, it can be said:

-Some wings (two to four) occur around the inclusion similar to the butterfly wings observed in rolling contact fatigue. Micro cracks are observed along the boundary between the wings and the matrix,Fig 11. In comparison with the rolling contact damage it seems that a phase transformation or grain refinement occurs. . In both cases, it is reasonable to assume that the microstructure of the wings should be a nano- ferrite phase. [11] Figure 12 compares the initiation of a fatigue crack in rolling fatigue and in push pull fatigue for a same bearing steel. Indeed the features are very similar.

-It is of interest to point out the relation between the wings, the oxide at the centre of the fish eye and the former austenitic grain boundaries, which is clear in figure 12. To prove this relation, a fish eye originating from a failure of high strength steel specimen was observed via electron backscatter diffraction (EBSD). To obtain a good EBSD map, the surface of the fractured specimen was polished slightly, with care taken to track the location of the particle at the center of the fish eye. The results are shown in figure 13. It is shown that the oxide inclusion, from which the initiation starts, is located at a triple point of former austenitic grains. The wings or the phase transformation appear along these grain boundaries producing internal stress and cracking along the wings for a length of about 200 microns. The orientations are colored according to the inverse pole figure color key shown in the figure. There is no indication of phase transformation from these images, but EBSD will not discern readily between bainite and martensite, so the nature of the microconstituent along the wings remains unknown.

This approach proves that the initiation of a fish eye in gigacycle fatigue is not only due to PSB or polygonisation, with or without the effect of hydrogen as mentioned by Murakami [4]. The grain boundary, the interaction between the defect and grain boundary, and sometimes the phase transformation or the refining of the microstructure are involved in a complex process leading up to the formation of a crack in stage 2.

6-Conclusions

When the cyclic stress is low, plasticity vanishes at the surface of the fatigue specimens, depending of the yield stress and the size of the defect. However, in low yield stress iron the initiation in VHCF is always at the surface in round and flat specimens. But, for high strength steels, the initiation around a defect occurs at the interior, even in flat specimens, due to the stress concentration in plane strain, in the gigacycle regime.

In high strength steels, the stability of the microstructure and the grain boundaries are involved in the plastic deformation to explain crack initiation in the fish eye. It seems that martensite or bainite could be transformed in nanoferrite inside butterfly wings, similar to what is observed in rolling contact fatigue. This mechanism is affected by the former austenite grain boundaries.

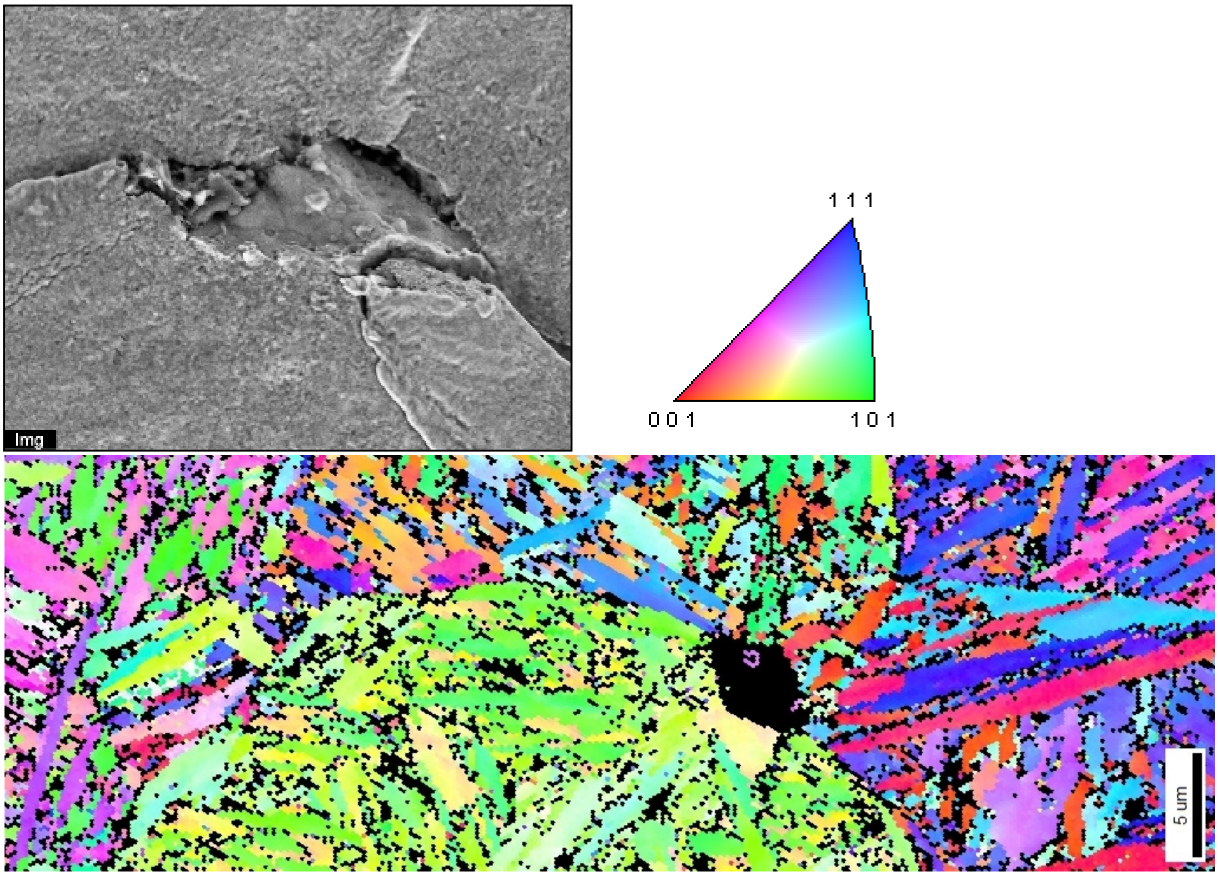


Figure 13 Relation between an oxide inclusion located at a triple point and three wings along the prior austenitic grain boundaries. Fish eye in a bearing steel failed in the gigacycle regime.

References

[1] Mughrabi H. Specific features and mechanisms of fatigue in the ultrahigh-cycle regime, *Int. Jl of fatigue* 28 (2006) 1501-1508

[2] Bathias C. and Paris P. C (2004). Gigacycle fatigue in mechanical practice, editor: Marcel Dekker, Section **7**, and ISBN 0-8247-2313-9

[3] Quian G., Zhou C. , Hong Y. Experimental and theoretical investigation of environment and theoretical investigation of environmental media on VHCF behavior for a structural steel. Acta Met. 59 (2011) 1321-132.

[4] Murakami Y. The Mechanisms of Fatigue Failure in the Ultra long Life Regime. *Metal Fatigue.* Elsevier. Oxford. 2002. UK

[5] Sakai T. Review and prospects for current studies on very high cycle fatigue of metallic materials for machine structural use, Fourth International Conference on Very High Cycle Fatigue (VHCF-4), *TMS* (The Minerals, Metals& materials Society),2007

[6]Shiozawa, K.Morii, Y. Nishino. Lu L. Subsurface crack initiation and propagation mechanisms in high strength steel in VHCF regime *IFJ* 2006, 28, 1521-1532

[7] Bathias C., Paris P.C. Initiation in the gigacycle fatigue regime, Fourth International Conference on Very High Cycle Fatigue (VHCF-4), *TMS* (The Minerals, Metals& materials Society),2007[

[8] P. Lukás, L. Kunz, L. Navrátilová, O. Bokuvka: Fatigue Damage of Ultrafine-Grain Copper in Very-High Cycle Fatigue Region, Materials Science and Engineering A, vol. 528, 2011, pp.7036– 7040]

[9] Muller-Bollengen C., Zimmermann M. , Christ H.J; VHCF behavior of austenitic steel and the effect of induced martensite

[10 C. Bathias. ASTM A01Symposium, Tampa, Nov 2011,Gigacycle fatigue: A new Tool For Exploring Bearing Steel; J.ASTM,2012

[11] Wang Chong, Wagner D., Bathias C.Gigacycle Fatigue Mechanisms in Armco Iron, IJF,June 2012

[12] Evans M. H. White Structure Flaking in Wind Turbine Gearbox bearings. Mat Sc. And tech. Aug 2011, 1-19.