Very-high-cycle fatigue behavior of a structural steel with and without induced surface defects

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Abstract

Fatigue tests via rotary bending were performed on the specimens with and without induced surface defects for a structural steel of medium carbon content to investigate the effect of surface defects on fatigue behavior in high-cycle fatigue and very-high-cycle fatigue (VHCF) regimes. The S–N data showed that induced surface defects substantially degraded the related fatigue strength. For the specimens without surface defects failed in VHCF regime, crack initiated from the interior of specimens with inclusions or matrix inhomogeneities as crack origin and the initiation regions were of different extents of rough surface. The observations on the profile samples cut from crack initiation regions revealed that the region was a layer of nanograins for the case of inclusion as crack origin, and was without grain refinement for the case of grain boundary as crack origin. For the specimens with induced surface defects, crack initiated from surface defects and the initiation region was without grain refinement. The characteristics of crack initiation were carefully examined and the effect of surface defects on fatigue strength degradation was analyzed by available models.

1. Introduction

Since the work of Naito et al. [1], very-high-cycle fatigue (VHCF) behavior has received increasing attentions in fatigue research community [2–8]. For high-strength steels, cracks are prone to initiate at specimen subsurface or interior [9–13] in VHCF regime, and a distinct crack initiation feature of “fish-eye” morphology embracing a region of “fine-granular-area (FGA)” usually presents at fracture surface. Another typical feature of VHCF behavior for high-strength steels is the S–N curve is a stepwise or duplex shape [14–21] with regard to surface-induced and interior-induced crack initiation, respectively. Bathias and Paris [22] investigated several high-strength steels via ultrasonic fatigue test technique and revealed that subsurface crack initiated from either nonmetallic inclusions or other microstructural inhomogeneities. They gave an explanation: the probability of a sufficient stress concentration inhomogeneity is much higher in the interior of material than that at the surface. Chai [13] reported that the formation of subsurface non-defect fatigue crack was caused by a material damage process of soft phase due to cyclic plastic deformation. Yang et al. [23] measured the FGA of two spring steels and proposed a criterion to estimate the size of FGA. Hong et al. [24] performed tests of a high carbon chromium steel and calculated fatigue life from FGA to fish-eye and from fish-eye to the critical crack size. Their result demonstrated that the formation of FGA is responsible for a majority part of total fatigue life and the fraction of fatigue life contributed by FGA is beyond 95% in VHCF regime. Further, a $D_\text{c}$ parameter has been proposed to discuss the competition of crack initiation from the surface and from the interior of specimen [20,21], which gave an explanation for the preference of fatigue crack initiation either from the surface or from the interior of specimen.

For the formation of FGA, Murakami et al. [25,26] proposed a model of “hydrogen assisted crack growth”. It was considered that hydrogen trapped by an inclusion caused the crack growth at a very slow rate, and FGA was a kind of rough fracture surface formed at the crack initiation stage. When the size of FGA reached a critical value, the crack growth proceeded without the assistance of hydrogen. Shiozawa et al. [10] considered that the spherical carbides in steels interspersed around the inclusion would debond first from the matrix and form the microcracks during the fatigue process, and then the microcracks connected to form FGA. The crack propagation was independent of the spherical carbide decohesion after FGA reached a critical size. Sakai [27,28] stated that a fine granular layer was first generated in the vicinity of an inclusion during a large number of cyclic loadings. The microcracks formed by the debonding between the fine granular layer and...
that fatigue life, from $10^5$ to $10^7$ cycles, is controlled by crack initiation even for the initiation from defects. Although a number of results have been reported regarding the effect of surface defects, the behavior of crack initiation induced by surface defects (especially in VHCF regime) is still an essential issue requiring further investigation.

In this paper, rotary bending fatigue tests were performed on the specimens with and without induced surface defects of a structural steel with medium carbon content, and the effect of induced surface defects on the fatigue strength was investigated. The fracture surfaces of the specimens with and without induced surface defects were observed with scanning electron microscopy (SEM). The micro-morphologies of crack initiation regions were carefully examined by transmission electron microscopy (TEM) equipped with selected area electron diffraction (SAD) detection unit on the samples prepared by focused ion beam (FIB) cutting. The detail observations revealed that for the specimens without induced surface defects, the FGA region with an inclusion as crack origin is a thin layer of nano-sized grains. For the specimens with induced surface defects, cracks solely initiated from the surface defects even in high-cycle fatigue and VHCF regimes, and the micro-morphology of crack initiation region is different from the cases without surface defects. In addition, the effect of surface induced defect on the fatigue strength was evaluated with available models and the result was compared with experimental data in literature.

2. Test material and experimental methods

The material used in this paper is a structural steel with medium carbon content, and the chemical compositions (wt.%) are: 0.42 C, 0.31 Si, 0.82 Mn, 0.0072 P, 0.0084 S, 0.02 Al, 0.0037 N, 0.0006 O and Fe balance. Two groups of specimens were machined for this investigation. One group of specimens (group A) were heated with high frequency induction heater for 3 s then quenched in water (BW water base quenching liquid) and tempered for 2 h at 220 °C. The other group of specimens (group B) were heated at 860 °C for 10 min in salt-bath furnace then quenched in nitrate solution at 170 °C and tempered for 2 h at 230 °C. Such heat-treatment procedures were conducted to ensure the same resultant microstructure and mechanical properties for the two groups. As a result, the microstructure was tempered martensite for the two groups, and the average micro-hardness was 550 Hv (kgf/mm²) for both groups. The yield strength was 1552 MPa and the tensile strength was 1883 MPa, which was higher than the specified value of 850 MPa.

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The shape and dimensions of group A and group B specimens are shown in Fig. 1. Before fatigue testing, the round notch surface was ground and polished for both group A and group B specimens. For each specimen in group B, two surface defects (holes) were introduced in the smallest section symmetrically (180° in between) with a micro milling machine and such specimens were tempered at 220 °C for 2 h to eliminate possible residual stress resulted from the drilling process. The fatigue tests were conducted on a rotary bending machine at a frequency of 52.5 Hz at room temperature in air with the stress ratio of $R = -1$.

The fracture surface morphologies of all broken specimens were observed by SEM, and the chemical compositions of crack initiation spots (inclusions or other inhomogeneities) were examined by energy dispersive spectroscopy (EDS). Further, profile samples,
each with the size of 10 \( \mu \text{m} \) (width) \( \times 5 \) \( \mu \text{m} \) (depth) \( \times 80 \) nm (thickness), were precisely sliced from crack initiation regions with FIB cutting, and the characteristics of crack initiation regions were carefully examined via TEM with the equipped detection unit of SAD. The size of SAD was 200 nm in diameter for all cases except for specimen A4 for which the size of SAD was 250 nm in diameter.

3. Experimental results

3.1. S–N data

Fig. 2 shows the results of S–N data for the two groups of specimens. It is seen that, for group A specimens, the fatigue strength decreases with the increase of fatigue life and the crack tends to initiate from the interior of specimen when the fatigue life beyond \( 5 \times 10^5 \) cycles. For group B specimens, the fatigue strength is substantially lower than that of group A, and there is a plateau region between \( 10^5 \) and \( 10^6 \) cycles. Fatigue cracks for all broken specimens in group B initiated from the induced surface defects.

3.2. Fracture surface morphology

For group A, crack initiation for most specimens was from the surface of specimen in low-cycle fatigue and high-cycle fatigue regimes, and the typical morphology was illustrated in Fig. 3. In VHCF regime, crack initiation for most specimens was from the inclusion in the subsurface of specimen and a typical morphology of fracture surface was shown in Fig. 4. A couple of specimens failed due to crack initiation from grain boundary in the subsurface of specimen in VHCF regime and the typical fractography was shown in Fig. 5. It is evident that for group A specimens, either inclusion initiation mode or grain boundary initiation mode prevailed to result in the characteristic region of fish-eye and FGA morphology in VHCF regime.

Different from the cases of group A described above, the specimens of group B all failed from the induced surface defects from the whole range of low-cycle fatigue to VHCF regimes. Fig. 6 is the fractography of a specimen failed in VHCF regime. It is seen that the crack initiation is from the surface of hole root.

3.3. Observations of crack initiation profiles

In order to further investigate the crack initiation characteristics, profile samples were cut from the crack initiation regions of five specimens (four from group A: A1, A2, A3, A4 and one from group B: B1) via FIB. Specimen A1 (\( \sigma_{\text{max}} = 1000 \) MPa, \( N_f = 2.1 \times 10^7 \)) failed from non-metallic inclusion in VHCF regime with clear FGA morphology in crack initiation region. Specimen A2 (\( \sigma_{\text{max}} = 825 \) MPa, \( N_f = 1.6 \times 10^8 \)) failed also from non-metallic inclusion in VHCF regime but with more developed FGA morphology in crack initiation region. Specimen A3 (\( \sigma_{\text{max}} = 850 \) MPa, \( N_f = 5.3 \times 10^7 \)) failed from grain boundary in high-cycle fatigue regime with FGA-like morphology in crack initiation region. Specimen A4 (\( \sigma_{\text{max}} = 900 \) MPa, \( N_f = 3.1 \times 10^8 \)) failed also from grain boundary with FGA-like morphology in crack initiation region. For specimen B1 (\( \sigma_{\text{max}} = 500 \) MPa, \( N_f = 1.8 \times 10^8 \)), the crack initiation was from surface defect without FGA morphology in crack initiation region. The fracture surface morphologies together with the position for FIB sample cutting of five specimens are shown in Fig. 7.

In addition, EDS examinations indicated that the chemical compositions of the inclusion in specimens A1 (Fig. 7a) and A2 (Fig. 7b) primarily consist of Al_2O_3. EDS results of crack initiation origin for specimens A3 (Fig. 7c) and A4 (Fig. 7d) are primarily Fe element confirming that the crack initiation is due to the inhomogeneities of the matrix.

Fig. 8 shows the TEM observation result of A1. From Fig. 8a, it is observed that the microstructure in the whole TEM sample was almost common tempered product except for the thin layer underneath the fracture surface. The SAD patterns of Fig. 8b–d show a kind of slightly elongated spots for the locations underneath the FGA surface, which is a reflection of a couple of grains within the diffraction area with texture-like feature (by the diffraction principle [40]), whereas in the location away from the FGA surface, the SAD image exhibits a clear pattern of isolated spots (Fig. 8e), implying just one grain (by the diffraction principle [40]) in the diffraction area.

Fig. 9 shows the TEM image and SAD patterns of FIB sample cut from specimen A2. As seen in Fig. 9a, the microstructure beneath the FGA surface is different from that from the inside: the former is a layer of fine grains and the thickness is about several hundred nanometers. The SAD patterns from this layer (Fig. 9b and c) are discontinuous diffraction circles, suggesting that several grains exist within the diffraction area (by the diffraction principle [40]), while the SAD pattern away from the surface (Fig. 9d) shows the feature of single grain diffraction.

Fig. 10 is an example (specimen A3) of TEM image with SAD examinations for crack initiation from grain boundary. It is observed that the microstructure (Fig. 10a) was the tempered product from just underneath the surface to the inside of the specimen. The SAD patterns for the locations underneath FGA-like surface (Fig. 10b–d) or away from the fracture surface (Fig. 10e) are all isolated spots, indicating that the microstructure under-
neath the fracture surface or away from the fracture surface is the coarse grains of ordinary tempered martensite.

Fig. 11 presents the TEM image with SAD examinations of specimen A4 (crack initiation due to grain boundary), which shows the microstructure image almost consistent at the locations underneath FGA-like fracture surface and inside the specimen. Five SAD examinations (Fig. 11b–f) were performed for the locations from just underneath the fracture surface to away from the surface. For just underneath the surface, Fig. 11c shows one set of isolated spots and Fig. 11e shows two sets of isolated spots. Away from the fracture surface, the SAD examinations of Fig. 11b, d and f are also the patterns of isolated spots. The SAD results of specimen A4 together with those of specimen A3 suggest that for the case of crack initiation from grain boundary in VHCF regime, no evidence of grain refinement exists in the crack initiation region.

Fig. 12 shows the examinations on the sample cut from specimen B1. Fig. 12b and c are two results of SAD examinations just underneath the fracture surface, with Fig. 12b showing two sets of isolated spots and Fig. 12c showing one set of isolated spots. Fig. 12d is an example of SAD result away from the fracture surface, which shows one set of isolated spots. These results indicate that for the case of crack initiation from induced surface defects, no evidence of grain refinement presents in the crack initiation region.

4. Discussion

4.1. Effect of induced surface defect on fatigue strength

As illustrated in Fig. 2, the presence of induced surface defects leads to a substantial decrease in fatigue strength. For example,
at the fatigue life of $10^7$ cycles, the fatigue strength decreases by about 41% for the case with induced surface defects, and it decreases by about 37% at the fatigue life near $10^8$ cycles. The role of induced surface defects in the degradation of fatigue strength can be explained in terms of the related stress intensity factor, i.e. the driving force for crack initiation. With regard to crack initiation, the value of stress intensity factor range at the periphery of inclusion ($\Delta K_{\text{inc}}$) was calculated by the following equation [41]:

$$\Delta K_{\text{inc}} = \Delta \sigma \left( \pi \frac{\text{area}}{r} \right)^{1/2},$$

where \( \text{area} \) represents the inclusion projection area, and \( \Delta \sigma \) is the maximum applied stress (for the case of $R = -1$). For the interior inclusion, parameter $\pi$ is 0.5, and $\sigma$ takes the form of $\sigma_{\text{max}} \left( 1 - \frac{d_{\text{inc}}}{r} \right)$, with $r$ being the radius of cross section, $d_{\text{inc}}$ the depth of the inclusion away from fracture surface, and $\sigma_{\text{max}}$ the maximum stress at specimen surface.
The values of stress intensity factor ranges for FGA ($\Delta K_{\text{FGA}}$) and fish-eye ($\Delta K_{\text{FE}}$) were calculated similarly. For a surface defect, area takes the value of surface defect projection area, $\alpha$ is 0.65, and $\sigma$ equals to the maximum stress at specimen surface. The calculated results of $\Delta K$ values are shown in Fig. 13. It is seen that the value of $\Delta K_{\text{Def}}$ is much larger than that of $\Delta K_{\text{Inc}}$ or $\Delta K_{\text{FGA}}$ at a given applied maximum stress ($\Delta K_{\text{Def}}$ is the $\Delta K$ value for induced surface defect). The large value of $\Delta K_{\text{Def}}$ is responsible

Fig. 8. TEM observations with SAD examinations of specimen A1. (a) TEM image showing microstructure of fracture surface profile, (b)–(d) SAD patterns just underneath fracture surface, and (e) SAD pattern away from fracture surface.

Fig. 9. TEM observations with SAD examinations of specimen A2. (a) TEM image showing microstructure of fracture surface profile, (b) and (c) SAD patterns just underneath fracture surface, and (d) SAD pattern away from fracture surface.

for the crack initiation from the induced surface defects of group B specimens.

Here, we adopted the models proposed by Murakami [33] and by Shyam et al. [35] to interpret the effect of induced surface defect on the degradation of fatigue strength. The model proposed by Murakami [33] is
\[
\sigma_W = \frac{1.43(H_v + 120)}{(\sqrt{\text{area}})^{1/6}},
\]
where \(\sigma_W\) is the fatigue limit (fatigue strength), \(H_v\) is the Vickers hardness, and \(\text{area}\) is the projected area on the plane perpendicular to the loading direction. Recently, Shyam et al. [35] also proposed a model based on elastic plastic fracture mechanics (EPFM model) for predicting fatigue limit \((\sigma_W)\) in the presence of submillimeter holes, which is
\[
\sigma_W = \frac{2\sigma_0}{\pi} \arccos \left[ \exp \left( -\frac{\pi E}{32\sigma_0 a} \right) \right],
\]
where \(\sigma_0\) is the flow stress, which is the arithmetic mean of the yield strength and the ultimate tensile strength, \(E\) is the Young's modulus, and \(a\) is half of the surface crack length.

Based on Eqs. (3) and (4), we calculated the values of fatigue limit (fatigue strength at \(10^7\) cycles) of the present case and several cases in literature [34,42–44], and the calculated values were normalized by experimental data. These results are shown in Fig. 14, with Fig. 14a based on Murakami model and Fig. 14b based on EPFM model.

It is seen that the present data together with the results from literature [34,42–44] are reasonably consistent within a scatter band described by both models. The scatter band of Fig. 14a is between 0.82 and 0.98, and that of Fig. 14b is between 0.98 and 1.35. It is noted that the predictions by Murakami model are of a feature of underestimation for experimental data, whereas the predictions by EPFM model are of a feature of overestimation for experimental results. It seems that both models may reasonably
describe the effect of surface defect on the degradation of fatigue resistance and estimate the resulted fatigue strength. However, it should be noted that the crack or the defect size described by both models shown in Fig. 14a and b is in a range between 100 μm and 300 μm. If the crack or defect size is outside this range, the predictions are likely to deviate far from unity, i.e. a large deviation may present between prediction values and related experimental data. It seems that for the case of defect size smaller than 100 μm, the defect is too small to become a dominant crack origin, and for the case of defect size larger than 300 μm (e.g. hole diameter), the defect is too large to be regarded as a crack.

One may note that the fatigue testing of present investigation was via rotary bending at the frequency of 52.5 Hz. For the loading cycles extended to VHCF regime, the method of ultrasonic vibration (normally with the frequency of 20 kHz) has been commonly used to substantially accelerate the testing process (e.g. [7,17,45–47]). The use of ultrasonic vibration method will more or less cause the frequency effect on the related fatigue behavior. Such effect may vary with respect to the lattice type and the strength level of test materials [7,17,45–47].

4.2. Crack interior initiation from inclusion

It has been mentioned that most specimens of group A failed in the mode of crack interior initiation from an inclusion beyond \( \frac{5}{10} \times 10^{6} \) cycles of cyclic loading (Fig. 2). Observations for such specimens showed the crack initiation region of FGA morphology. However, the FGA region is not well developed for the cases of fatigue life between \( 10^{7} \) and \( 10^{8} \) cycles compared with the cases of the fatigue life beyond \( 10^{8} \) cycles. As shown in Fig. 15, the morphology of FGA region is clear and with an evidently large area at the fatigue life of \( 1.6 \times 10^{8} \) (Fig. 15b) compared to that at the fatigue life of \( 2.1 \times 10^{7} \) (Fig. 15a).

The TEM observations further indicate that the well-developed FGA region at the fatigue life of \( 1.6 \times 10^{8} \) is a layer of nanograins (Fig. 9b and c). While for the FGA region which was less developed (Fig. 7a), the spots of SAD patterns were just slightly elongated (Fig. 8b–d), indicating that the grain refinement was insufficient. This result is in agreement with our recently proposed NCP model [31] that sufficient pressing process between originated crack surfaces is necessary for the formation of the nanograins. It is noted that, the TEM observations for the FGA at the fatigue life of \( 1.6 \times 10^{8} \) cycles (Fig. 9) also indicate that the nanocrystalline layer is thinner compared with the situation in high carbon steels [31]. This may be caused by the different volume fractions of retained austenite between a medium carbon steel and a high carbon steel. During the process of fatigue crack initiation and early growth, the
energy produced by local plastic deformation and by crack surface formation may cause the transformation of retained austenite (fcc lattice) to tempered microstructure (bcc lattice) in the crack wake, so that to result in a volume expansion in the local region. Such a volume expansion is one of the important factors to increase the possibility of the contacting between two crack surfaces and therefore to cause crack closure in the NCP process; and the volume expansion is mainly provided by the transformation of retained austenite in steels. For the medium carbon steel used in this paper, the possible volume fraction of retained austenite was smaller than that in high carbon steels, so that the crack surface contacting (and therefore the grain refinement) was not as substantial as that in the situation of high carbon steels.

4.3. Crack interior initiation from grain boundary

The fracture surface observations on group A specimens showed that crack initiation from the interior of specimen in VHCF regime. Inclusions within the control volume [3] are the majority of the weakest spots for crack initiation, and in some rare cases, grain boundary as a kind of matrix inhomogeneities may also be the possible location for crack initiation. For group A, 2 out of 12 specimens that failed by crack interior initiation were due to grain boundary as crack origin. This implies that crack initiation mode for VHCF is not only the competition between surface type and interior type, but also the competition between inclusion initiation and grain boundary initiation for the interior type. Normally, the interface between a relatively large inclusion and matrix is more prone to debond, thus inclusions are the preferred origins for crack interior initiation. However, the control volume of specimen for rotary bending is relatively smaller than that for axial loading [3]. Therefore, the probability of inclusion initiation for rotary bending method will be restricted, and grain boundary especially

the triple point like the case of Fig. 5 will increase the possibility for being the crack origin to cause fatigue failure in VHCF regime.

For the case of grain boundary as crack origin in VHCF regime, the morphology of crack initiation region is of rough surface like FGA (Fig. 5). The observations on the profiles of specimens A3 and A4 (crack initiation due to grain boundary) showed that the microscopic feature of the crack initiation region is without the evidence of grain refinement (Figs. 10 and 11), which differs from what happened in the case of inclusion as crack origin to form an FGA region (a layer of nanograins). The possible reason is that for the debonding of grain boundary like a triple point, a dis-match between the two parts of debonded grain boundary may be incurred due to the volume expansion (retained austenite transformation) and the slightly displacement (relaxation of residual stress) at the initiation location, which will retard the contacting of the originated crack surfaces and the process of grain refinement.

4.4. Crack initiation from induced surface defects

The fractography observations of the specimens with induced surface defects showed that all specimens failed due to crack initiation from the surface defects. This indicates that the surface defect size of 200 µm in diameter and 200 µm in depth is an overwhelming source responsible for crack initiation. As plotted in Fig. 13, the ΔK values for surface defects are evidently larger than those for inclusions, FGAs and even fish-eyes, i.e. the ΔK value or the driving force for crack initiation pertained by a surface defect is large enough to be the predominant site for crack initiation from low cycle fatigue to VHCF regimes, and the related fatigue strength is substantially degraded. If expressed in terms of fatigue life, the value is reduced by more than two orders of magnitude at the applied maximum stress of 800 MPa (Fig. 2). It is vital to note that
if an engineering component contains a surface defect with a considerable size due to different reasons, the estimated fatigue life will be remarkably reduced.

The examinations on the profile of crack initiation region originated from surface defects showed that there is no evidence of grain refinement even experienced VHCF process (Fig. 12), which differs from the case of crack interior initiation from an inclusion, for which the initiation characteristic region of FGA is a nanograin layer. The fracture surface of crack initiation region due to surface defects remains coarse microstructure and is without the evidence of grain refinement, which may be explained as the follows. For the case of inclusion induced crack interior initiation, the sizes of the characteristic region for crack initiation of FGA are within a certain range, the related $\Delta K$ values are also within a certain range, and the crack growth rate is extremely slow [24]. For the present case of crack initiation from surface defects, the defect size is evidently larger than that of common FGA, the related $\Delta K$ values are considerably larger than those pertaining by FGA (Fig. 13), and the related crack growth rate will be much faster than that of FGA crack. Thus the condition for FGA formation does not maintain and the initiation characteristics differ from the case of crack interior initiation due to inclusions.

It is obvious that for the specimens with induced surface defects (drill holes), the severe location of stress concentration is at the root of the drill hole, which is the location of fatigue crack initiation. For the specimens that failed at high-cycle fatigue and VHCF regimes, the cycling stress that causes failure is quite small. Evidence of plastic strain at the root of the notch is difficult to measure using conventional methods. The local strain at the defect root is an important issue and is a topic of future investigation.

5. Conclusions

The conclusions of this investigation for a structural steel with medium carbon content are drawn as follows:

(1) For the specimens with induced surface defects, the fatigue strength decreased by about 40% in high-cycle fatigue and VHCF regimes.

(2) The effect of induced surface defect on the degradation of fatigue strength can be predicted by Murakami model and EPFM model for the defect size between 100 $\mu$m and 300 $\mu$m.

(3) For the case of crack initiation from an inclusion, the region of FGA is a layer of nanograins. The FGA region is well developed in the specimens with the fatigue life beyond $10^8$ cycles and is less developed in the specimens with the fatigue life below $10^8$ cycles. For the case of crack initiation from grain boundary, the FGA-like morphology in the crack initiation region is just a rough area but is not nanograin layer due to less contacting between the originated crack surfaces.

(4) For the specimens with induced surface defects, crack initiation is from the surface defect due to the large driving force at the root of surface defect. The microstructure underneath the fracture surface of crack initiation region remains coarse grains even in VHCF regime, which is a result of insufficient contact between the originated crack surfaces.

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