Relation between the Mechanical Behaviour of a High Strength Steel and the Microstructure in Gigacycle Fatigue

Zhi Yong Huang, Wei Wei Du, Danièle Wagner, Claude Bathias

Relation Between the Mechanical Behaviour of a High Strength Steel and the Microstructure in Gigacycle Fatigue

Z. Huang[1, a], W. Du[2,b] , D. Wagner [2,c] and C. Bathias[2,d]

[1] Nanjing University of Aeronautics and Astronautics, 29 YuDao street, 210016 Nanjing,China

[2] Université ParisOuest Nanterre La Défense, 50 Rue de Sèvres, 92410 Ville d'Avray, France

[a]zhiyong.huang@u-paris10.fr, [b]wei_wei.du@u-paris10.fr , [c]daniele.wagner@u-paris10.fr, [d] claude@bathias.com

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Abstract. Many components can reach or exceed 10^9 cycles in their service time. When fatigue life is beyond 10^6, the Wöhler S-N curve was always considered to be asymptotic in horizontal axis, but the fatigue behaviour over 10^6 cycles can not be neglected. It is not usual to carry out a fatigue test beyond 10^9 cycles due to the conventional fatigue test's constraints, time consuming and expensive. High strength steel is widely applied in automobile, railway industry after surface treatment in order to improve performance of material in practice. Carburizing process hardens surface to increase wear and fatigue resistance and shot peening has a beneficial effect on the material fatigue strength from the surface residual compressive stresses. A piezoelectric gigacycle fatigue machine is used to do the tests in gigacycle regime on specimens with different surface treatments. The effect of different surface treatments is investigated in gigacycle regime at a frequency of 20KHz with a fixed stress ratio R=0.1 at room temperature. Moreover, Scanning Electron Microscopy (SEM) observations of fracture surfaces are analyzed to evaluate the mechanism of damage related to surface treatments, microstructure scored inclusion size. The role of inclusions and microstructure is emphasized at 10^9 cycles.

Introduction

In fatigue tests, according to the strain or stress level, three domains exist. For a few number of cycles at fracture ($Nf < 10^4$ cycles), it is the low cycle fatigue domain; for intermediate number of cycles at fracture ($10^4 < Nf < 10^7$ cycles), it is the high cycle fatigue domain (megacycle domain) and for very high number of cycles at fracture ($Nf > 10^7$ cycles), it is the very high cycle fatigue domain (gigacycle domain) [1]. The latter domain is now investigated 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 requires design fatigue life often superior to 10^8 cycles.

At a macroscopic scale, according to the fatigue domain, different types of crack initiation occur in cylindrical samples with a polished surface depending on whether it is low cycle, mega or giga-cycle fatigue range. For the smallest number of cycles at failure, the initiation sites are multiple and located on the surface. For intermediate number of cycles at failure, there is only one surface initiation site, whereas in gigacycle fatigue domain, the initiation site may be located in an internal zone or at the surface.

So, the problem is: what is the effect of surface treatment on the fatigue strength in the gigacycle fatigue domain? A review of the surface treatment effect in the gigacycle domain has been done by Bayraktar et al [2]. Generally, the shot peening increases the fatigue strength, and compressive residual stresses in surface promote subsurface crack initiation. When a hardening treatment is used only, the hard layer depth induces no effect on the fatigue strength.

In this study, the effect of different surface treatments (carburizing and shot peening) on a low alloyed steel was investigated in the gigacycle fatigue domain.

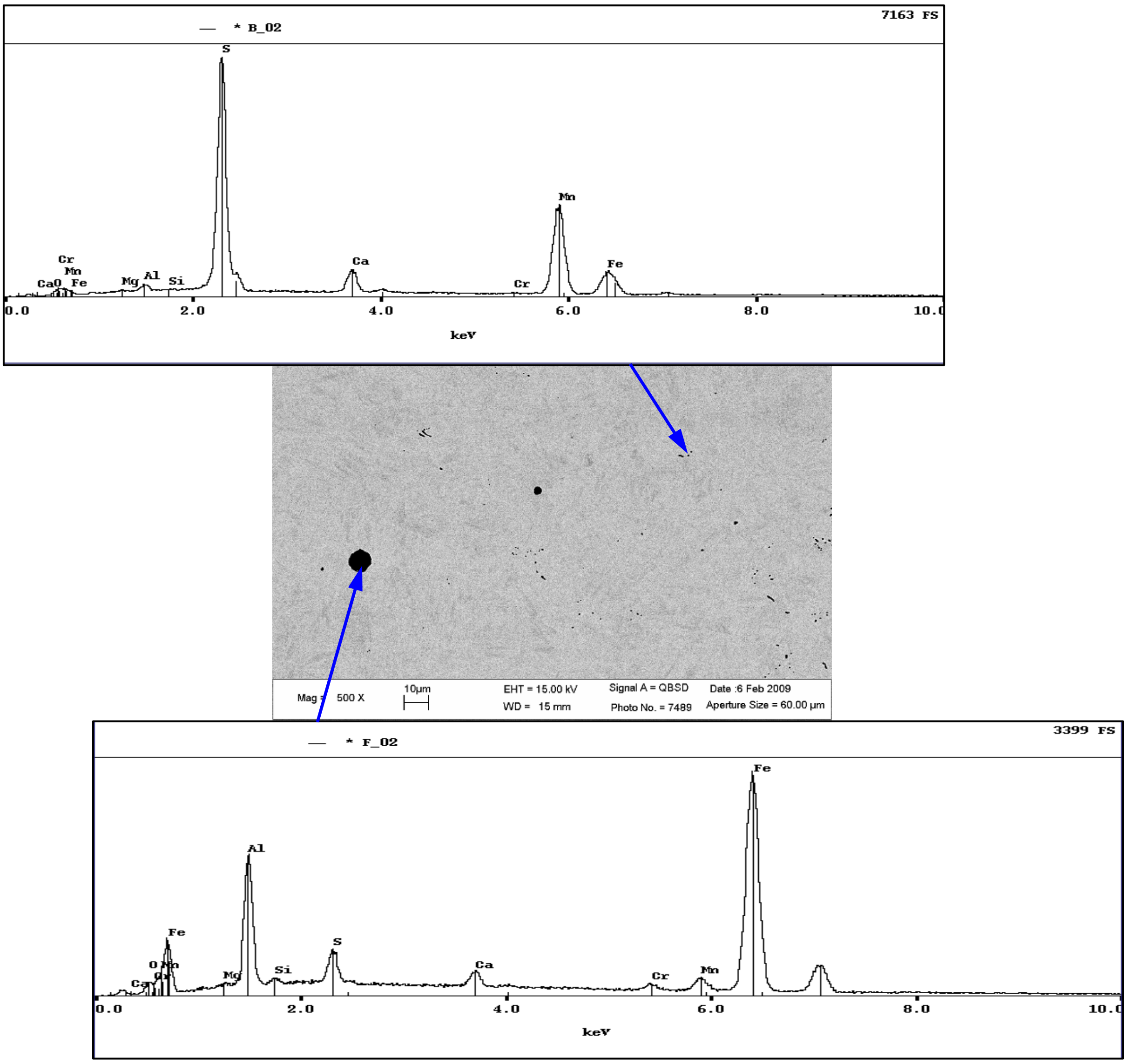
Materials

This study was conducted on a low alloyed steel in quenched and tempered condition whose chemical composition is given in Table 1.

Table 1. Chemical composition of the steel.

	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Al	N	O
wt%	0.23	0.83	0.012	0.03	0.22	0.15	0.8	0.04	0.15	0.031	0.008	0.003

The observations of polished sections in a scanning electron microscope with X-ray analysis have displayed prominently two kinds of inclusions (Fig 1): very small inclusions of manganese sulphides MnS and mixed inclusions (Al, Si, Ca, Mg, Mn, S) whose diameters are lower than 20µm and often comprised between 5 and 10 µm.



In order to improve the performance of material in practice, several surface treatments are used for this steel. Carburizing process hardens the surface to increase wear and fatigue resistance, whereas shot peening leads to more important residual compressive stresses on the surface which delays the fatigue crack initiation.

In this study, four serials of different surface treatments are performed on fatigue test specimens. Table 2 gives the details of each surface treatment.

Table 2. Surface treatment of each serial.

Serial	Surface treatment
A	Carburizing + final grinding (circular)
B	Carburizing + final grinding + Shot peening + isotropic finishing
D	Without surface treatment
E	Low Pressure Carburizing (LPC) + final grinding (circular)

The micro hardness Vickers (load = 100g) on a radius of a polished section taken at the end of the specimen for each serial is given on Fig. 2.

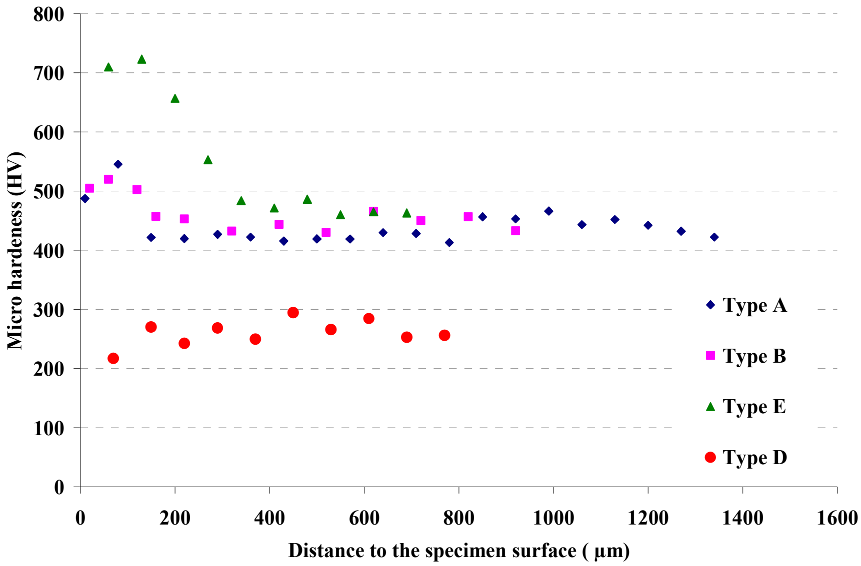


Fig.2. Microhardness profiles.

The low pressure carburizing process (serial E) gives a more important hardness on the surface (700HV to compare to 500HV) and a greater carburizing depth (300µm to compare to 150µm). The shot peening process doesn't change in an important manner the hardness of the carburizing layer (serial B compare to serial A).

For specimens A,B,E, the microstructure is martensitic with retained austenite, and for specimen D, it is ferrite-perlite microstructure.

Experimental technique in gigacycle fatigue regime

The first ultrasonic fatigue machine was constructed in 1950 by Mason [3]. With the development of computer techniques, C. Bathias and co-workers [4,5] have built a fully computer controlled piezoelectric fatigue machine (Fig.3) working at 20kHz ±0.5 kHz in which the converter changes an electronic signal (from the generator) into a mechanical vibration. The vibration of the specimen is induced with a piezo-ceramic transducer, which generates an acoustical wave to the specimen through a power concentrator (horn, Fig.3) in order to increase the displacement and an amplification of the stress amplitude. The resonant length of the specimen and concentrator is calculated by finite element

method (FEM). In our machine, there is a linear relation between the electric potential and the dynamic displacement amplitude of the ceramic in order to keep the stress constant, during the test, via computer control. The converter, horn and specimen compose a mechanical vibration system where there are four stress nodes (null stress) and three displacement nodes (null displacement for an intrinsic frequency of 20 kHz). To avoid the use of a load sensor, the stress in the mid-section of the specimen is computed from the displacement of the piezo-ceramics system after calibration. The test is automatically stopped when the frequency falls below 19.5 kHz.
In this study, the specimens were tested in tension-tension (R = 0.1). So, in this case, the bottom of the specimen is loaded in tension by a static tensile machine.

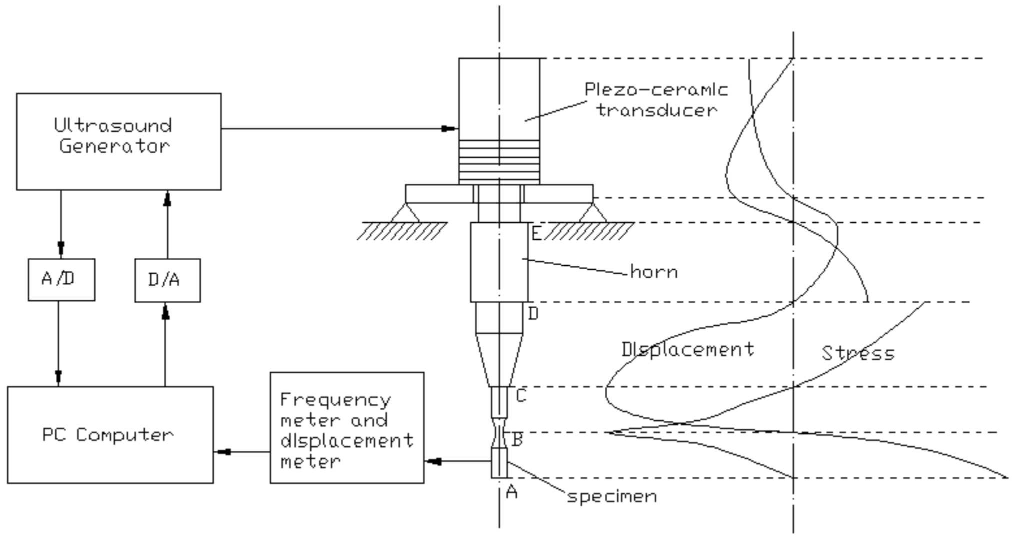


Fig.3. Schematic diagram of Gigacycle fatigue test machine.

Results

The S-N curves in the gigacycle fatigue domain ($10^6 < N < 10^{10}$) are given in Figs. 4,5,6,7 for each serial. In each figure of test results, the five symbols indicate different test and failure states. The filled diamond means surface initiation crack; the empty square is crack initiating from subsurface; the filled round is not failed in gigacycle test until 10^9 cycles; the empty triangle shows the result of retesting the no failed specimens until 10^9 with 20MPa higher stress amplitude augmentation than before and the crack initiation is from surface; the filled triangle is the same retesting situation but the crack initiation is from subsurface.

For serials A, the fatigue strength seems keeping constant between 10^6 and 10^{10} cycles. For the shot peened specimens (serial B), beyond 10^9 cycles, there is no failure, but the scattering is important. The large scatter of serial B is related to shot peening and residual stress field. For serial E, between 10^6 and 10^{10} cycles the fatigue strength slightly decreases, and all specimens (except one) are failed. For serial D, its lower hardness decreases the fatigue strength.

For all serials, among failed specimens, some crack initiations are on surface and some others are subsurface crack initiations leading to fish eyes. Table 3 gives the percent of surface crack initiations in the different domains.

The shot peening decreases the initiation fatigue crack on the surface (serial B comparing to serial A). A polishing after the shot peening favours more the subsurface crack initiation, but no improvement of the fatigue strength is measurable. For serial E, the LPC process promotes a hard layer on the surface which inhibits the surface initiation.

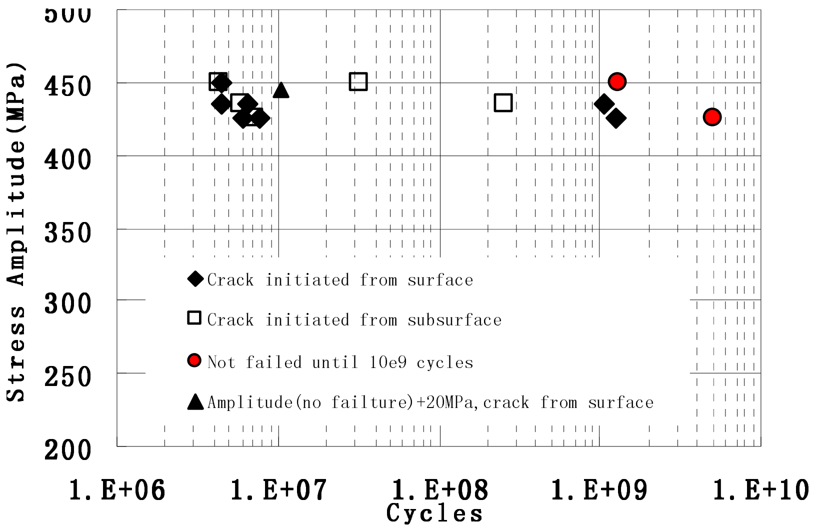


Fig. 4. S-N curve for serial A, R=0.1.

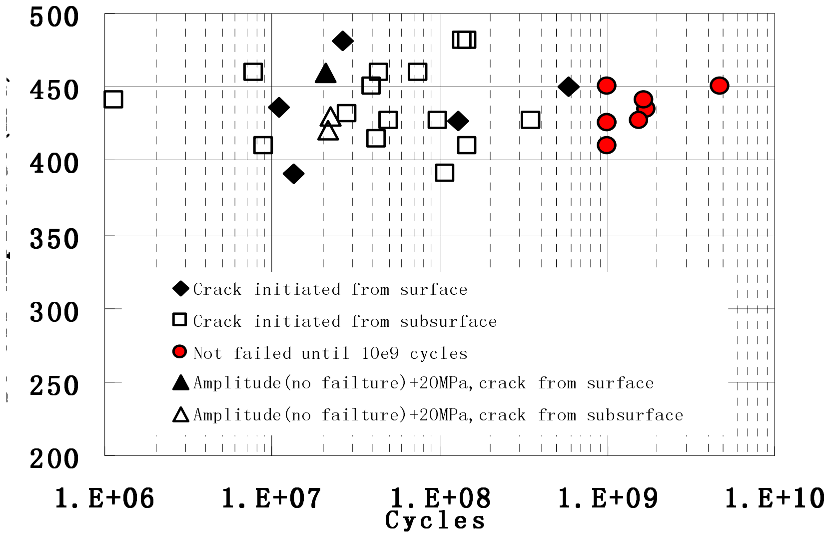


Fig. 5. S-N curve for serial B, R=0.1.

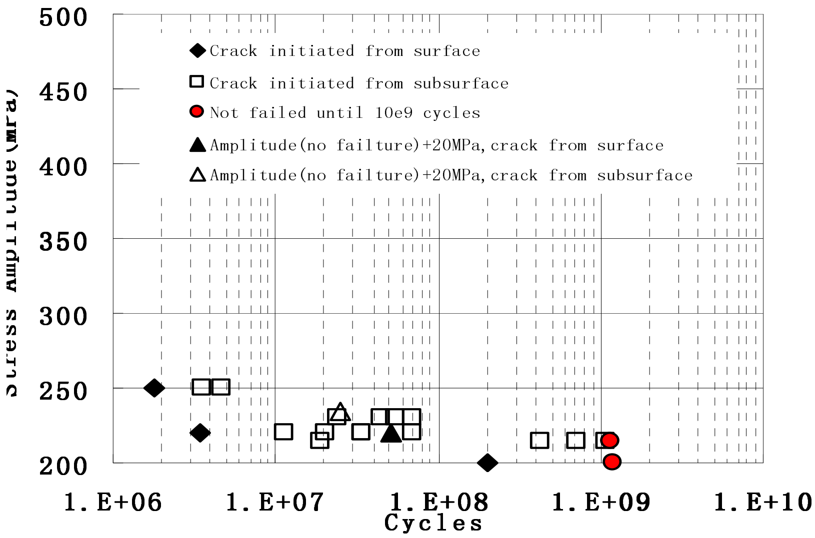


Fig. 6. S-N curve for serial D, R=0.1.

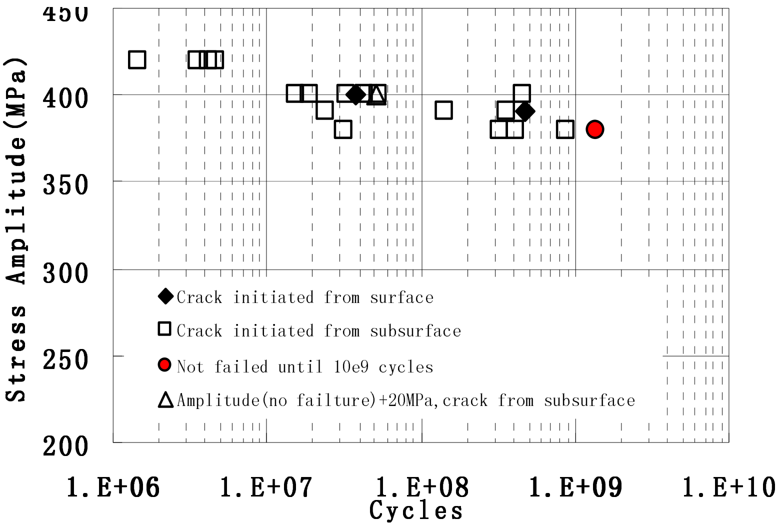


Fig 7. S-N curve for serial E, R=0.1.

Table 3. Percent of surface crack initiation for failed specimens.

	A	B	D	E
% surface initiation total	50	26	25	10
% surface initiation in 10^6-10^7 cycles	35.7	4.3	10	0
% surface initiation in 10^7-10^{10} cycles	14.3	21.7	15	10

Fractographic observations. Fracture surface observations have been performed with binocular microscope and Scanning Electron Microscope.

For subsurface crack initiations (fish eye), the origin of the crack initiation is either a mixed inclusion (the largest inclusions) (Fig. 8) or a “supergrain” (Fig. 9). It is difficult to know what this “supergrain” is. More investigations are needed. One hypothesis is a grain of retained austenite, whose glide dislocation planes is in the maximum shear orientation.

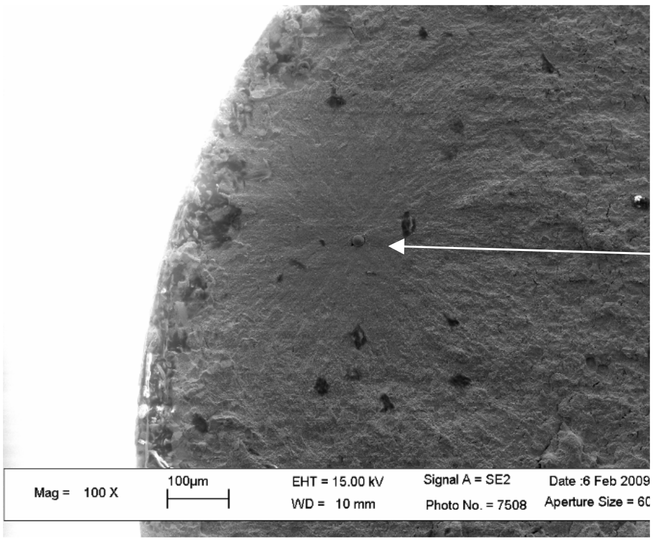


Fig.8a. Fish-eye (serial E, N_f = 1.38×10^9cycles).

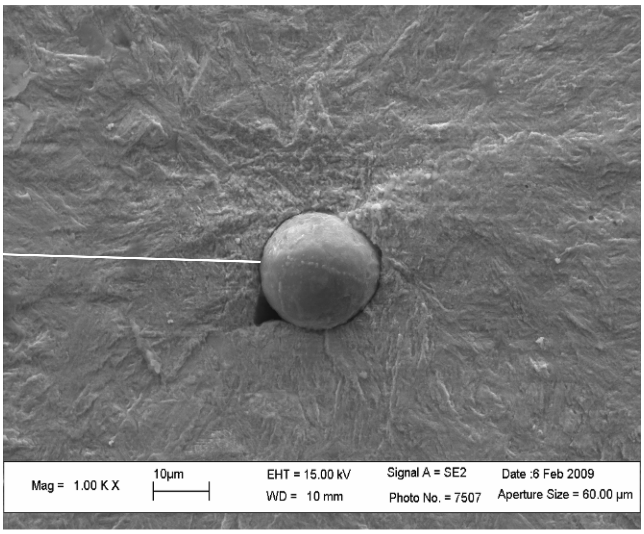


Fig.8b. Inclusion in the fish-eye.

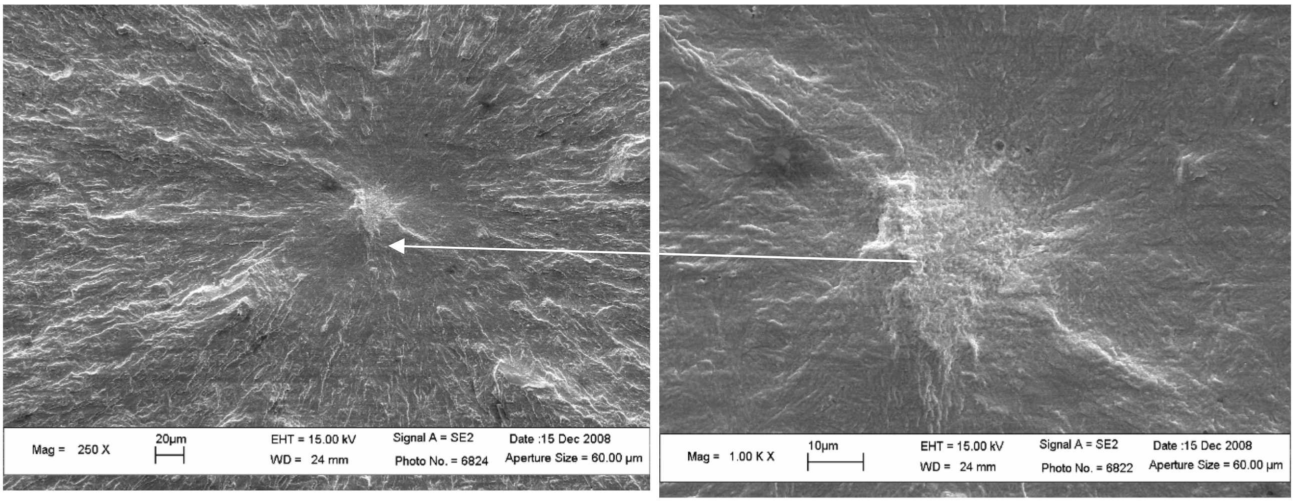


Fig.9a. Fish-eye (serial E, $N_f = 3.61\times10^8$ cycles).

Fig.9b. “supergrain”in the fish eye center.

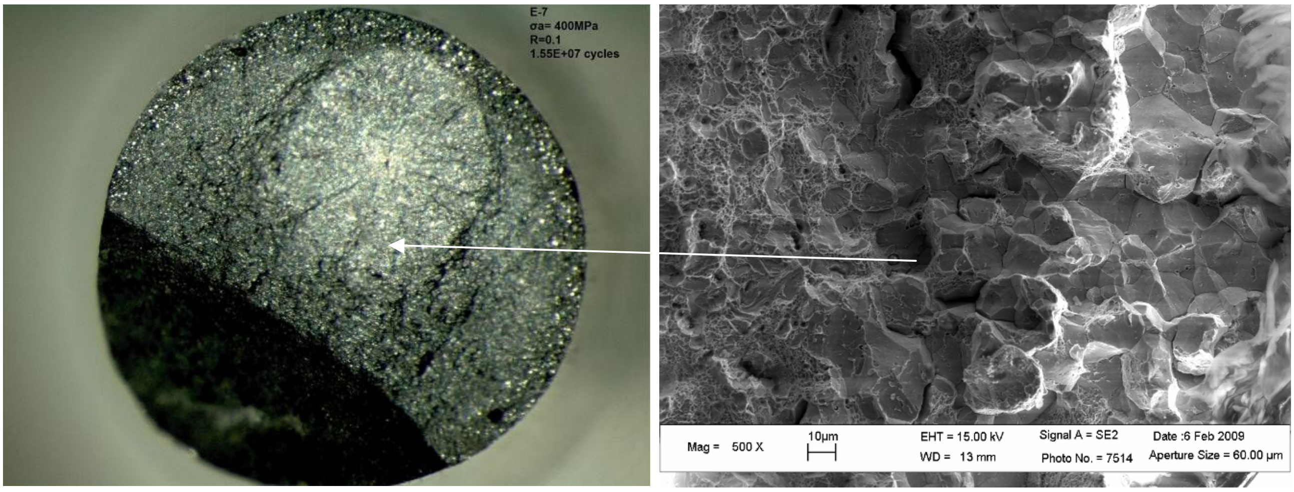


Fig.10a. Carburizing layer and fish eye in serial E.

Fig.10b. Intergranular fracture in carburized layer.

In the E serial, the carburized layer is important (300 µm depth) and the hardness is high (700HV). In this case, the initiation is only subsurface and the final fracture in the carburized layer is intergranular (Fig 10). This behaviour comes from the phosphore segregation in the prior austenite grain boundary during the carburizing process (austenitization)[6]. This zone is brittle and stops the fish eye crack propagation.

Discussion – Conclusion

The effect of carburizing and shot peening is well established in the Woëhler regime: the fatigue strength is improved by surface hardening and compressive residual stresses. But, this is only true up to 10^7 cycles. In the gigacycle regime, the effect of surface hardening is more complex. There is a competition between surface and subsurface initiation which leads to reduce drastically the effect of hardening when the fatigue life is ranging between 10^7 and 10^9 cycles.

The carburizing process performed in serial A/B with weak depth and hardness of carburized layer show that at 10^9 cycles and beyond, the specimens are not failed (neither on surface or subsurface). This means that none surface markings are sufficiently deep to initiate the fatigue crack initiation, and the cleanness of the investigated steel (small inclusions) do not allow the subsurface fatigue crack initiation. It is the inclusion diameter or the “supergrain” size which controls the fatigue strength in the gigacycle regime even after surface hardening.

The low pressure carburizing process (serial E) gives a brittle hard layer which inhibits the surface initiation, and leads to subsurface initiation in almost all specimens. In this case, the fatigue strength decreases slightly.

In the gigacycle fatigue regime, the shot peening process with subsequent polishing (serial B) promotes the subsurface initiation. The shot peening don't provide improvement of the fatigue strength.

In the gigacycle fatigue regime, when the inclusions content is weak, the crack initiation in subsurface can start from "supergrain" of the microstructure.

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