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Small crack growth model from low to very high cycle fatigue regime for internal fatigue failure of high strength steel

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ABSTRACT

Fatigue failure of high strength steels mostly originates at nonmetallic inclusions. An optically dark area (ODA) beside the inclusion can be observed in specimens fractured at very high cycle fatigue (VHCF) regime. The present paper proposes fatigue life prediction models from low to VHCF regime. *The fatigue life prediction model* inside ODA has been constructed in the VHCF regime based on *the master curve of the growth of ODA* where fatigue failure is caused by cyclic loading assisted by hydrogen trapped by inclusion. The fatigue crack growth law is proposed for a small crack outside ODA within the framework of the $\sqrt{area}$ parameter model where the concept of *"continuously variable fatigue limit"* for small crack is introduced. The life and scatter of fatigue life originating at inclusions can be well evaluated by the proposed models.

1. Introduction

Fatigue failure of high strength steels mostly originates at nonmetallic inclusions [1–5]. This paper reveals the crucial factors for solving this problem and proposes the model for predicting the fatigue life of components. First, fatigue failure mechanism of low or medium strength steels will be reviewed where fatigue cracks usually initiate at free surface of materials. And then, internal fatigue failure mechanism of high strength steels will be reviewed.

Even in very high cycle fatigue (VHCF) regime beyond 10^7 cycles of low strength steel, crack would not originate at inclusion but at persistent slip band in the surface of specimen or component. It is known [6–10] that the persistent slip bands are irreversible during fatigue cycles and some of them can be the origin of crack initiation. But in this case, the effects of moisture and oxygen in the air on the fatigue mechanism cannot be ignored during long test period. This irreversibility should be different from the mechanism of very high cycle fatigue originating at subsurface inclusions.

At and even below the fatigue limit of low strength steels many microcracks can be observed and so the fatigue limit should be defined as the threshold stress for the growth of cracks which are nucleated under the stress. These cracks initiate at very early stage of fatigue test and stop propagation much before 10^7 cycles if environmental factors such as humidity, oxygen, temperature, etc do not affect by continuing test for long period [1]. The threshold condition (or fatigue limit) of a material is determined by the non-propagation of these microcracks that initiated in the original microstructure [1,11,12] on the surface of unnotched specimens where the most crucial and rational mechanism to explain the non-propagation phenomenon is the plasticity-induced crack closure found by Elber [13,14]. The oxide induced crack closure [15] and the surface roughness induced crack closure [16] have additional effects on crack closure behavior depending on the case.

When cracks initiate along slip bands or at grain boundaries, good correlations have been obtained among ultimate tensile strength, σ_U, hardness, HV and fatigue limit [17–20]. The fatigue limit σ_{FL} is proportional to the Vickers hardness regardless of various microstructures with different grain sizes, e.g.: in steels $\sigma_{FL} = 1.6HV$ for $HV = <400$ where σ_{FL} is in MPa and HV in kgf/mm^2.

On the other hand, in high strength steels of $HV > 400$, material defects such as nonmetallic inclusions are often observed at fracture origin. The fatigue limit is not simply proportional to the Vickers hardness for the materials with $HV > 400$. The fatigue limit is strongly influenced by defect size. The quantitative fatigue analysis of the effect of defect size using artificial small defects was systematically studied by Murakami and Endo [21]. Here, the fatigue threshold is also determined by the threshold condition of cracks emanating from such defects [22].

The early works of Naito et al. [23] and Asami and Sugiyama [24] have shown that fatigue failure does occur at lives longer than

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$N = 10^7$ at stress levels lower than the conventional fatigue limit. For high strength steels especially in rotary bending fatigue tests, fatigue failure can be initiated both at the surface and the interior presenting two knees in S–N diagram [25,26]. This two-stage material behavior in S–N diagram is called as the stepwise or duplex S–N property. Since the duplex S–N diagram is not observed in tension–compression fatigue tests [27], it can be understood that the duplex S–N diagram is resulted from stress gradient in bending.

The loading frequency has been always a concern in the test of VHCF [28–35]. Stanzl-Tschegg [29] and Bathias [30,31] showed the VHCF data obtained by ultrasonic fatigue testing machines with very high frequency of 20 kHz. Some researchers found that the effect of loading frequency is very small in high strength steels by Furuya et al. [34], titanium alloy by Ritchie et al. [32] and aluminium alloy by Mayer et al. [33]. In contrast, some papers show the load frequency effects on fatigue strength for mild steels [28,35].

Qian et al. [36] and Sun et al. [37] reviewed the VHCF behavior and its life prediction models. Many of them are based on for example, Tanaka and Mura model [38] for fatigue crack initiation life [39] and are based on the Paris law [40] for fatigue crack growth life [25,41–46]. Recently, Sun et al. [37] studied the cumulative damage model for fatigue life estimation of high-strength steels in HCF and VHCF regime based on the ultrasonic fatigue test data. But this model has not taken into account the small crack effects [47] that the crack growth rate and the threshold stress intensity factor range definitely depends on its crack size.

Fatigue strength prediction models for small cracks [3–5,48–50] have been studied by many researchers using the $\sqrt{area}$ parameter model [21]. Murakami et al. proposed the fatigue life prediction method using the $\sqrt{area}$ parameter model in combination with the statistics of extreme values of internal defects in VHCF regime [22].

Most of the researches have not taken into account the hydrogen effect coupled with cyclic stresses on fatigue failure originating at non-metallic inclusion. The fact that hydrogen is densely trapped by inclusions cannot be ignored in the discussion of fatigue mechanism. Also it must be noted that the fatigue failure from small defects such as nonmetallic inclusions is essentially the small crack problem and the models must be based on the mechanics of small crack.

Especially in the VHCF regime of high strength steels, interior crack initiation emanating from internal inclusion often occurs with a distinct fracture surface morphologies beside the inclusions called the Optically Dark Area (ODA) (see Fig. 1, [1]). Murakami et al. [3–5] detected densely trapped hydrogen around inclusions. They pointed out that the fatigue failure accompanying a peculiar morphology, ODA, at the fracture origin of the center of fish-eye mark is caused by the assistance of the hydrogen trapped by inclusion with cyclic stresses. This assistance of hydrogen results in the elimination of the conventional fatigue limit.

Considering the very different morphologies of the fracture surfaces inside ODA and outside ODA, it is presumed that the fatigue mechanisms inside ODA and outside ODA are substantially different. It has been found by Murakami et al. [4] that there is a good correlation between the ODA size normalized by the inclusion size and the number of fatigue cycles to failure originating at nonmetallic inclusions. This relationship was named the master curve of the growth of ODA. One of the design approaches was performed in [50]. However, these studies have not taken into account the difference of the fatigue crack growth mechanism inside ODA and outside ODA but based only on the master curve of the growth of ODA [4].

Fatigue crack growth models for small cracks inside ODA and outside ODA have not been well developed in the practical fatigue design procedure. It must be noted that these two models should be different. The objective of this study is to elucidate the basic fatigue mechanism in these two domains, inside ODA and outside ODA, and to develop fatigue life prediction method for components of high strength steels from low to very high cycle fatigue. On the basis of the experimental findings, the present paper proposes a fatigue life prediction model based on *the-mechanism-inside-ODA* and *the-mechanism-outside-ODA* for high strength steels which fails from subsurface nonmetallic inclusions.

2. Mechanism of fatigue failure originating at nonmetallic inclusion

2.1. Optically dark area

Murakami et al. [2–5] pointed out the presence of a particular morphology called Optically Dark Area (ODA) beside the inclusion at the center of the fish-eye mark as shown in Fig. 1(a) [4]. This finding was firstly reported in [2]. It is surprising that specimens having a longer life have a larger ODA relative to original inclusion size. They suggested [27] that the formation of ODA is presumed to be influenced by hydrogen trapped by inclusions. The chemical compositions of the inclusions have been mostly Al_2O_3, $Al_2O_3\cdot(CaO)x$, TiN, and MnS [4,5,27].

2.2. Fracture surface morphology

The surface at the optically dark area shows a very rough morphology [51] which is quite different from that outside ODA showing a typical structure of martensite lath. When an ODA is observed by SEM with the electron beam normal to fracture surface, ODA surface is observed as granular as shown in Fig. 1(b). This granular morphology is called by other namings of ODA as FGA (Fine Granular Area) [52] or GBF (Granular bright facet) [53]. However, the exact surface morphology exhibits not as granular but as sharp zigzag surface with observing under the inclined-direction by SEM as shown in Fig. 1(c). This indicates that the *mechanism-inside-ODA* is different from that *outside ODA*. When fatigue failure originates at artificial hole in the surface, an ODA cannot be observed. In this case, a non-propagating crack can be observed at definite fatigue limit where the most crucial mechanism is the plasticity-induced crack closure [13,14] and it must be recognized that a small crack problem is essential [1].

2.3. Hydrogen trapped by nonmetallic inclusions

Fig. 2(a) shows the hydrogen trapped by inclusions with the aid of autoradiographic observations of tritium absorption in JIS SCM435 [54,55]. It should be noted that the ODA cannot be found in the fracture surface beside the inclusions in low cycle fatigue regime (see Fig. 1(a)). Nonmetallic inclusions strongly trap hydrogen [54,56,57]. The ODA is formed only around nonmetallic inclusions. It is significant that a decrease in hydrogen content of a high strength steel leads to a reduction in the size of the ODA.

When failure originates at other microstructures such as bainite [1] and defects such as small artificial defects, ODA cannot be observed, because hydrogen is not trapped by bainite and artificial defects. An important evidence of hydrogen effect on breaking non-propagation behavior of cracks emanating only from nonmetallic inclusion and not from an artificial defect is shown in the well planned experiment [58] in which a fatigue crack emanating from an artificial surface defect showed non-propagation behavior without ODA though a crack emanating from subsurface inclusion *smaller in size than the artificial defect* showed ODA and led the specimen to final fracture.