ULTRA LONG LIFE FATIGUE-IMPLICATION ON THE CONVENTIONAL THRESHOLD

Y.KATZ*, W.W GERBERICH* AND Y.MURAKAMI**

**: CEMS- University of Minnesota, Minneapolis MN, 55455 U.S.A*
***: Department of Mechanical Science and Engineering. Kyushu University, Fukuoka 812-8554, Japan*

ABSTRACT

In fatigue design one of the key practical criteria is embodied in the concept of small crack fatigue threshold. Explorations in steels as expressed by S-N curves while extending the life span toward the giga cycle regime calls for re-evaluation.
The current study was conducted on Cr-Mo low alloy steel. Following surface modification, fatigue tests were performed by utilizing smooth uniform round specimens. Here tension-compression fatigue at ambient temperatures was carried out with frequency range of 30 to 100 Hz and load ratio of R= -1. Near surface residual stresses were determined by X-ray diffraction. In addition optical, Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM) supplemented post fracture surface visualization. Finally, Auger Electron Spectroscopy (AES) and X-ray Photoelectron Spectroscopy (XPS) was conducted for surface analysis.
The study revealed that by approaching the giga cycle regime micro crack instability even below the conventional threshold occurred. In ultra long life, surface analysis has established sharp concentration gradients of embrittling species at the vicinity of internal micro cracks. A micro mechanical model rationalized the morphological as well as the obtained kinetic findings. This was associated with local mechanical/environmental interactions beside the occurrence of operative crack shielding mechanisms at the early crack extension stage.

KEYWORDS

Ultra long fatigue life, fatigue threshold, low alloy steel, surface analysis, embrittling species, semi cohesive zone, crack shielding.

INTRODUCTION

The current phenomenological study is centered on at least two major issues. First, on the effort to establish the mechanical response of elastic-plastic solid under ultra long fatigue loading. The mechanical response is meant and expressed here by the S- N curves extending towards the giga cycle regime. Second, recent exploration in steels [1-3] has already called for the threshold stress value re-evaluation. In this context the following notion is recalled that in high strength steel traditional fatigue limit is normally quoted. Previous research activities in steel [3-5] indicated however that for extremely long fatigue life a traditional fatigue threshold is not achieved. Moreover, by following micro crack initiation very slow crack growth rates occur and the discontinuous crack instabilities is manifested by typical fine scale features.
Such findings that appeared “anomalous” alluded to additional factors that might be involved in the sub critical crack extension process even beyond “pure” micro plasticity-cumulative damage considerations. In fact the study is also engaged with the special case of specimens since all followed external surface modification. Such treatment assisted in suppressing

kinetically the critical role of surfaces in enhancing fatigue crack initiation and propagation. In this case of near surface residual compressive stresses, crack initiation sites were dominated by second phase oxide inclusions that enabled further insights into long fatigue life behavior. In this framework while stretching the envelope of understanding to ultra long life several critical questions emerged: (a) What kind of micro mechanism can provide cyclic dependency of the traditional fatigue threshold? (b) What are the necessary sequential events at the long life regime that might explain the cycle dependency of crack stability, the fatigue growth rate and the post fracture surface morphology (c) Finally, how physical is a proposed model considering quantitative argumentations. Thus, the intention of the present study is to provide more input in approaching the giga cycle fatigue application. By considering long life it seems that the traditional irreversible slip contribution to damaging might offer only a partial physical description. Specifically, can embrittlement phenomena occur by chemical segregation with chemical gradients that might facilitate local degradation under near threshold cyclic loads. In sorting out the aforementioned issues the study emphasize various techniques in visualizations and surface analysis that are assessed on the background of the mechanical response.

MATERIAL AND EXPERIMENTAL PROCEDURES

Low alloy Cr-Mo steel was selected. The chemical composition was (in wt%) 0.36C,0.19Si,0.77Mn,0.014P,0.006S,1.0Cr,0.15Mo,0.13Cu and Fe balanced with impurities (in ppm) 8 oxygen and 0.7-0.9 hydrogen. Standard mechanical characterization was performed by closed loop electro hydraulic machines supplemented by hardness testing. All tests were conducted at ambient temperatures. Uniform smooth and round specimens of 7mm in diameter and 20mm in gage length were utilized for fatigue tests. In addition to an applied heat treatment of 850C and 170C quenching and tempering respectively all specimens were surface modified by carbonization and nitriding. In tempered martensitic microstructure significant differences prevail between the specimens interior and the near surface external layer.

Tension/compression constant amplitude fatigue test were conducted with extra care to ensure uniaxial loading conditions while avoiding bending. Load ratio of R= -1 and frequency range of 30 to 100 Hz was used. Residual stresses were determined by X-ray diffraction techniques following the method for randomly oriented polycrystalline material [6]. Post failure surface analysis was conducted by Auger electron spectroscopy (AES) in order to reveal embrittling species in conjunctions with X-ray photoelectron spectroscopy (XPS). The latter provided information concerning the chemical state of the relevant species. The scanning Auger micro probe was a Perkin-Elmer model PHI595 and the small area X-ray photoelectron spectrometer was the Perkin-Elmer PHI5400 model. Both instruments were equipped with sputtering guns for ion etching of the surface with required rapid chambers.

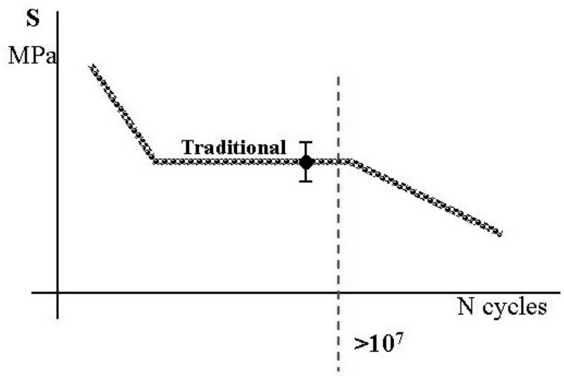
Initial pressure of $2x10^{-10}$ torr allowed only the increase by a factor of two to take place during the analysis. Sputtering rate was calibrated by standard references. Time dependent experiments followed the verification in avoiding any ground contamination during the data acquisition.

Fracture surface visualization was supplemented by scanning electron microscopy (SEM) and by atomic force microscopy (AFM).

EXPERIMENTAL RESULTS AND DISCUSSION

The S-N response for ultra long fatigue life remained consistent with other studies that have addressed the fatigue threshold under similar circumstances [1-5].

Thus it became evident that in steel at the range of 10^8 to 10^9 cycles the stress is lower than the conventional fatigue limit (see Figure1). In this context an additional notion is added. Issues that are related to practical models regarding the fatigue threshold prediction are beyond the current paper scope. The same applies to the phenomenological distinction between the load state effects or material approach aspects. Here the description is solely focused on the present experimental based findings.
Accordingly it seems advisable to cope with or assess the origins concerning the morphological fracture surface features and the initial extremely low fatigue crack extension rate. At this point it becomes apparent not to consider only the driving force but also possible developments that might affect the material resistance. The latter is already alluding to the possibility of some kind of embrittlement process that might lead to a local Ductile-Brittle Transition.
Surface modification resulted in residual compressive stress of about 500MPa at the near surface layer of about 1700µm. In this context standard Vickers hardness values of 7.8Gpa compared to 5.6Gpa were determined in the specimens near surface and the interior respectively. Under such circumstances micro crack initiation sites were dominated by internal inclusions that were identified by X-ray analysis to be Al_2O_3. $(CaO)_x$ globular duplex inclusion type. The higher propensity for micro crack initiation at the interior provided special conditions in tracking the morphology at the oxide vicinity during the fatigue process. A typical crack initiation origin at an oxide inclusion is illustrated in Figure 2.



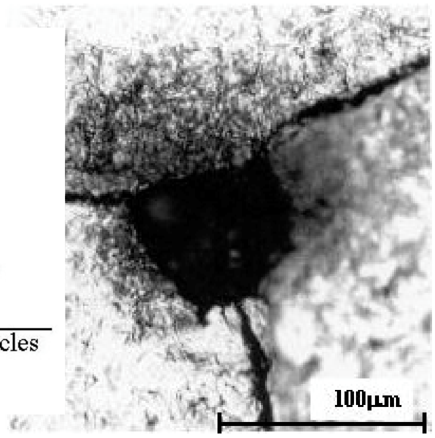


Fig.2. The oxide inclusion or crack site and its vicinity for a stress of 510MPa 9.70x10^7 cycles.

Additional feature that was observed near the crack origin was associated with an area designated ODA (Optically Dark Area) that was cyclic dependent. Dependency here means the actual occurrence and the size as well. For example this area was hardly developed at smaller fatigue life of 10^5 to 10^6 cycles. Moreover the ODA indicated different fracture mode that appeared as interfacial rough surface as compared to a typical tempered martensitic mode. This peculiar mode was also formed during low crack extension rates of 10^{-12} to 10^{-11}m/cycles. AFM fractography images are demonstrated in Figure 3. This high resolution confirmed once again the typical sub grain features with higher surface energy always adjacent to the crack initiation site.
Regarding the surface analysis a brief elaboration seems desirable. Takai et al [7,8] have addressed previously the important issue of trapped internal hydrogen at oxide inclusions. For this purpose Secondary Ion Mass Spectroscopy (SIMS) was applied. These studies also

concluded that non-metallic inclusion provide higher binding energy for hydrogen trapping as compared to dislocations or grain boundaries.

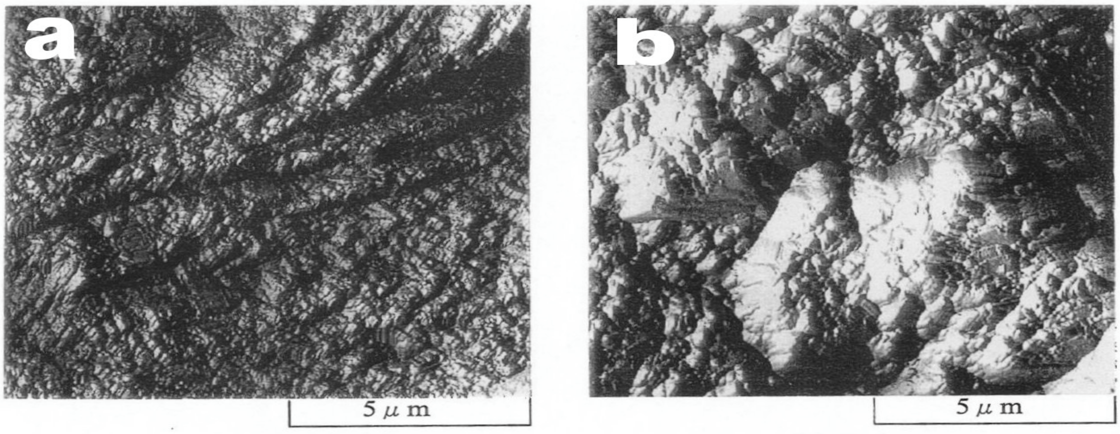


Fig.3. AFM image illustrating (a) Outside the process zone (b) At the process zone

As such the current surface analysis intents to provide more of comprehensive information concerning chemical redistribution or time dependent gradient formation. Nevertheless the trapped hydrogen environment is well recognized which might allow arguments regarding synergetic mechanism to be effective.

The AES and XPS are appropriate surface analytical techniques where the detected emitted electrons from the surface layer are less than 15Å deep. Moreover, the provision to probe deeper enables a depth profile to be accomplished by sputter-etching the surface and analyzing continuously the newly exposed surfaces. For the AES all the data is based on Auger electron spectrum that is numerically differentiated and expressed by dN(E)/ dE vs. E were N (E) is the electron yield and E the electron pass energy. In the current application two locations were selected assisted by the AES surface analysis. Location A was adjacent to the oxide inclusion and B a remote location of about 300μm from the inclusion namely the micro crack initiation site. For both locations depth profile analysis was performed up to 200Å in depth. At the final depths higher resolution was added by point analysis namely data collection from 1x1μm area as compared to the relatively larger area of 10x10μm.

The data is summarized in Table 1 indicating clearly the embrittling species enrichment at location A of C,O,P and S in a consistent fashion.

Table.1. For the location A and B, concentration gradient is given in normalized values relative to iron. Fatigue span 2.17×10^8 cycles.

Depth in Å	Location A				Location B			
	O/Fe	C/Fe	P/Fe	S/Fe	O/Fe	C/Fe	P/Fe	S/Fe
10	2.316	4.827	0.214	0.06	1.179	0.633	0.063	0.02
20	1.978	3.015	0.244	0.05	1.127	0.332	0.048	0.02
30	1.775	2.089	0.231	0.05	1.136	0.269	0.044	0.02
40	1.433	1.456	0.181	0.02	1.035	0.181	0.026	0.01
50	1.174	1.12	0.132	0.02	0.938	0.177	0.022	0.01
100	0.179	0.536	0.071	0.02	0.269	0.11	0	0
200	0.224	0.216	0.028	0.02	0.120	0.122	0	0
200 {1 μm × 1 μm point analysis}	0.571	1.126	0.218	0.02	0.135	0.125	0	0

Even recognizing that quantitatively chemical analysis by AES has a composition error bound of several atomic percent the extremely sharp chemical gradient at the crack tip vicinity (as measured) remains very convincing. The surface analysis as shown in Table 1 emphasizes also the valuable information that has been obtained by the higher resolution. The XPS that was performed on a relatively higher area supplemented information about the chemical state of the embrittling species. For the carbon the existence of two states namely carbidic and graphitic were confirmed. Thus experimentally based in ultra long fatigue life, the following sequential events are hypothesized that combines two important elements of material degradation beside micro crack shielding mechanism at the early stages of crack propagation. This explains that extremely high cycles can be accommodated but at the same time a conventional fatigue threshold is not archived. Thus crack propagation bounded by the conventional near threshold stress, the crack stability can be challenged by environmental changes highly dependent on the number of cycles. The crack as such provides hydrostatic stresses and a continuous redistribution of embrittling species might be accentuated even by intensive dislocation transfer. Consequently the micro fracture semi cohesive zone is gradually developed confined to interfacial site on the sub grain scale. The key issue is that such a process zone carries a crack arrest/shielding potential on one hand but local enrichment of embrittling species results in alternating crack extension, hesitations and/or arrest. These elements are depicted in Figures 4 and 5.

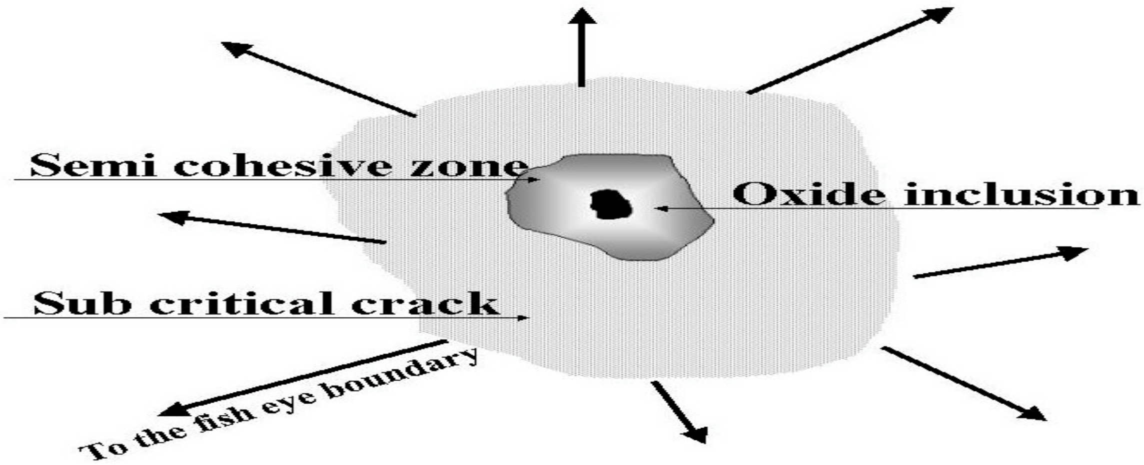


Fig.4. Schematic typical regions at the inclusion vicinity

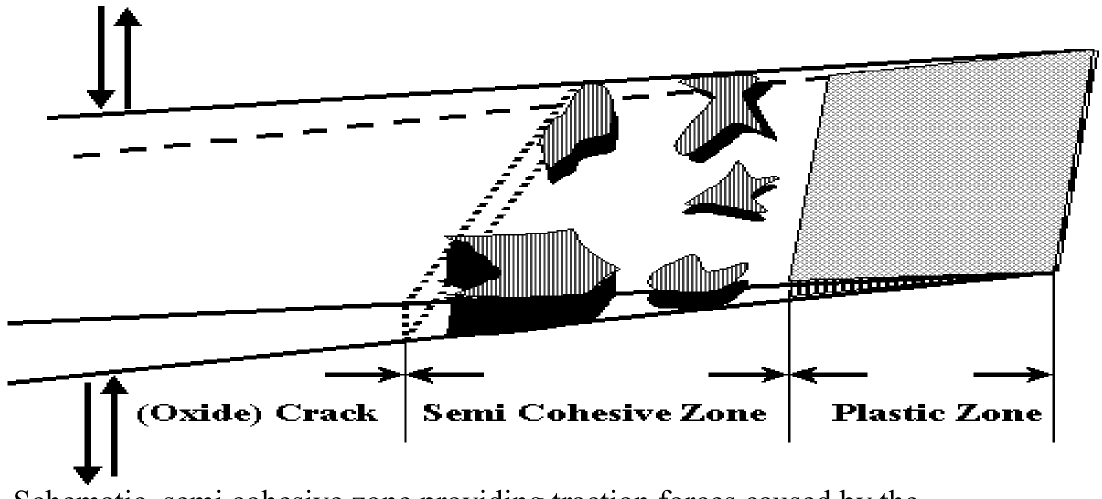


Fig.5. Schematic, semi cohesive zone providing traction forces caused by the ligaments

After an additional crack growth the fatigue process shifts again to a regular process i.e. a process that is dominated by micro plasticity in a undegraded material. This model actually matches the morphological and the fractographical fine scale features. In order to consider such a sequential scenario which includes the crack shielding aspects, a brief quantitative arguments are finally added. Crack shielding or anti shielding with the end result of local effective stress intensity is always compared to the normalized applied stress intensity that is called by the remote stress. Distinction here can originate from numerous factors and their combination. For example, crack tip dislocation arrangements, semi cohesive process zone, crack bifurcation or side ligaments due to crack front tunneling can affect the local crack intensity. The particular shielding factor due to a semi cohesive zone has been addressed elsewhere [9-11]. Considering several applications the evaluation has been founded on a three zone modified Dugdale-Barenblatt model for equilibrium,

$$Kapp+Kco+Ksco=0 \qquad (1)$$

Where Kapp, Kco and Ksco are the applied, cohesive and semi cohesive stress intensity factors. Models for ligaments or process zone assessments have been previously suggested although in the special case of single crystal of copper the estimation of the driving force changes due to a semi cohesive zone was concluded to be minor. However this could not be stated in general and in fact was conditioned to specific experimental system. For example, in dynamic cleavage of Fe-3% Si a significant effect in lowering the driving force was substantiated. This has been addressed also by Pugh in fcc alloys (e.g. Cu-30Zn) [11] where discontinuous crack propagation was strongly affected by unfractured ligaments trailing behind the crack front. Accordingly it was concluded that such semi cohesive zone could exert restraining affects even sufficient to arrest the crack. Experimental studies in Fe-3%Si single crystal with hydrogen indicated for a long crack remarkable affects as confirmed by Selected Area Channeling Pattern (SACP). Here reduction of more than 15% in the applied driving force was indicated [12]. Clearly such effects depend on the exact morphological situation namely if the ligaments are numerous and if such a zone extents to a significant size behind the crack tip. By following this chain of thinking strong argumentations regarding the ultra long fatigue life can be developed and prevail. Notice that in the current application the process zone size is in the same order as the small oxide crack, in addition to the unique condition of near threshold loading that requires special attention. Such conditions might be sufficient to cause oscillating crack stability at least in the early stages of crack propagation that is manifested by a well-defined fracture surface zone.

SAMMARY AND CONCLUSIONS

In the case of ultra long fatigue life in low alloy steel the role of environment/deformation on fatigue behavior becomes a key factor in terms of the near threshold crack stability. This was founded on surface analysis that emphasized the chemical gradient formation at the vicinity of a small initiated crack. Supplementary information regarding hydrogen trapping , variations in the fracture surface features by heat treatment and cyclic span are supportive and consistent. Both effects of embrittling species and local enrichment besides crack tip shielding (due to a semi cohesive process zone) provide rational to the current phenomenological findings. Thus the following is concluded;

1. Small crack threshold validity can be explored in low alloy steel by focusing on ultra long fatigue life behavior. In the present study this was assisted by surface modification activating interior crack initiation at oxide inclusion sites.

2. Surface analysis in post 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.
4. The combined effects of gradual development of embrittling species enrichment beside crack tip shielding explain the phenomenological results in terms of typical fracture surface morphology and the extremely low fatigue crack extension rates.

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