Local and Global Approaches to Giga Cycles Fatigue Threshold

Y.Katz[1], Y.Murakami[2] and W.W. Gerberich[1]

[1]Department of chemical engineering and material science, University of Minnesota, Minneapolis, MN 55455 U.S.A.
[2]Departmnet of mechanical engineering science, Kyushu University, Fukuoka 812-8581 Japan.

ABSTRACT: *Even after consecutive decades of intensive activities, fatigue remains the subject of great interest due to its critical role on structural integrity aspects regardless the application scale. As such, significant efforts have been continuously devoted to cyclic lading on various scientific/engineering interfaces. The current study is centered on the ultra long fatigue life regime which might stress the beneficial role of local vs. global approaches, particularly in terms of the fatigue threshold concept. Beside information concerning the mechanical response under cyclic loading up to the giga cycles regime in high strength Cr-Mo steel, fine scale features visualization and surface analysis were supplemented. The study explores some of the basic elements in the sub critical micro crack stability behavior. In addition the inherent cyclic dependency of fatigue damage evolution is emphasized. Experimentally based, relevant arguments emerged regarding the possible role of embrittling species in terms of mechanical/chemical interactions on the ultra long fatigue life behavior.*

INTRODUCTION

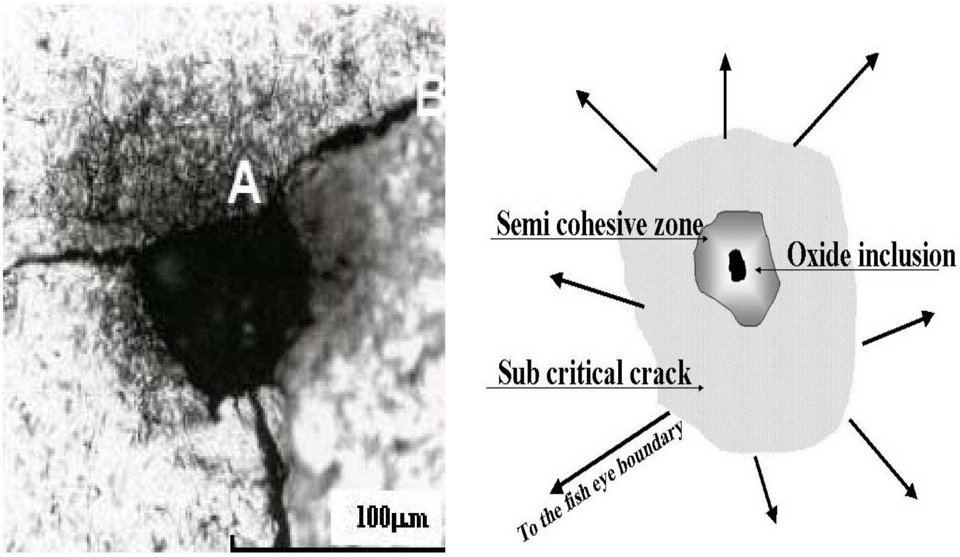
Engagement with fatigue processes introduces at least three important issues. First the concerns about the fatigue driving force. This is controlled by the applied (global and remote) load/stress or the strain (total or plastic) amplitude. For small defects or sharp notches the independent variable for the driving force can be expressed by fracture mechanics parameters e.g. the applied stress intensity factor range. The additional two issues are related to the material response either mechanical and/or geometrical as well as dislocation structure modifications. The latter are revealed by local mechanical tracking and visualization. In this framework the threshold concept becomes frequently viable beside fatigue life determination. In addition threshold predictions are attempted particularly for the sake of design procedures. However, phenomenological based, ample complexities emerged associated with loading conditions and other facets. Microstructural or geometrical aspects might influence or even dominate the exact experimental findings. In fact, the current investigation is entirely connected to the aforementioned elements. For this purpose, low alloy Cr-Mo steel was selected with attention to the giga cycle fatigue behavior. Here, a vital incentive has been invoked for a designer benefit. In this context several studies have indicated already that the conventional fatigue limit deserves more input in general and specifically for the ultra long fatigue life [1-3]. The current study assisted by novel techniques considers a fatigue threshold prediction methodology suggested as a practical model beside dilemma regarding its validity in the giga fatigue cycle regime [4].

MATERIAL AND EXPERIMENTAL PROCEDURES

Low alloy SCM 435 Cr-Mo steel was selected. The chemical composition (in Wt %) consisted of 0.36C,1.0Cr, 0.15Mo, 0.77Mn, 0.13Cu, 0.19Si, 0.014P, 0.006S balanced by Fe. The as received impurities level (in Wt ppm) was 8 and 0.7-0.9 oxygen and hydrogen respectively. The fatigue specimens were surface modified followed by heat treatment resulting in temper martensitic microstructure. Surface hardening provided a surface layer of 1700 μm with higher hardness value of 30% as compared to the interior. Tension-compression fatigue tests were conducted on smooth specimens at ambient temperatures by using closed loop electro-hydraulic computerized machine. Load ratio of $R= -1$ was applied with frequency range of 30 to 100 Hz. The uniaxial cyclic loading on 7mm round specimens was carefully performed avoiding invalid conditions due to possible bending. Residual stresses caused by surface modification were determined by X-Ray diffraction technique. Fracture surface visualization was assisted by optical, Scanning Electron Microscopy (SEM) and by Atomic Force Microscopy (AFM). In addition special attention was given to the post failure surface analysis. This was supplemented by Auger Electron Spectroscopy (AES) and by X-ray Photo Electron Spectroscopy (XPS).

EXPERIMENTAL RESULTS

The performed surface modification by carbonization and nitriding resulted in compressive residual stresses of about half the yield stress of the near surface layer.The fatigue crack initiation sites were dominated by the second phase oxide inclusion. Damage origin in the interior provided conditions that facilitated the exploration of the giga cycle fatigue process features. The fracture surface morphology for fatigue life exceeding 10^7 cycles indicated the development of a semi-cohesive zone at the oxide vicinity. By approaching the giga fatigue cycles typical fractographical features became evident. The process zone occurred with initial rough morphology with sub grain fine scale micro structure. At this stage the initial fatigue crack extension rate was extremely slow, only in the order of 10^{-11} m / cycle. Clearly crack stability did not prevail but most of the fatigue life was associated with the early stage. Typical near oxide initiation sites are illustrated in Figure 1.



(a) **(b)**

Figure 1: (a) near oxide inclusion locations A and B for the surface analysis are indicated, (b) schematic, sub critical crack extension.

The sequential events that followed micro crack initiation are a sub critical crack extension forming the so called “fish eye” prior to mechanical instability. Crack initiation and the fine scale features associated with the sub critical crack require fractografical and kinetic attention. However the most striking results were explored by the AES and the XPS surface analysis. For a fracture surface after almost a giga cycles fatigue life, the occurrence of chemical species redistribution at the crack tip became apparent. For the analysis two locations were selected. Location A near the inclusion in the process zone and B at a remote location about 300 µm from

A. With the assistant of point analysis higher resolution provided a consistent depth profile analysis up to 200A^{o}. the important contribution of the XPS analysis (generally consistent with the AES) enabled to sort out the chemical state of some of the element compounds. As shown in Table 1

Table 1: Normalized AES values for locations A and B (see Figure 1)

Location A				Depth in Å
S/Fe	**P/Fe**	**C/Fe**	**O/Fe**	
0.06	0.214	4.827	2.316	10
0.05	0.244	3.015	1.978	20
0.05	0.231	2.089	1.775	30
0.02	0.071	0.536	0.179	100
0.02	0.028	0.216	0.224	200
0.02	0.218	1.126	0.571	200*
Location B				Depth in Å
0.02	0.063	0.663	1.179	10
0.02	0.048	0.332	1.127	20
0.02	0.044	0.269	1.136	30
0	0	0.11	0.269	100
0	0	0.122	0.120	200
0	0	0.125	0.135	200*

(*) 1 µmX1µm point analysis this enabled higher propensity for cracking onset at the interior.

enrichment of embrittlement species were decisively substantiated. Here to mention that the supplementary information by the XPS confirmed beside carbides also graphitic carbon. As an appropriate background [5,6] potential role of trapped hydrogen at the oxides has been recognized. This finding was provided by Secondary Ion Mass Spectroscopy (SIMS) alluded to the cause for local decohesion. Thus, local chemical gradient on top of hydrogen up take introduce locally a dramatic change in the environmental sense. In the current investigated system such environmental changes were confined to the crack tip vicinity enabled local embrittlement interaction arguments. Crack stability below the fatigue limit is normally attributed to a diminishing driving force. However, at extremely long life solely mechanical effects that are related to the local driving force are acting also in a cycling dependent material resistance variation which is decreasing gradually but in a monotonic fashion.

DISCUSSION

Enhanced chemical redistribution at the sub critical crack tip, by continuous cycling introduces an additional facet to the understanding of small crack stability and thus to the fatigue threshold concept. Specifically, trapped hydrogen at inclusions and confirmed embrittling species gradient already invoked the appropriate conditions for synergetic effects. Based on the AFM images early crack extension is involved in the developments of sub grain interfacial process zone. This became more visible in conditions that allow hydrogen dissociation, reduce binding energy and free hydrogen mobility caused by dislocation dynamic and local adiabatic heat. Here the meaning of a “process zone” is a semi cohesive zone formation that provides crack tip shielding component affecting as such the local driving force. This is a different scenario by involving in the long fatigue life the possibility of deformation/environment interaction. Consequently, prediction based on geometrical or mechanical aspects might be or even should be short coming in circumstances in which the role of local embrittlement prevails. Two remarks as related to the current experimental findings are in order.

Mechanical/environmental interactions

Either hydrogen embrittlement (HE) per se or synergistically hydrogen enhanced embrittling species activity requires a local approach. Regarding HE the current study leans toward generic hydrogen enhanced decohesion model (HEDE) allowing quantitative engagement with experiment. Following a comprehensive series of research activities [7-9] as related to brittle fracture further development has been achieved with regarding HE. The model is considering local conditions of the stress field and the given cohesive energy. Thus, the driving force vs. the material resistance is locally evaluated. Changes in the driving force due to the crack tip shielding effects or resistance variations due to environmental effects control the instantaneous crack stability. This approach is even advanced nowadays particularly in small volumes problems (e.g. thin films) with and with no environmental interactions [10]. In this sense even the global description by the S-N traditional curve is dominated by the near oxide small volume behavior. Regarding the threshold in fracture mechanic representation K_{Ith} a linear decrement of the critical local Griffith value k_{1G} with increasing local hydrogen concentration C_H is given by;

$$K_{\mathrm{I}th} = \frac{1}{\beta'} \exp\left\{ \frac{(k_{1G} - \alpha C_H)^2}{\alpha'' \sigma_{YS}} \right\} \qquad (1)$$

were β' and α'' are constant and σ_{YS} is yield stress [11]. Following Eq 1, variation in the local environmental concentration might cause local decohesion either interfacial or cleavage. Analogical evidences are now gathered also interfacial engineering of thin films. It has been established already that interfaces can be dramatically embrittled by segregation. As addressed by Lipkin et al [12] a quantified illustration indicated a reduction in toughness from about 250 to 2 Jm^{-2} only due to the infusion of carbon into Au/Al_2O_3 interface, this with no yield stress change of the gold. Degradation in toughness has been attributed here to the effects of carbon segregation on the work of adhesion and the bond strength. Similar results were obtained in the γ-Ni/Al_2O_3 interface caused by different degree of the interfaces “cleanness” [13]. Thus carbon enrichment which was established in the current study by surface analysis (see Table 1) as well as other embrittling species can be accentuated by hydrogen as a major agent for local instability.

Crack tip semi cohesive zone interaction

The fracture surface morphology indicates typical process-zone development at the oxide cracking site vicinity. The meaning here is related to a semi-cohesive micro fractured zone. Fractographical observations by AFM support the occurrence of a sub grain interfacial embrittled zone. A crack tip semi-cohesive zone interaction has been previously analyzed in connection to static and fatigue threshold values in hydrogen [14]. The analysis has considered a modified Dugdale-Barenblatt model for equilibrium. As such, a semi cohesive zone has been included beside a cohesive zone to be the plastic zone. The concept was also experimentally verified by Chen by utilizing Selected Area Channeling Pattern (SACP) technique. Here Fe-3%Si single crystal was tested under sustained load conditions while hydrogen enhanced crack extension [15]. Notice that crack shielding near the threshold might be critical with significant implications on the early stage kinetic of the fatigue crack extension.

SUMMARY AND CONCLUSION.

Global approaches either by S-N or by plastic strain vs. life relationship hardly guarantee a sound physical view regarding the fatigue threshold concept. This issue emerged again in exploring the giga fatigue cycle regime particularly vis-à-vis consistent prediction models. Better understanding of the exact micro mechanism that is operating at a specific cycles domain appears essential. The contribution here of the local approach turned out to be beneficial regarding few issues. First, how to explain the typical fracture modes (also designated by the Optical Dark Area zone), that occurred at long life. Second, in resolving the cause for the extremely slow crack extension rate at the early stages resulting almost in initiation controlled process. Third, the modification of the Murakami area model for the ultra long life. The current proposed micro mechanical/environmental mechanism suggests an appropriate explanation for the experimental findings. Notice that in contrast to the Murakami model a fictitious crack size correction as an adjustment parameter has been addressed by El Haddad et al [6] even for a conventional threshold model. In this respect, the Murakami model distinction between mechanical/environmental regimes involves only an effective area correction which remains physical and consistent with the proposed area model [3]. Distinction between irreversible micro plasticity mechanism and the combined local deformation/environment mechanism might become important in ultra long fatigue life. Accordingly the following is concluded.

1. Small crack threshold validity can be explored in low alloy steel by focusing on ultra long fatigue life behavior.
2. Surface analysis in the giga cycle regime has confirmed sharp concentration gradients at the crack tip vicinity. These gradients consisted from embrittling species like C,O,P and S segregation.

3. Such segregations are sufficient to develop a local semi cohesive zone mainly in sub grain interfacial locations. Enhancement by hydrogen only supports such micro mechanical mechanism.
4. The combined effects of gradual development of embrittling species enrichment with cycles besides crack tip shielding explain the current phenomenological results.

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