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Brief review on high-cycle fatigue with focus on non-metallic inclusions and forming

Joona Vaara[1], Antti Mäntylä and Tero Frondelius

Summary. Professor Y. Murakami has been a dominant figure in the field of fatigue, pinpointing the most important things for research. However, in order to further improve the prediction methods, knowing the history, discussions and decisions in the fatigue community are necessary. This paper aims to give a brief and historical review on various high-cycle fatigue phenomena focused around non-metallic inclusions and forming.

Key words: fracture mechanics, fatigue, inclusions, forming

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Introduction

In the product design process [11] of major components for internal combustion engines (ICE), the components are validated nowadays by using advanced FE-simulations together with measurements (see [32, 16, 7, 8, 34]). Understanding the nature of fatigue together with stochastic methods becomes more and more important in controlling the underlying uncertainties and thus decision making [33].

Fatigue of higher strength steels is commonly agreed to be dominated by the underlying nonmetallic inclusions. Thus modern quality inspection methods are often based on the characterization of the realized inclusions in a component during manufacturing. A comprehensive review on methods for finding inclusions is given in [2].

Variables in fatigue

Murakami and Endo did a thorough review on efforts made to analyze the relation between fatigue and inclusions in 1994 [22]. They analyzed a large data set and came to the conclusion that the Vickers hardness H_V of a metal and the size of the inclusion, described by square root of the inclusion area $\sqrt{area}$ projected normal to the maximum principal stress direction, were the main parameters needed to describe the fatigue behavior observed in their data set. The $\sqrt{area}$ size measure was based on the maximum stress intensity factors of elliptical cracks of modest aspect ratios ($a/b < 5$) under normal

[1]Corresponding author. joona.vaara@wartsila.com

loading [37]. The popularity of this model is no surprise as it requires no fatigue test to be used and has so far fit well to most experimental observations. The version of the model we present is given in [18]. The stress intensity factor range of arbitrary inclusion with dimension of $\sqrt{area}$ is

$$\Delta K = 0.65 \Delta\sigma \sqrt{\pi \sqrt{area}}, \tag{1}$$

where $\Delta\sigma$ is the stress range acting in the direction of maximum tensile stress. The threshold stress intensity factor range ΔK_{th} is

$$\Delta K_{th} = 3.3 \times 10^{-3} \left(H_V + 120\right) \sqrt{area}^{1/3}. \tag{2}$$

Finally, their model predicts the lower limit of fatigue limit σ_w

$$\sigma_w = \frac{F\left(H_V + 120\right)}{\left(\sqrt{area}\right)^{1/6}} \left(\frac{1-R}{2}\right)^{0.226+10^{-4} H_V}, \tag{3}$$

where F is a constant depending on whether the inclusion is located on the surface or inside, R is the stress ratio $\sigma_{min}/\sigma_{max}$.

Before this, various other parameters had been discussed to be relevant as well. The shape and Young's modulus of the inclusion were regarded factors that should exist in the model assessing the severity of inclusions. First order approximations were given by simply considering the elastic stress concentration factor [1]. Murakami stated that any slight deviation from smooth shapes greatly affects the stress concentration factors and thus the use of stress concentration factors is not only unreasonable but also impractical [22]. Internal stresses stemming from different thermal expansion coefficients and residual stresses from forming methods have been considered as well [9].

The severity of inclusions has been thought to be linked with the matrix hardness - inclusion in soft matrix acts as hardener and only in hard matrix it limits the fatigue properties [10]. Critical ultimate tensile strengths, under which inclusions do not limit the fatigue properties, have been studied (see the short review in [37] for more). Historically, brittle oxides are known to be more severe than soft sulphide inclusions due to a higher stiffness [2].

The critical size of an inclusion, under which fatigue properties were not affected, was regarded a material specific constant [37]. Melander and Ölund performed high-cycle rotating bending fatigue tests for the AISI 52100 bearing steel and found that the smallest alumina-based spherical inclusion found on the fracture surface was of 17 μm in size whereas the smallest angular titanium nitride was 3 μm [17]. Similar findings were presented in [5] for 100Cr6 bearing steel. Murakami and Endo based the validity of their model's shape ignorance on the experimental findings by Duckworth and Ineson who artificially introduced spherical and angular alumina particles into ingots and found no definite difference in fatigue properties already in 1963 [6]. In 1999, Murakami and Beretta revisited the data from [20] and the shape independence was again emphasized [18]. The shapes drawn in the paper were still relatively regular (aspect ratio $a/b < 5$), and looking at the results, TiN seems to show once again a different kind of behavior.

The scatter in fatigue has been explained by inclusions (see e.g. [23]), but it is worth to note that Sangid et al. have recently successfully used a physically-based crack initiation criterion and micromechanics to predict non-inclusion-induced fatigue scatter for U720 [27, 28, 29]. Their model stems from the material sciences side and dislocation dynamics.

Environmental effects, creep, non-proportional multiaxiality, wavy slip mode characteristics and low-cycle fatigue phenomena were left out of the scope of this paper.

Very high cycle fatigue

A point to be made is that the highest lifetime shown for TiN-induced fatigue failures in [18] was approximately 20 million cycles. The test lengths have been increased from those days up to gigacycles by means of higher load frequencies using ultrasonic fatigue testing, and fatigue failures continue to occur after 20 million cycles [12]. The optically dark area (ODA), often found in very high cycle fatigue (VHCF), has been a focus of discussion. Murakami proposed that the VHCF crack does not grow cycle-by-cycle as a conventional crack inside the ODA but instead, due to the combined effect of hydrogen trapped by the inclusion along with cyclic stress [21, 23]. The proposed change to equation (3) was to use the size of the ODA instead of the inclusion size, and the ratio of ODA and inclusion sizes was shown to increase with cycles to failure. Nakamura et al. contradicted this theory by pointing out that, in higher stress ratio tests, the ODA becomes less clear [25]. They also performed tests in a vacuum where the fatigue crack from a notch was first grown and then the stress levels dropped to such a level that the fatigue crack did not grow. Finally they grew the crack with a high 0.3 stress ratio in order to get the fracture surface that they carefully inspected, finding signs of ODA from the area that the crack had grown through very early in the test. They proposed that ODA is formed in a high vacuum due to the cyclic compression cycles of the mating surfaces that is emphasized with an increase in the number of cycles.

Strain age hardening

Recently, Li et al [14] found experimentally a 40.5% higher fatigue crack growth threshold value ΔK_{th} (calculated from (1) at the fatigue limit) for Fe-0.017C (wt.%) compared to the prediction by equation (2) and suspected it to be likely a result of strain-age hardening. Interstitial free steel in this study followed the predictions of equations (1)-(2). Hardness evolution due to the strain-age hardening was not measured during the test though. Wilson concluded in 1970 [35] that for low-carbon steel the strain age hardening must promote fatigue strength. In a larger review by Wilson in 1977 [36], the characteristics of strain age hardening and effects on fatigue were discussed. Nakagawa et al. did careful experiments on carbon steel with the objective to clarify the effect of strain ageing on the fatigue limit in 1979 [24]. They proposed that the fatigue process is a competitive process between three factors: damage due to dislocation multiplication, strengthening due to work hardening and strain ageing. Murakami studied coaxing effects in 1984 [19] and concluded that cracks initiated at lower stress levels that endure the subsequent increased stress levels are of primary importance in this field. The nature of strain age hardening is such that, once the stress is increased enough to make new dislocations and existing locked ones mobile, the density of mobile dislocations increases rapidly [30]. The effectiveness of fatigue strengthening by strain age hardening is limited by the instability of the atmosphere-locked substructure [36]. Wilson acknowledged that crack initiation is often controlled by nonmetallic inclusions but the strain age hardening retards the stage I crack propagation by suppression of the plastic zone. Understanding the strain age hardening will become more important in future, especially for applications like cylinder heads [13].

Forming effects

Metallurgists have categorized inclusions on the basis of, e.g., their plasticity index ν - it is 0 for undeformable inclusions and 1 for inclusion that deforms - together with the metal matrix [10]. Cracks and cavities are formed to matrix in heavy deformation when $\nu < 0.5$ [31].

Makino performed very high-cycle fatigue tests on rolled steel with multiple end-plate thicknesses in 2008. The specimen were cut in parallel and orthogonally to the rolling direction [15]. The inclusions found from the fracture surfaces were vastly different especially in the aspect ratio - in parallel the inclusions were mostly regular oxides and also failures from the matrix occurred whereas, in the other direction, aspect ratios were shown to be in the range of 5-30, being mostly oxides, oxide clusters and sulfides. The manganese sulfides are known for their ability to deform and thus emphasize the anisotropy created in such deformation [26]. Makino highlighted that, for such elongated inclusions, the $\sqrt{area}$ overestimates the maximum stress intensity factor. The stress intensity factors for elliptical embedded and surface cracks are given in [3] and [4], respectively. An important reminder on the elliptical cracks is that the smaller dimension dominates the maximum stress intensity factor as aspect ratios get higher. Makino found that, for such elongated inclusions, the formed ODA could be explained by the elliptical crack stress intensity factor rather well. In the extreme cases, the ODA emanated only from the center area of the very elongated sulfide (high stress intensity area of the elliptical crack), yielding a smaller ODA area compared to the inclusion area.

Murakami concluded in [37] that the third dimension (the dimension parallel to the stress) is an unimportant one. However, the authors would like to point that, if the sulphide or cluster of oxides is very elongated in the direction of stress, the stress intensities are relatively high on a longer portion of the inclusion and the probability of finding a weak crack initiation spot in the surrounding microstructure should increase. Very much like the case where the probability of finding a bigger inclusion increases with the volume [2]. If this point is valid, then it should apply when assessing the severity of high-aspect-ratio inclusions found in the fracture surfaces as well. On the other hand, by using flow of forces analogy, the forces should have it easier finding a route around this kind of a discontinuity that starts softly compared to an ideal crack that has no dimension in this direction - thus the stress intensities should be lower as well.

Conclusions

Some of the major phenomena in fatigue were reviewed with the objective of understanding the underlying assumptions and limitations of status quo. Understanding these phenomena together with the current prediction methods yields natural possibilities to improve the methodology as well. For example, when dealing with forged or rolled components, elongated clusters of oxides or sulfides can be expected. In these situations understanding the Murakami model's limitation of aspect ratios should not be forgotten.

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Joona Vaara, Antti Mäntylä and Tero Frondelius
Wärtsilä
Järvikatu 2-4
65100 Vaasa
joona.vaara@wartsila.com, antti.mantyla@wartsila.com
tero.frondelius@wartsila.com