



This is an electronic reprint of the original article. This reprint may differ from the original in pagination and typographic detail.

Åman, M.; Okazaki, S.; Matsunaga, H.; Marquis, G. B.; Remes, H.

Interaction effect of adjacent small defects on the fatigue limit of a medium carbon steel

Published in: Fatigue and Fracture of Engineering Materials and Structures

DOI: 10.1111/ffe.12482

Published: 01/01/2017

Document Version Peer-reviewed accepted author manuscript, also known as Final accepted manuscript or Post-print

Published under the following license: Unspecified

Please cite the original version:

Åman, M., Okazaki, S., Matsunaga, H., Marquis, G. B., & Remes, H. (2017). Interaction effect of adjacent small defects on the fatigue limit of a medium carbon steel. *Fatigue and Fracture of Engineering Materials and Structures*, *40*(1), 130-144. https://doi.org/10.1111/ffe.12482

This material is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.

Interaction effect of adjacent small defects on the fatigue limit of a medium carbon steel

M. Åman¹, S. Okazaki², H. Matsunaga^{3, 4, 5}, G.B. Marquis¹, H. Remes¹

¹Department of Applied Mechanics, School of Engineering, Aalto University, Espoo, Finland

²Graduate School of Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

³ Department of Mechanical Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

⁴ International Institute for Carbon-Neutral Energy Research (I2CNER), Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

⁵ Research Center for Hydrogen Industrial Use and Storage (HYDROGENIUS), Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

Correspondence: Mari Åman, E-mail: mari.aman@aalto.fi

Abstract. Structural steels contain various material irregularities and natural defects which 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 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, nonpropagating crack

Nomenclature

 σ_a = stress amplitude $\sigma_{w, exp}$ = fatigue limit $\sigma_{w, pred}$ = predicted fatigue limit ΔK_{th} = threshold stress intensity factor range $\Delta K_{eff, th}$ = effective threshold stress intensity factor range

 a_i = half-crack length of a crack *i* at specimen surface

area = area of the defect projected to the plane perpendicular to the maximum tensile stress

 $area_{eff}$ = the effective area of the defect projected to the plane perpendicular to the maximum tensile stress

 d_i = diameter of the defect i

 $d(2a_i)/dN = crack$ growth rate of a crack *i*

 h_i = depth of the defect *i*

HV = Vickers hardness

 I_i , O_i = inner/outer point of the defect *i*

 $K_{I, max}$ = the maximum mode I stress intensity factor

N = number of cycles

 $N_{\rm co}$ = number of cycles to coalescence

 $N_{\rm f}$ = number of cycles to failure

R =stress ratio

s = spacing between the drilled holes

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 past¹⁻¹⁷. It is well known that defects cause local stress concentrations, regardless of their size^{1, 18}. 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 limit¹. This is because the fatigue

limit is defined by the non-propagation condition of cracks which have emanated from small defects. Hence, even 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 type of 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.

Analytical studies of interaction problems of three-dimensional surface cracks have been conducted previously¹⁹⁻²⁶ and experimental results have also been published²⁷⁻³⁴. The most important analytical finding has been the concept of critical distance, i.e., the distance between the cracks at which the interaction effect is negligible. Analytically, the critical distance can be explained as follows^{1, 19-24}:

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, $K_{I, max}$, is approximately equal to that of the larger crack in isolation (Fig.1).

However, due to the complex nature of the phenomenon, this interaction effect cannot be expressed by a simple equation. Thus, experimental verification is necessary for analytical findings in order to establish the general rule for interaction.

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 closure³⁵, 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 \sqrt{area} parameter model^{1, 36}:

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

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. Since the behaviour of the interacting cracks on the fatigue limit was unknown prior to the experiments, the effective *area* of the initial defect in Eq. 1 was evaluated by different methods, according to the distance between the defects, with conclusions based on the analytical results. Hence, with reference to Fig. 1, if the spacing between the defects was smaller than

the critical distance (i.e., if $s < d_2$, where *s* is the spacing between the defects and d_2 is the diameter of the smaller defect), the defects were assumed to behave in concert as a larger single defect, formed by the envelopment of two defects by a smooth contour¹. Otherwise, only the area of the larger defect was used in the fatigue limit prediction.

In this paper, the behaviour of interacting small defects and their effect on the fatigue limit are systematically studied experimentally, to determine under which conditions the analytical stress intensity factors for single cracks are applicable, i.e., whether or not the critical distance concept applies to the fatigue limit. In addition, using the plastic replica method, detailed observation of crack growth behaviour and the non-propagation of cracks emanating from the adjacent defects are comprehensively discussed. This paper also examines the shapes of non-propagating cracks and the effect of microstructural features on crack initiation, crack propagation and non-propagation.

2 Experimental procedure

2.1 Material and specimens

Tension-compression fatigue tests were carried out using electro-polished, 0.45% C carbon steel (JIS-S45C) specimens. The microstructure and specimen geometry are shown in Figs. 2 and 3, respectively. The original round bars were annealed at 865°C for 30 minutes, before machining followed by air 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 σ_{LY} is the lower yielding point, σ_{B} is the tensile strength and φ 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 (Fig. 4) 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.

2.2 Fatigue tests

Fatigue tests were performed using servo-hydraulic testing machines under fully-reversed, tension-compression loading (stress ratio R = -1), at a test frequency of $10 \sim 20$ 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 nonpropagating cracks on the surface of a non-failed specimen, a 5 MPa-stress step was used to precisely determine fatigue limit. 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 limit¹. 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). The first series considered symmetrical cases with two identically-drilled holes ($d_i = h_i = 100 \text{ }\mu\text{m}$). In the second series, the holes were disparate in size ($d_1 = h_1 = 200 \text{ }\mu\text{m}$, $d_2 = h_2 = 100 \text{ }\mu\text{m}$). The space between the holes was varied using three combinations for each series, $s = 0.5d_2$, d_2 or $1.5d_2$, where d_2 is the diameter of the smaller drilled hole. Recalling the analytical critical distance (Fig. 1), the interaction effect was assumed to be negligible when $s \ge d_2$, and defects were presumed to behave as one in fatigue limit predictions for such cases.

3 Results and discussion

3.1 Finite life regime and crack growth

S-N data for both series are shown in Figs. 5 (a) and (b). In the finite life regime, the fatigue test results demonstrated a clear tendency. When spacing between the defects was either $s = d_2$ or $s = 1.5d_2$ (i.e., when the interaction effect was negligibly small), the finite life was always shorter for the case $s = 1.5d_2$ than for the case $s = d_2$ at the same stress amplitude. However, early coalescence did not necessarily signify shorter life as is shown in Fig. 5 (c). In addition, the difference in life was almost constant at all stress levels, whether $s = d_2$ or $s = 1.5d_2$. These phenomena may appear to be strange, but can be explained by the significant stepwise jumps in stress intensity factors with respect to the original spacing between the defects. Simply put, as defects lie further away from each other in the beginning, they form a larger crack after coalescence, resulting in a decrease in the remaining life.

The crack growth curves at the stress amplitude of 200 MPa for similar defects with different spacing in between are illustrated in Figs. 6 (a)-(c). When the spacing was small (Fig. 6 (a)), the cracks coalesced after a relatively small number of cycles and, consequently, behaved like a larger single crack. When spacing between the defects became larger (Figs. 6 (b)-(c)), the cracks behaved like isolated cracks just prior to the onset of crack coalescence. Fig. 6 (d) presents the crack behaviour at a stress amplitude slightly above the fatigue limit. It can be noted that while the cracks grew slowly, growth was suddenly accelerated just before coalescence. No significant crack growth was observed on the surface subsequent to coalescence since during this period, the crack started to grow towards the interior of the material so as

to form a more stable, semi-elliptical shape. At the point ($N \approx 1.0 \times 10^6$), significant crack acceleration started again on the surface and the specimen failed soon afterwards. This phenomenon is similar to the so-called *stop-hole effect*³⁷. A few chosen crack growth rate curves are featured in Fig. 7. The crack growth rates, d($2a_i$)/dN, demonstrate large variations before coalescence, with crack growth becoming more linear after coalescence.

Illustrative crack growth behaviours are presented in Fig. 8. In the case of $s = 1.5d_2$ (Fig. 8 (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 . The discovery of large ferrite grain adjacent to point I_1 explains the crack behaviour, since cracks propagate more easily into ferrite grains than into pearlite structures.

Another example is shown in Fig. 8 (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, while crack lengths of 94 µm and 157 µm were observed. A crack finally initiated from point I_2 after 8.4×10^5 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 applies. 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 strong 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 near 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 $s \ge d_2$ 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. 8 (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)). Similar conclusions have previously been documented in the existing literature³⁸.

3.2 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. 9. 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 μ m and 140 μ m. In some cases, several hole pairs were drilled onto the surface of the same specimen (Fig. 9 (c), (d)). When comparing the obtained non-propagating cracks in Fig. 9 (c), it is very interesting to note that large pearlite bands completely prevented crack initiation and coalescence, as shown in Fig. 9 (c-4), even though there was clear evidence of the strong interaction effect when $s < d_2$. Therefore, in order to draw the correct conclusions, it is important to understand the scatter observed, even in a single specimen. Another interesting finding is that the crack in Fig. 9 (c-2) propagated into pearlite instead of ferrite after coalescence. This phenomenon is unlikely because when the crack attained a stable, semielliptical shape, the stress concentration was approximately equal at points O_1 and O_2 , but threshold conditions were much higher at O_1 due to the pearlite texture. It is possible that, after coalescence, the crack grew into the interior of the specimen and later propagated from the inside out towards the surface.

After the tests, the non-failed specimens were heat-treated (400 °C for 6 hours) to obtain a darker oxidized layer on the free surfaces, in order to examine the shapes of the non-propagating cracks. After heat treatment, the specimens were broken using a stress ratio R = 0.1, in order to avoid any deformations of the initial fracture surfaces due to compressive loading. In some cases, the oxidized region was not very well-defined, so in the remaining tests, other methods from the existing literature³⁹ were successfully applied in order to create marker bands. In addition, a large breaking stress amplitude was applied to ensure the marker lines became clearer on the fracture surface. The shapes of non-propagating cracks are also presented in Fig. 9. The heat treatment method was used in Figs. 9 (a), (b), (d), (e) and (g).

Three of the hole pairs in Fig. 9 (c) were clearly coalesced and behaved as larger single cracks at the fatigue limit. In Fig. 9 (c), three crack surfaces were obtained, with only the non-coalesced hole pair not located in the fractured plane (Fig. 9 (c-4)). The improved breaking method and high breaking stress made crack growth possible in many cracks at once and, as a result, many non-propagating crack shapes were able to be examined. At lower breaking stress amplitudes, the specimens failed due to the largest crack alone, as was the case of single defects in Fig. 9 (d). In Fig. 9 (e), no non-propagating cracks were

observed at the fatigue limit (170 MPa). The test was repeated at 175 MPa, but the specimen failed ($N_f = 1.76 \times 10^6$). Since, in Fig. 9 (a), no non-propagating cracks were discovered ($\sigma_a = 180$ MPa), and the specimen failed at $\sigma_a = 185$ MPa, this test was repeated at $\sigma_a = 180$ MPa, where four hole pairs were drilled into the specimen surface. In the case of Fig. 10, crack growth was observed after $N = 5.0 \times 10^6$. 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 8.4×10^6 cycles due to the coalesced hole pair (d). However, σ_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 comparison of the predicted and experimental results of this study is provided in Fig. 11.

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 4.0×10^6 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. 9 (f), it is clear that the cracks behaved individually, whereas in Fig. 9 (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 $s \ge d_2$, 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 8 (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.

3.3 The effect of local microstructure on crack behaviour

Major studies have been undertaken in the past about the manner in which small cracks behave in inhomogeneous microstructures, e.g., in ferritic-pearlitic structures⁴⁰⁻⁴⁴. 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 Murakami⁴⁵.

If $\Delta K_{\text{eff,th}}$ exceeds the ΔK_{th} for pearlite, a crack continues to grow, as proven by the observations in this study. Although the $\Delta K_{\text{eff,th}}$'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 ΔK_{th} 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.

Confusion has arisen from the anonymous crack behaviour observed, influenced by a scatter of microstructure, with respect to the definition of a small crack as being either *microstructurally small* or *mechanically small*. This topic has been explored in detail by Murakami¹, in terms of the fatigue crack behaviour in the annealed 0.46% C carbon steel specimen containing 12 small holes with diameters of 40

or 50 μ m. The holes were drilled onto the specimen surface at four equidistant points on three circumferences, each equally spaced in the axial direction. Non-propagating cracks were not always observed. There were holes without cracks, as well as holes with either one or two non-propagating cracks on the periphery of the holes.

The same phenomenon was observed during the experiment for this research. 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 specimen's 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 I_1 or I_2 , stress intensity factors at these points increase significantly. However, crack initiation from points O_1 or O_2 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 ($s \ge d_2$), 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 ($s < d_2$), defects coalesced at the fatigue limit and behaved as a larger single defect from the outset, regardless of the local microstructure between the defects. One exception is to be noted, as seen in Fig. 9 (c-4). 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 (see also^{46, 47}).

5 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:

- (1) The behaviour of defects is similar to that of isolated cracks if $s \ge d_2$, where d_2 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 $s \ge d_2$. On the contrary, when $s < d_2$, defects coalesced after a small number of cycles, regardless of the microstructural features between the defects.
- (2) Fatigue limits are approximately the same with similar isolated cracks when $s \ge d_2$. 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.
- (3) 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

The first author would like to express her sincerest gratitude to the School of Engineering, Aalto University, Finland, for its financial support during her research visit to Kyushu University, Japan.

References

1 Murakami Y (2002). Metal Fatigue, the Effects of Small Defects and Nonmetallic Inclusions. Elsevier, Oxford, UK.

- Beretta S, Foletti S & Valiullin K (2011). Fatigue strength for shallow defects/cracks in torsion.
 International Journal of Fatigue, 33, 287–299.
- 3 Berto F, Lazzarin P & Yates R (2011). Multiaxial fatigue of V-notched steel specimens: a nonconventional application of the local energy method, Fatigue and Fracture of Engineering Materials & Structures, 34, 921–943.
- 4 Endo M & Yanase K (2013). Effects of small defects, matrix structures and loading conditions on the fatigue strength of ductile cast irons, Theoretical and Applied Fracture Mechanics, 69, 34–43.
- 5 Querchais R, Morel F, Saintier N & Robert C (2015). Influence of the microstructure and voids on the high-cycle fatigue strength of 316L stainless steel under multiaxial loading, Fatigue and Fracture of Engineering Materials & Structures, 38, 1087–1104.
- 6 Jono M & Sugeta A (1996). Crack closure and effect of load variation on small fatigue crack growth behaviour, Fatigue and Fracture of Engineering Materials & Structures, 19, 165–174.
- 7 Leopold G, Nadot Y, Billaudeau T & Mendez J (2015). Influence of artificial and casting defects on fatigue strength of moulded components in Ti-6Al-4V alloy, Fatigue and Fracture of Engineering Materials & Structures, 38, 1026–1041.
- 8 Matsunaga H, Shomura N, Muramoto S & Endo M (2010). Shear mode threshold for a small fatigue crack in a bearing steel, Fatigue and Fracture of Engineering Materials & Structures, 34, 72–82.
- 9 Socie D.F, Hua C.T & Worthem D.W (1987). Mixed mode small crack growth, Fatigue and Fracture of Engineering Materials & Structures, 10, 1–16.
- 10 Morel F, Guerchais R & Saintier N (2015). Competition between microstructure and defect in multiaxial high cycle fatigue, Frattura ed Integrità Strutturale, 33, 404–414; DOI: 10.3221/IGF-ESIS.33.45.
- 11 Tokaji K, Ogawa T & Aoki T (1990). Small fatigue crack growth in a low carbon steel under tension-compression and pulsating-tension loading, Fatigue and Fracture of Engineering Materials & Structures, 13, 31–39.
- 12 Matsunaga H, Sun C, Hong Y & Murakami Y (2015). Dominant Factors for Very-High-Cycle Fatigue of High-Strength Steels and a New Design Method for Components, Fatigue & Fracture of Engineering Materials & Structures, Article first published online.
- 13 Kashiwagi M, Kudou T, Kubota M, Sakae C & Kondo Y (2003). Effect of crack closure on the fatigue limit of material containing small defect, J. Soc. Mat. Sci., Japan, 52, 1345–1350.

- 14 Kondo Y, Sakae C, Kubota M & Kudou T (2003). The effect of material hardness and mean stress on the fatigue limit of steels containing small defects, Fatigue & Fracture of Engineering Materials & Structures, 26, 675–682.
- 15 Lorenzino P, Okazaki S, Matsunaga H & Murakami Y (2015). Effect of small defect orientation on fatigue limit of carbon steels, Fatigue & Fracture of Engineering Materials & Structures, Article first published online, 1–11. DOI: 10.1111/ffe.12321.
- 16 Zerbst U & Madia M (2015). Fracture mechanics based assessment of the fatigue strength: approach for the determination of the initial crack size, Fatigue & Fracture of Engineering Materials & Structures, 38, 1066–1075.
- 17 Serrano-Munoz I, Buffiere J-Y, Verdu C, Gailland Y, Mu P & Nadot Y (2015). Influence of surface an internal casting defects on the fatigue behavior of A357-76 cast aluminium alloy, International Journal of Fatigue, 82, 361–370.
- 18 Murakami Y (2005). Introduction to Stress Concentration (in Japanese), Yokendo, Co. Ltd., Tokyo, Japan.
- 19 Murakami Y & Nemat-Nasser S (1982). Interacting dissimilar semi-elliptical surface flaws under tension and bending, Engineering Fracture Mechanics, 16, 373–386.
- 20 Patel S.K, Dattaguru B & Ramachandra K (2010). Multiple interacting and coalescing semielliptical surface cracks in fatigue - Part-I: Finite Element Analysis, SL, 3, 37–57.
- 21 Nisitani H & Murakami Y (1981). Stress intensity factors for interacting equal semi-elliptical surface cracks in tension, Trans. Japan Soc. Mech. Engineering, JSME 47, 295–303.
- 22 Åman M (2015). Interacting three-dimensional surface cracks under tensile loading, Master's Thesis, available: https://aaltodoc.aalto.fi/bitstream/handle/123456789/16692/master_%C3%85man_Mari_2015.p df?sequence=1.
- Noda N.-A, Kobayashi K & Oohashi T (2001). Variation of the stress intensity factor along the crack front of interacting semi-elliptical surface cracks, Archive of Applied Mechanics, 71, 43–52.
- 24 Murakami Y & Nemat-Nasser S (1983). Growth and stability of interacting surface flaws of arbitrary shape, Engineering Fracture Mechanics Volume, 17, 193–210.
- 25 Kotousov A & Chang D (2015). Theoretical and experimental study of fatigue growth of interacting cracks, International Journal of Fatigue, 70, 130–136.

- 26 Kaneko S, Okada H & Kawai H (2012). Development of Automated Crack Propagation Analysis System (Multiple Cracks and their Coalescence), JSME, 6, 97-112.
- 27 Grandt Jr. A. E (1986). An experimental and numerical investigation of the growth and coalescence of multiple fatigue cracks at notches, ASTM STP 905, 239–252.
- 28 Patel S.K, Dattaguru B & Ramachandra K (2010). Interaction Multiple Interacting and Coalescing Semi-Elliptical Surface Cracks in Fatigue-Part II: Experimental Study, SL, 3, 59–86.
- 29 Iida K (1983). Shapes and coalescence of surface fatigue cracks, Proc. of ICF International Symposium on Fracture Mechanics, Beijing, China, 679–693.
- 30 McComb T.H. Pope J.E & Grandt Jr A.F (1986). Growth and coalescence of multiple fatigue cracks in polycarbonate test specimens, Engineering Fracture Mechanics, 24, 601-608.
- 31 Soboyejo W.O, Knott J.F, Walse M.J & Cropper K.R (1990). Fatigue crack propagation of coplanar semi-elliptical cracks in pure bending, Engineering Fracture Mechanics 37, 323–340.
- 32 Soboyejo W.O, Kishimoto K, Smith R.A & Knott J.F (1989). A study of the interaction and coalescence of two coplanar fatigue cracks in bending, Fatigue & Fracture of Engineering Materials & Structures, 12, 167–174.
- 33 Leek T.H & Howard I.C (1996). An examination of methods of assessing interacting surface cracks by comparison with experimental data, International Journal of Pressure Vessels and Piping, 68, 181–201.
- 34 Kotousov A & Chang D (2015). Theoretical and experimental study of fatigue growth of interacting cracks, International Journal of Fatigue, 70, 130–136.
- 35 Elber W (1971). The significance of fatigue crack closure, Damage Tolerance in Aircraft Structures, ASTM STP 486, 230-242.
- 36 Murakami Y & Endo M (1983). Quantitative evaluation of fatigue strength of metals containing various small defects or cracks. Engineering Fracture Mechanics, 17, 1–15.
- 37 Makabe C, Murdani A, Kuniyoshi K, Irei Y & Saimoto A (2009). Crack growth arrest by redirecting crack growth by drilling stop holes and inserting pins into them, Engineering Failure Analysis, 16, 475–483.
- 38 Tan J.T & Chen B.K (2013). A new method for modelling the coalescence and growth of two coplanar short cracks of varying lengths in AA7050-T7451 aluminium alloy, International Journal of Fatigue, 49, 73–80.
- 39 Schijve J (2015). The application of small overloads for fractography of small fatigue cracks initiated under constant-amplitude loading, International Journal of Fatigue, 70, 63–72.

- 40 Goto M (1994). Statistical investigation of the behaviour of small cracks and fatigue life in carbon steels with different ferrite grain sizes, Fatigue & Fracture of Engineering Materials & Structures, 17, 635-649, DOI: 10.1111/j.1460-2695.1994.tb00262.x.
- 41 Goto M, Yanagawa Y & Nisitani H (1990). Property in the Initiation and Statistical Propagation of Microcracks of a Heat-Treated 0.45% C Steel, JSME, Series 1, Vol. 33 (2), 235-242.
- 42 Marx M, Schaef W & Welsch M.T (2012). The microstructure as crack initiation point and barrier against fatigue damaging, International Journal of Fatigue, 41, 57–63.
- 43 De Los Rios E.R, Mohamed H.J & Miller K.J (1985). A micro-mechanics analysis of short fatigue crack growth, Fatigue & Fracture of Engineering Materials & Structures, 8, 49–63.
- 44 Graig D, Ellyin F & Kujawski D (1995). The behaviour of small corner cracks in a ferritic/ pearlitic steel: experiments and analysis, Fatigue & Fracture of Engineering Materials & Structures, 18, 861–873.
- 45 Murakami Y (2012). Material defects as the basis of fatigue design, International Journal of Fatigue, 41, 2–10.
- 46 Barter S.A, Molent L & Wanhill R.J.H (2012). Typical fatigue-initiating discontinuities in metallic aircraft structures, International Journal of Fatigue, 41, 11–22.
- 47 Kucharczyk P, Sharaf M & Münstermann S (2012). On the influence of steel microstructure on short crack growth under cyclic loading, International Journal of Fatigue, 41, 83–89.

List of figures and tables

Fig. 1 The definition of the critical distance between two defects.

Fig. 2 Etched microstructure with 2 % nital.

Fig. 3 Shape and dimensions of specimen, in mm.

Fig. 4 Shapes and dimensions of artificial defects, in μ m: (a) $d_1=d_2$, (b) $d_1=2d_2$.

Fig. 5 *S*-*N* curves: (a) $(d_1, d_2) = (100, 100) \mu m$, (b) $(d_1, d_2) = (200, 100) \mu m$.

Fig. 6 Crack growth curves: (a) $(d_1, d_2, s) = (100, 100, 50) \ \mu\text{m}, \sigma_a = 200 \ \text{MPa}$, (b) $(d_1, d_2, s) = (100, 100, 100) \ \mu\text{m}, \sigma_a = 200 \ \text{MPa}$, (c) $(d_1, d_2, s) = (100, 100, 150) \ \mu\text{m}, \sigma_a = 200 \ \text{MPa}$, (d) $(d_1, d_2, s) = (100, 100, 150) \ \mu\text{m}, \sigma_a = 190 \ \text{MPa}$.

Fig. 7 Crack growth rates: (a) $(d_1, d_2, s) = (100, 100, 150) \ \mu\text{m}, \sigma_a = 200 \ \text{MPa}, (b) (d_1, d_2, s) = (100, 100, 100) \ \mu\text{m}, \sigma_a = 190 \ \text{MPa}, (c) (d_1, d_2, s) = (100, 100, 100) \ \mu\text{m}, \sigma_a = 200 \ \text{MPa}.$

Fig. 8 Microstructure observation near the defects and crack(s): (a) $(d_1, d_2, s) = (100, 100, 150) \mu m$, $\sigma_a = 200 \text{ MPa}$, (b) $(d_1, d_2, s) = (100, 100, 100) \mu m$, $\sigma_a = 190 \text{ MPa}$, (c) $(d_1, d_2, s) = (200, 100, 50) \mu m$, $\sigma_a = 170 \text{ MPa}$.

Fig. 9 Non-propagating cracks: (a) $(d_1, d_2, s) = (100, 100, 100) \ \mu\text{m}$, (b) $(d_1, d_2, s) = (100, 100, 150) \ \mu\text{m}$, (c) $(d_1, d_2, s) = (100, 100, 50) \ \mu\text{m}$, (d) $(d_1, d_2, s) = (100, 100, \infty) \ \mu\text{m}$, (e) $(d_1, d_2, s) = (200, 100, 100, 100) \ \mu\text{m}$, (f) $(d_1, d_2, s) = (200, 100, 150) \ \mu\text{m}$, (g) $(d_1, d_2, s) = (200, 100, 50) \ \mu\text{m}$.

Fig. 10 Crack growth observation after $N = 5.0 \times 10^6$, $(d_1, d_2, s) = (100, 100, 100) \mu m$, $\sigma_a = 180$ MPa $(N_f = 8.4 \times 10^6)$: (a) No crack, (b) Two non-propagating cracks, (c) One non-propagating crack, (d) Coalesced hole pair.

Fig. 11 Effect of adjacent small defects on the fatigue limit.

Table 1. Chemical composition (wt%) and mechanical properties of JIS-S45C.

Table 2. The configuration of defect size and spacing between the defects.

Table 3. Experimental results:

(a) $(d_1, d_2) = (100, 100) \mu m$,

(b) $(d_1, d_2) = (200, 100) \mu m$.



if $d_2 < d_1$ and $s = d_2 \rightarrow s = s_{cr}$

Figure 1



Figure 2



Figure 3



(a)



Figure 4



Fig. 5 *S-N* curves: (a) $(d_1, d_2, s) = (100, 100, 100) \, \mu\text{m}$, (b) $(d_1, d_2, s) = (200, 100, 100) \, \mu\text{m}$.



Figure 5





Figure 6



(a)



Figure 7



 $N_{\rm f} = 6.3 \times 10^5$



Figure 8a Figure 8b







Figure 8c



(a)

Figure 9a



Figure 9b





(c-1)





(c-2)









(c-4)

Figure 9c







(d-3)

Figure 9d



(d-2)



(d-4)



Figure 9d



Figure 9e



(f)

Figure 9f





Figure 9g











(c)



100 µm

(d)

Figure 10



Figure 11

Table 1

| - | С | Si | Mn | Р | S | Fe | σ_{LY} [MPa] | σ _B [MPa] | $\varphi(\%)$ |
|---|------|------|------|-------|-------|------|---------------------|----------------------|---------------|
| | 0.43 | 0.22 | 0.78 | 0.014 | 0.004 | bal. | 339 | 620 | 54 |

Table 2

| | $d_1[\mu m]$ | <i>d</i> ₂ [µm] | <i>s</i> [µm] | . d1 | . s |
|----------|--------------|----------------------------|---------------|------|-----|
| Series 1 | 100 | 100 | 50 | 1 | |
| | 100 | 100 | 100 | | |
| | 100 | 100 | 150 | | J |
| Single | 100 | | | | |
| Series 2 | 200 | 100 | 50 | | |
| | 200 | 100 | 100 | 1 | |
| | 200 | 100 | 150 | • | |

Table 3

| s/d_2 | √area _{eff} [µm] | Schematic figure of area _{eff} | $\sigma_{w, \ pred}[MPa]$ | $\sigma_{w, exp}[MPa]$ |
|---------|---------------------------|--|---------------------------|------------------------|
| 0.5 | 140 | UU | 192 | 175 |
| 1.0 | 89 | | 206 | 180 |
| 1.5 | 89 | UU | 206 | 190 |
| 00 | 89 | | 206 | 180 |

(a)

| <i>s/d</i> ₂ | √area _{eff} [µm] | Schematic figure of area _{eff} | $\sigma_{w, \ pred} [MPa]$ | σ _{w, exp} [MPa] |
|-------------------------|---------------------------|--|----------------------------|---------------------------|
| 0.5 | 223 | ДЪ | 177 | 170 |
| 1.0 | 177 | | 184 | 170 |
| 1.5 | 177 | | 184 | 170 |

(b)