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The effect of interacting small defects on the fatigue limit of a medium carbon steel

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Abstract

Structural steels contain various material irregularities and natural defects. These cause local stress concentrations, from which fatigue cracks tend to initiate. Two defects in close proximity to each other may affect local stress distributions and thus, begin to interact. In this paper, the effect of interacting small cracks on the fatigue limit is systematically investigated in a medium carbon steel. The growth of interacting cracks, as well as the characteristics of non-propagating cracks and microstructural aspects were closely examined via the plastic replica method. It was found that although the fatigue limit is essentially controlled by the mechanics of interacting cracks, based on their configuration, the local microstructure comprised of ferrite and pearlite has a statistical scatter effect on the behaviour of interacting cracks and non-propagating thresholds. With respect to the fatigue limit, when two defects were in close proximity, they behaved as would a larger single defect. However, with greater spacing between defects, rather than mechanical factors, it is the local microstructure which determines the location and characteristics of non-propagating cracks.

Keywords: small crack; interacting cracks; interaction effect; fatigue limit; medium carbon steel; non-propagating crack

1. Introduction

Engineering components contain various material irregularities and natural defects which may act as crack initiation sites. These natural defects are results, for example, of the material manufacturing or machining processes, or of...
surface finishing. The effect of a single defect on fatigue has been extensively studied in the past. It is well known that defects cause local stress concentrations, regardless of their size. However, even though stress concentrations have an effect on finite life, it has been proven that stress concentration is not the crucial factor which controls the fatigue limit (Murakami, 2002). This is because the fatigue limit is defined by the non-propagation condition of cracks which have emanated from initial defects. Hence, if a small defect acts as a crack initiation site, but a crack becomes non-propagating at the fatigue limit, the final state is nevertheless acknowledged to be a crack. Therefore, the small defect can be considered to be mechanically equivalent to a small crack from the viewpoint of the fatigue limit. However, the severity of these small defects in relation to the fatigue strength of a component depends on numerous factors, such as the component’s material, the defect size, the location and contiguity of defects. If the defects are in close proximity, they may interact with one another and, therefore, may have a definite effect on the fatigue limit.

Due to the complex nature of the phenomenon, (3D) crack interaction is not able to be expressed by a simple equation. However, a very useful analytical finding is the concept of critical distance (Murakami & Nemat-Nasser 1982), i.e. the distance between the cracks at which the interaction effect is negligible. Analytically, the critical distance is defined as follows: If there is enough space between the two cracks to insert an additional crack of the same size as the smaller crack, then the maximum mode I stress intensity factor is approximately equal to that of the larger crack in isolation.

In the simplest case of two adjacent defects, the stress concentrations are enhanced, depending on the distance between the defects. Once cracks emanate from interacting defects, stress intensity factors of the cracks also interact and increase, depending on the crack size and shape, as well as the distance between the cracks. However, by taking into account crack closure, it is not obvious whether these cracks coalesce and, if coalescence occurs, whether it would necessarily lead to failure.

Considering the nature of small natural defects and their variation in shape and location, fatigue limits were predicted using the √ area parameter model (Murakami & Endo, 1983):

\[
\sigma_{w, pred} = 1.43(HV+120)/\sqrt{area}^{1/6}
\]

where, area is defined as the area projected to the plane perpendicular to the maximum tensile stress, and HV is the Vickers hardness (kgf/mm²) of the material.

2. Experiments

Tension-compression fatigue tests were carried out using electro-polished, 0.45% C carbon steel (JIS-S45C) specimens. The original round bars were annealed at 865°C for 30 minutes, before machining followed by furnace cooling. Two holes were drilled onto the surface of the electro-polished specimens. In some specimens, four pairs of two interacting drilled holes (i.e., eight holes), were introduced, thereby facilitating a more detailed examination of the variations in size and shape of non-propagating cracks. The average Vickers hardness by ten measurements at 9.8 N was HV = 186. The scatter of ten measurements of HV was ±15%. The chemical composition and mechanical properties of the material are presented in Table 1, where \( \sigma_{LY} \) is the lower yielding point, \( \sigma_{B} \) is the tensile strength and \( \phi \) is the reduction of area. The effect of various configurations of the artificial defects are investigated and the combinations of defect size, geometry and distance between two defects are presented in Table 2. Since the 7 mm-diameter of the cylindrical specimens used is sufficiently large in comparison with the defects (in the range of 100 μm), the effect of specimen diameter on interaction between two holes can be ignored.

Fatigue tests were performed using servo-hydraulic testing machines under fully-reversed, tension-compression loading (stress ratio \( R = -1 \)), at a test frequency of 10 ~ 20 Hz. The tests were periodically interrupted to observe crack growth and behaviour using the plastic replica method. Fatigue limits were determined by testing at 5-10 MPa-stress steps. Each fatigue limit was defined as the maximum stress amplitude at which the specimen did not fail after ten million cycles. In the absence of non-propagating cracks on the surface of a non-failed specimen, a 5 MPa-stress step was used. This is due to the fact that, in general, non-propagating cracks appear only in very narrow stress bands, i.e.,
2-3% below the fatigue limit (Murakami, 2002). Understanding this tendency of non-propagating cracks is important from the viewpoint of the definition of the threshold conditions.

The experiments were divided into two series (cf. Table 2). Recalling the analytical critical distance, the interaction effect was assumed to be negligible when \( s \geq d_2 \), and defects were presumed to behave as one in fatigue limit predictions for such cases.

Table 1: The chemical composition (wt. %) and mechanical properties of the JIS-S45C steel.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Fe</th>
<th>( \sigma_{Y} ) [MPa]</th>
<th>( \sigma_{B} ) [MPa]</th>
<th>( \varphi(%) )</th>
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<tbody>
<tr>
<td></td>
<td>0.43</td>
<td>0.22</td>
<td>0.78</td>
<td>0.014</td>
<td>0.004</td>
<td>Bal.</td>
<td>339</td>
<td>620</td>
<td>54</td>
</tr>
</tbody>
</table>

Table 2: The investigated artificial defect geometries, sizes \((d_1, d_2)\) and their distances \( s \) \((d_i = h_i)\).

<table>
<thead>
<tr>
<th></th>
<th>( d_1 ) [( \mu m )]</th>
<th>( d_2 ) [( \mu m )]</th>
<th>( s ) [( \mu m )]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series 1</td>
<td>100</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Single</td>
<td>100</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Series 2</td>
<td>200</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>100</td>
<td>150</td>
</tr>
</tbody>
</table>

3. Crack growth

Illustrative crack growth behaviours are presented in Fig. 1. In the case of \( s = 1.5d_2 \) (Fig. 1 (a)), the interaction effect was negligible, but a crack initiated from point \( I_1 \) and grew rapidly towards the other defect. The failed specimen was etched for observation of the microstructure in the vicinity of the defects, to determine the reason for crack initiation and the somewhat aggressive growth from point \( I_1 \). This case will be discussed later in terms of microstructures.

Another example is shown in Fig. 1 (b). In this case, where \( s = d_2 \), analytically, any interaction effect should be negligible. Cracks initiated from points \( O_1 \) and \( O_2 \) and grew during many cycles. A crack finally initiated from point \( I_2 \) after \( 8.4 \times 10^5 \) cycles. The two cracks soon coalesced \((N_{co} = 8.6 \times 10^{5})\) and the specimen eventually failed \((N_f = 1.26 \times 10^6)\). Thus, considering these facts, it can be concluded that the interaction effect was indeed negligible and that the critical distance concept holds. On the contrary, when \( s < d_2 \), first cracks never initiated from points \( O_1 \) or \( O_2 \). However, observation of the microstructure revealed pearlites close to all other points except point \( O_1 \). Consequently, microstructure alone does not explain such crack initiation and growth behaviour, but provides additional evidence that the interaction effect is negligible when \( s = d_2 \).

Regarding defects of different sizes, crack behaviour was not as clear. In these cases, the cracks initially tended to grow sub-surface, especially at points between the defects. This means that nothing was observed on the surface between the defects until the cracks had already coalesced. However, the coalescence life, \( N_{co} \), was relatively long when \( s \geq d_2 \) and consequently, the interaction effect was not strong. Nevertheless, when \( s = 0.5d_2 \), defects of different sizes coalesced after a small number of cycles and a crack became non-propagating at the fatigue limit Fig. 1 (c). It was observed that the crack penetrated through a few pearlite structures until it was finally arrested and stopped within the pearlite. This case will be discussed later in terms of microstructures.

One of the important findings has been that the size of the larger defect seems to have more influence on the finite life, as well as on the fatigue limit, than the actual interaction effect and presence of the smaller defect, or the spacing between the defects. This is due to the fact that the \( \sqrt{area} \) parameter model is not very sensitive to small differences in defect size. Thus, \( area_{eff} \) is almost the same, with or without the smaller defect, and the larger defect alone determines the fatigue limit and fatigue crack growth behaviour (cf. Table 3 (b)).
Table 2: The investigated artificial defect geometries, sizes (explains the crack behaviour, since cracks initiate more easily into ferrite grains than into pearlite structures.

<table>
<thead>
<tr>
<th>Defect Geometry</th>
<th>Size (µm)</th>
<th>Crack Behaviour</th>
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<tbody>
<tr>
<td>Series 1</td>
<td>(100, 100, 100)</td>
<td>Coalesced and non-propagating</td>
</tr>
<tr>
<td>Series 2</td>
<td>(200, 100, 100)</td>
<td>Coalesced and non-propagating</td>
</tr>
</tbody>
</table>

Regarding defects of different sizes, crack behaviour was not as clear. In these cases, the cracks initially tended to grow sub-surface, especially at points between the defects. This means that nothing was observed on the surface during the cycles. However, the coalescence life, as well as on the fatigue limit, than the actual interaction effect and presence of the smaller defect, or the spacing area effect was assumed to be negligible when

$O_d \geq d_2$ and consequently, the interaction effect was not strong. Nevertheless, when $O_2 < d_1$ and $d_1 \geq d_2$, first cracks never initiated from points $O_1$ or $O_2$. However, $O_2$ or $O_1$ and $O_2$ were presumed to behave as one in fatigue limit parameter model is not very sensitive to small differences

$O_1 \geq d_2$ and consequently, the interaction effect was negligible. Cracks initiated from points $O_1$ and $O_2$, respectively, and grew during many cycles. A crack finally initiated from point $O_2$ (Fig. 1 (a)), the interaction effect was negligible, but a crack initiated from point $O_1$ and $O_2$, analytically, any interaction effect should be

$O_2 = 0.5 d_2$ and $O_1 = 1.5 d_2$ (Fig. 1 (b)), in this case, the interaction effect was negligible and the pearlite. This case will be discussed later in terms of microstructures.

Another example is shown in Fig. 1 (b). In this case, where $O_1 = 200$ µm, $O_2 = 100$ µm, and $s = 100$ µm, no crack initiation was observed. However, the coalescence life, $N_{co}$, was relatively long $N_{co} = 3.8 \times 10^5$. Furthermore, the distance between the defects was $d_1 = 200$ µm and $d_2 = 100$ µm, and defects of different sizes coalesced after a small number of cycles and a crack became non-propagating at the fatigue limit $\sigma_a = 170$ MPa.

Figure 1: Microstructure observation near the defects and crack(s): (a) $(d_1, d_2, s) = (100, 100, 150)$ µm, $\sigma_a = 200$ MPa, (b) $(d_1, d_2, s) = (100, 100, 100)$ µm, $\sigma_a = 190$ MPa, (c) $(d_1, d_2, s) = (200, 100, 50)$ µm, $\sigma_a = 170$ MPa.

4. Fatigue limits

The fatigue limit was determined by the non-propagation condition of cracks after 10 million cycles. All the non-propagating cracks observed are illustrated in Fig. 2. Nonetheless, not all specimens had non-propagating cracks at the fatigue limit and, naturally, scatter was observed in the sizes of the non-propagating cracks. The lengths of non-
propagating cracks measured from the hole edges varied between 20 µm and 140 µm. In some cases, several hole pairs were drilled onto the surface of the same specimen (Fig. 2 (c), (d)).

![Image](image-url)

Figure 2: Non-propagating cracks: (a) \((d_1, d_2, s) = (100, 100, 100) \mu m\), (b) \((d_1, d_2, s) = (100, 100, 150) \mu m\), (c) \((d_1, d_2, s) = (100, 100, 50) \mu m\), (d) \((d_1, d_2, s) = (100, 100, \infty) \mu m\), (e) \((d_1, d_2, s) = (200, 100, 100) \mu m\), (f) \((d_1, d_2, s) = (200, 100, 150) \mu m\), (g) \((d_1, d_2, s) = (200, 100, 50) \mu m\).

Three of the hole pairs in Fig. 2 (c) were clearly coalesced and behaved as larger single cracks at the fatigue limit. In Fig. 2 (c), three crack surfaces were obtained, with only the non-coalesced hole pair not located in the fractured plane. Fig. 2 (d) shows the non-propagating crack that emanated from a single hole. In Fig. 2 (e), no non-propagating cracks were observed at the fatigue limit (170 MPa). The test was repeated at 175 MPa, but the specimen failed \(N_f = 8.4 \times 10^6\). Of the four hole pairs in this specimen, it was observed that the hole pair (a) had no cracks, the hole pairs (b) and (c) displayed non-propagating cracks without coalescence and another hole pair (d) had coalesced. The specimen eventually failed after \(8.4 \times 10^6\) cycles due to the coalesced hole pair (d). However, \(\sigma_a\) of 180 MPa was taken as the fatigue limit in this case, because the non-propagation of cracks was definitely confirmed in the two hole pairs.

The fatigue limits obtained for defects of the same size, but with different spacings, are presented in Table 3 (a). When \(s < d_2\), \(area_{eff}\) was calculated, having taken into account the area of both defects and the space between them, the fatigue limit (190 MPa) for the case \(s = 1.5d_2\) was 10 MPa higher than the fatigue limit for a similar single defect (180 MPa), which failed at 190 MPa after \(4.0 \times 10^6\) cycles. The fatigue limit for \(s = d_1 = d_2 = 100 \mu m\) was equal to that for a similar single defect.

Additional relevant tests were not conducted as it was concluded that the fatigue limits in all cases of \(d_1 = 2d_2\) were nearly the same, regardless of the spacing between the defects. In other words, it seemed that the larger defect alone dominated the fatigue limit. However, the behaviour of the cracks at the fatigue limit diverged significantly, depending on the spacing between the holes. According to Fig. 2 (f), it is clear that the cracks behaved individually, whereas in Fig. 2 (g), the defects behaved jointly as a larger single crack.

Fatigue limits for various defects are shown in Table 3 (b). Again, when the interaction effect was negligibly small, i.e., when \(s \geq d_2\), cracks behaved as if they were isolated at the fatigue limit. However, when \(s = 0.5d_2\), cracks coalesced after a small number of cycles, continued to grow as a single crack at some extent and became non-propagating at the fatigue limit. Figure 1 (c) shows that the crack had stopped its propagation within the pearlite structure. Had this particular pearlite structure not existed, the crack closure in ferrite may not have been able to keep the crack non-
propagating. In addition, had the pearlite structure been more closely located to the defects, the crack may have been able to penetrate through the pearlite, as a result of insufficient crack closure. On the other hand, had this large pearlite structure been located further away and the crack able to penetrate through ferrites, crack length may have become large enough to exceed threshold conditions, even in the pearlite structure, resulting in crack propagation to failure.

![Figure 3: Crack growth observation after $N = 5.0 \times 10^6$, $(d_1, d_2, s) = (100, 100, 100)$ µm, $\sigma_a = 180$ MPa ($N_i = 8.4 \times 10^6$): (a) No crack, (b) Two non-propagating cracks, (c) One non-propagating crack, (d) Coalesced hole pair.](image)

<table>
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<th>$s/d_2$</th>
<th>$\sqrt{\text{area}_{\text{eff}}}$ [µm]</th>
<th>Schematic $\text{area}_{\text{eff}}$</th>
<th>$\sigma_{\text{w, pred}}$ [MPa]</th>
<th>$\sigma_{\text{w, exp}}$ [MPa]</th>
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<td>180</td>
</tr>
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</table>

**5. Microstructural effect**

Major studies have been undertaken in the past about the manner in which small cracks behave in inhomogeneous microstructures, e.g., in ferritic-pearlitic structures (DeLos Rios et al. 1985, Graig et al. 1995). However, discussions about microstructural effects gain greater importance with regard to crack interaction, because of their undisputed effect on crack closure, where cracks penetrate different microstructures and produce the various characteristics of non-propagating cracks. In this paper, detailed observation of crack growth and non-propagation behaviours demonstrate that the interaction between two defects is influenced not only by stress concentrations/intensities, but also by the microstructural nature of ferrite and pearlite structures. The influences of stress concentration and the stress intensity factor after crack initiation are naturally the mechanical basis for the interaction of two defects. However, the existence of pearlite or ferrite at the edges of drilled holes also definitely influences crack initiation and crack growth behaviour through the pearlite. Thus, the details of crack behaviour can be more fully understood from precise observation of the microstructure. It must also be noted that a pearlite structure cannot be the absolute resistance to
crack propagation. A detailed discussion about the influential factors of threshold properties has been offered by Murakami (Murakami, 2012).

If ΔK exceeds the ΔKth for pearlite, a crack continues to grow, as proven by the observations in this study. Although the ΔKeff,th’s are different locally, depending on where, in ferrite or pearlite, the crack front exists, propagation or non-propagation of the crack always occurs due to competition between the local effective stress intensity factor range and the local effective threshold stress intensity factor range. Evidence of such crack penetration can be seen in pearlite, followed by non-propagation in ferrite and, in some other cases, non-propagation in pearlite.

If the ΔKth is defined for an individual pair of holes, different threshold values may be defined for four pairs of two holes in one material, since the sizes of the non-propagating cracks observed at the fatigue limit (same stress amplitude) all varied at the four hole pairs. Moreover, no cracks were observed at one of the hole pairs, indicating a stress intensity factor of zero. However, such an approach is not appropriate from the viewpoint of fatigue strength prediction. In these cases, failure or non-failure and propagation or non-propagation occur within a narrow stress amplitude range, specifically, within ±10 MPa. If the threshold stress intensity factor is calculated based on the individual crack after fatigue testing, the values naturally contain a scatter, even for one specimen. Furthermore, this calculation cannot be performed before fatigue testing.

Therefore, in order to predict the fatigue limit or fatigue threshold for materials containing defects which may interact, the precise phenomenon related to crack growth behaviour must be understood. The specific results of this current study will serve as a good example for understanding both the fatigue phenomenon and fatigue strength prediction, particularly where small defects are concerned. Considering the aforementioned observations, the local microstructure should be considered a very crucial factor in the understanding of crack interaction problems. According to analyses, stress intensity factors increase exponentially as the space between cracks decreases. This means that once a crack initiates from points I1 or I2, stress intensity factors at these points increase significantly. However, crack initiation from points O1 or O2 may not be so crucial because as the crack grows, the shape of the crack also changes and stress intensity factors vary along the crack front. Hence, it may be possible to develop sufficient crack closure before the cracks become so large that they begin to interact.

It was revealed that in the case of 0.45% C steel, the scatter of microstructure, i.e., of ferrite and pearlite, influences the scatter of local fatigue strength and, ultimately, the fatigue limit. The nature of the interaction between two defects in this microstructure is influenced primarily by the distance between the pearlite structures, as produced by the rolling process during steelmaking. It was shown that if the interaction effect was negligible (s ≥ d2), pearlites on the hole periphery can prevent the local cracks from initiating at the fatigue limit. On the other hand, if the interaction effect was enhanced (s < d2), defects coalesced at the fatigue limit and behaved as a larger single defect from the outset, regardless of the local microstructure between the defects. However, it is important to understand that, in general, crack coalescence will not necessarily be a detrimental reduction factor, considering the fatigue limit or fatigue strength.

6. Conclusions

In the case of a medium carbon steel with a ferrite-pearlite structure, it was shown that both the spacing between the cracks and the local microstructural characteristics had a definite effect on crack initiation, propagation and non-propagation. Crack spacing influenced the stress intensity/concentration factors and had a significant impact on the results. It should be noted that non-propagation occurs in a very narrow stress band below the fatigue limit and thus, some scatter in results can be considered to be the consequence of an inhomogeneous microstructure. However, the unified conclusions are as follows:

- The behavior of defects is similar to that of isolated cracks if s ≥ d2, where d2 is the diameter of the smaller defect and s is the spacing between the initial defects. In the finite life regime, defects behave like isolated cracks as well before coalescence. Initiation is determined strongly by the local microstructure, as opposed to stress concentrations/intensities, when s ≥ d2. On the contrary, when s < d2, defects coalesced after a small number of cycles, regardless of the microstructural features between the defects.
• Fatigue limits are approximately the same with similar isolated cracks when \( s \geq d_2 \). However, in the cases where \( d_1 = 2d_2 \), fatigue limits were identical, regardless of the spacing between the defects. Thus, only the larger crack determines the fatigue limit.

• Local microstructure causes scatter in the results insofar as crack initiation and crack closure development are concerned. The scatter band is within ±10 MPa in the case of 0.45% C steel. Hence, defects can be treated as single defects when \( s > d_2 \). Otherwise, it is conservative to consider multiple defects as one larger single defect in fatigue limit evaluations.

If the microstructure is more homogeneous than the ferrite-pearlite structure, the scatter of the fatigue limit will be smaller. Naturally, the degree of homogeneity of the microstructure is considered to be relative to the size of the defects. Testing specimens with interacting defects that use more homogeneous material, such as martensitic or ferritic steels, should provide more information about the actual effects of interaction with respect to enhanced stress concentrations/intensities.

**Acknowledgements**

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**References**


