Short Fatigue Crack Growth Behaviour in Ferrite–Bainite Dual-phase Steels

Ashok KUMAR,1) Shiv Brat SINGH2) and Kalyan Kumar RAY2)

1) Formerly Department of Metallurgical and Materials Engineering, Indian Institute of Technology. Now at the Department of Metallurgical and Materials Engineering, National Institute of Technology, Jamshedpur-831 014, India.
2) Department of Metallurgical and Materials Engineering, Indian Institute of Technology, Kharagpur-721 302, India.
E-mail: kkrmt@metal.iitkgp.ernet.in
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The influence of bainite content on the short crack growth behaviour has been examined in a series of ferrite–bainite dual phase steels containing 50.3–90.3% bainite. Fatigue tests have been carried out using an earlier reported specimen configuration with the help of a rotating bending machine. These tests have been supplemented by characterization of the generated microstructures, determination of their hardness and tensile properties, and examinations of the nature of association of fatigue crack paths with microstructural constituents. The characteristic critical crack lengths above which linear elastic fracture mechanics may be applicable, the fatigue threshold values at the transition of short to long cracks, and the influence of microstructure on the crack path have been discussed. The maximum value of short crack fatigue threshold indicates a marginally increasing trend with increased amount of bainite. The fatigue crack path is found to be predominantly intra-granular for steels containing <70% bainite while it is predominantly inter-granular for steels containing >70% bainite.

KEY WORDS: short crack; dual-phase steel; bainite; fatigue threshold; crack path; tensile strength.

1. Introduction

Dual-phase steels are typically characterized by continuous yielding, low yield strength, high tensile strength, high uniform and total elongation, and high work hardening rate when compared to their conventional ferrite–pearlite plain carbon steels or high strength low alloy (HSLA) steels. In general, dual-phase steels can be categorized as ferrite–martensite and ferrite–bainite type. The mechanical properties of dual-phase steels vis-à-vis their microstructures has been the subject of interest for over almost the last four decades because of their potential structural applications in automobile, defence, machinery components etc.2–4) Considerable research efforts have been directed towards clarifying the tensile and impact toughness behaviour of dual-phase steels with respect to their microstructures,5–13) whereas efforts to understand their fatigue properties are limited. Some fatigue studies on the ferrite–martensite dual-phase microstructures have been carried out by earlier researchers14,15) with attempts to correlate this property with the volume fraction of martensite and its morphology. But fatigue studies on ferrite–bainite dual-phase (FBDP) steels are not known to the best knowledge of the present authors. In order to understand the role of bainite on the fatigue behaviour of FBDP steels, the present authors have undertaken a systematic research program to generate experimental data related to both long and short crack growth behaviour of these steels. The results related to short crack growth behaviour is the content of this report.

Short cracks are defined as the ones, which exhibit higher fatigue crack growth rate compared to what is predicted by Paris–Erdogan type equation at an identical stress intensity factor range value for long cracks and are known to propagate below fatigue threshold value for long cracks. These are generally categorized in three ways mechanically small cracks, microstructurally small cracks and physically small cracks16) based on their sizes. A substantial amount of evidences, well supplemented by a large number of investigations, has been accumulated over the last few decades which unambiguously exhibit faster short crack growth at low stress intensity factor ranges.17–19) Though some reports are available on the fatigue crack growth behaviour of ferrite–martensite dual phase steels, only Nakajima et al.20) have reported their short crack growth behaviour and Hussain et al.21) have attempted modeling this behaviour; but unfortunately no report is available on the fatigue characteristics of short cracks in FBDB steels. Attempt to fulfill this gap is the primary objective of this study.

In some recent reports while examining short crack growth behaviour of plain carbon steels, Ray and his co-workers19,22,23) have directed attempts to search for a possible quantitative relation between the length of crack paths and their associated microstructures. Studies of this nature can bring forth information about the weak links in a microstructure through which a crack passes through or the affinity of a crack to travel through any specific phase in the microstructure. Ray and his co-workers have also made
quantitative estimation of the fraction of segmental crack lengths passing through different phases of a few plain carbon steels to understand the affinity between microstructural features and crack path. Similar examinations are considered necessary to understand the short crack growth behaviour of dual phase steels.

In summary, this investigation aims to explore the short fatigue crack growth behaviour of FBDP steels containing different amounts of bainite. An emphasis has been specifically laid to understand the effect of microstructure on short crack fatigue threshold characteristics of the FBDP steels and to examine the effect of microstructural constituents on the nature of crack propagation.

2. Experiment Procedure

2.1. Material and Heat Treatment

Experimental investigations have been carried out on a steel with composition as shown in the parentheses (C - 0.08, Si - 0.49, Mn - 1.38, P - 0.017, S - 0.006, Al - 0.036, Nb - 0.022 in mass%, N - 46 ppm and Fe - balance). The steel is obtained in the form of 30 mm thick plate cut from a hot rolled transfer bar. The volume fraction of inclusions in the steel is estimated as per the Japanese standard JIS: G0555.24) A series of samples are heat treated to achieve ferrite–bainite microstructures with different amounts of bainite; the heat treatment consisted of austenitizing the steel at 1 373 K for 20 min, cooling at different rates in air prior to soaking these in a salt bath at 773 K for 1 h, and finally quenching in water; the heat treatment schedule is shown in Fig. 1.

2.2. Metallographic Examinations

Samples for metallographic examinations are ground, polished up to 0.25 μm finish using diamond paste, and are then etched with 2% Nital solution to reveal the microstructure. Microstructural studies are carried out using both optical and scanning electron microscopes. The absence of martensite in the FBDP steels has been established by etching the sample by Le Pera reagent (equal amounts of 4g picric acid in 100 mL of ethyl alcohol and 1 g sodium metabisulphite, Na2S2O5, in 100 mL of distilled water), and from XRD analysis. The latter analysis is carried out using an X-ray diffractometer (Model; Philips PW 1729) with Mo Kα (λ = 1.584 Å) target. The volume fractions of the phases in the developed microstructures have been measured by point counting technique as per ASTM standard E 562-02 using an image analyzer (Biovis Material Plus) coupled to an optical microscope (Leica model: 020-520-007 DM/LP).

2.3. Hardness and Tensile Tests

Macro-hardness values of the heat-treated specimens are determined at a load of 294.2 N using a Vickers hardness tester. Cylindrical specimens of 25 mm gauge length and 5 mm diameter are fabricated following ASTM standard E 8M-03 from the heat-treated bars for tensile tests. These tests are carried out with the help of a Universal testing machine (Shimadzu, model: AG-5000G) at a nominal strain rate of 3.3 × 10⁻³ s⁻¹ at the room temperature of 298 K. The estimated hardness and tensile properties of the steels are shown in Table 1.

2.4. Short Crack Growth Test

Fatigue studies have been carried out on specimen configurations following some earlier reports.19,23) Typical configuration of the specimens for short crack growth measurements are shown in Fig. 2. The purpose of the selected specimen configuration is to continuously monitor a crack together with its associated microstructure during a fatigue test. The specimens considered for short crack growth studies are machined from heat treated cylindrical blanks. The ends of the specimens are kept circular for the purpose of holding these in the collets of the rotating bending machine (RBM). The surfaces of the reduced sections of the specimens are ground and polished up to 0.25 μm diamond finish prior to the test. The short crack growth studies are made in a RBM of 560 N m s⁻¹ capacity, operating at a frequency of 50 Hz.

These tests have been carried out with an initial imposed load between 106.8 N and 133.5 N depending on the bainite content of the sample of interest and the machined notch acuity. Each test is continued till crack initiation could be
noticed by repeated interruptions at 15 kilocycle or multiples of it followed by recording the crack path together with the microstructure. When no crack appears after $7 \times 10^6$ cycles at an imposed load, its magnitude is then increased by 8.9 N. A typical event of crack initiation in a specimen is shown in Fig. 3. After crack initiation, its growth is studied at a reduced load ranging between 88.9 to 111.2 N. The recording is done with the help of an optical microscope and the crack-length is measured using an image analyzer. Each fatigue test has been continued till the crack reached a minimum length of 1200 $\mu$m. The estimated crack lengths ($a$) at varying number of cycles ($N$) are analyzed to obtain crack growth rate versus stress intensity factor range in order to determine short crack fatigue threshold ($\Delta K_{thsc}$). After the completion of a fatigue test, the surface of the specimen is etched using 2% Nital and the entire traverse of the crack path together with its associated microstructure is recorded in several frames using both optical and scanning electron microscopes.

3. Results and Discussion

3.1. Microstructure and Tensile Properties

The heat treatment schedules, for obtaining different amounts of bainite in the generated ferrite–bainite structures have been designed on the basis of the time temperature transformation diagram (TTT) computed using the software developed by Bhadeshia.27) Typical microstructures of the ferrite–bainite dual-phase steels, obtained from different heat treatments are shown in Fig. 4. The amounts of bainite in the developed steels have been estimated using point counting technique, and their amounts are found to vary between 50.3 and 90.3%. The specimens containing different amounts of bainite are coded as S50B, S62B, S72B, S82B and S90B for convenience of further discussion; the numerical in the code refer to the approximate amount of bainite in the heat treated steel specimens while the exact amounts are shown in Table 1.

Tensile tests have been performed on all types of FBDP steels (S50B to S90B), and the estimated engineering stress–strain curves have been analyzed to obtain tensile strength, yield strength, percentage elongation and the percentage reduction in area. Typical representative engineering stress–strain diagrams of the developed steels are shown in Fig. 5. The variation of tensile and yield strength with volume fraction of bainite is found to be insignificant. But the ductility of the steels first marginally increases and then decreases with increasing bainite content, exhibiting the highest value for S62B specimens. The estimated tensile properties of the developed steels are shown in Table 1.

3.2. Crack Initiation Studies Related to Short Crack

Crack initiation studies have been done on specimens as shown in Fig. 2. The selected specimen configuration possesses the merit of conveniently locating the crack initiation region and its subsequent growth.19) The crack usually initiates from the sharp corners (referred also as micro notch) of the specimen indicated as M and P in the front face or at M’ and P’ in the back side of the specimen (Fig. 2). The study on short crack requires small length of the initiated natural cracks. To obtain the initial crack with smaller size, the magnitude of load for fatigue cycling has been carefully selected. In order to study short crack growth behaviour on

![Fig. 3. Typical crack initiation (shown by an arrow mark) in a specimen during short crack growth test. The position of the crack corresponds to location M in Fig. 2. The stress direction during loading under rotating bending test is shown by thick arrow marks.](image3)

![Fig. 4. Typical microstructures of the 0.08% C steel containing: (a) 50.3% and (b) 90.3% bainite.](image4)

![Fig. 5. Typical stress strain diagrams of the dual-phase steels: S62B, S73B and S83B.](image5)
specimens having ferrite–bainite microstructures, the selected initial load is typically 88.9 N, based on some trial and error experiments.

The magnitude of the imposed load is sufficiently below the yield strength of the steels. The process of crack initiation depends on the stresses associated with the bending of the specimens. The stress will be maximum at the points M and N in the front face and at M’ and N’ in the back face of the specimen. The selected initial load of 88.9 N is equivalent to nominal bending stress of 150.2 MPa at the points M and N. These stresses are well below the crude estimate of the endurance limit (σₑ=275 MPa) obtained by using the relation σₑ=0.5σₜ, where σₜ is the tensile strength of the material.17,28)

The load at which crack initiation could be detected is found to be different for different specimens. Typically a load of 160.9 N is found to induce short cracks in the specimen containing 72.5% bainite; at this load the number of cycles for crack initiation is found to be approximately 2.7×10⁵. The values of stress to initiate cracks are found to range from 133.8 to 168.9 N. The magnitude of stress to initiate short cracks depends on the developed microstructure, and error experiments.

<table>
<thead>
<tr>
<th>Specimen code</th>
<th>a (µm)</th>
<th>c (µm)</th>
<th>a′2c</th>
<th>σ (MPa)</th>
<th>Q</th>
<th>Kₑ (MPa√m)</th>
<th>N (x10^5)</th>
<th>cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>S50B</td>
<td>8</td>
<td>25</td>
<td>0.32</td>
<td>101.2</td>
<td>1.64</td>
<td>1.33</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td>S62B</td>
<td>10</td>
<td>35</td>
<td>0.28</td>
<td>106.2</td>
<td>1.40</td>
<td>2.06</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>S72B</td>
<td>9</td>
<td>34</td>
<td>0.25</td>
<td>79.0</td>
<td>1.42</td>
<td>1.24</td>
<td>11.7</td>
<td></td>
</tr>
<tr>
<td>S82B</td>
<td>8</td>
<td>40</td>
<td>0.20</td>
<td>84.6</td>
<td>1.28</td>
<td>1.72</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>S90B</td>
<td>10</td>
<td>47</td>
<td>0.21</td>
<td>87.0</td>
<td>1.30</td>
<td>1.57</td>
<td>3.8</td>
<td></td>
</tr>
</tbody>
</table>

where

\[ a = \text{depth of elliptical flaw} \]
\[ c = \text{half width of elliptical flaw} \]
\[ b = \text{plate thickness} = 5 \text{ mm} \]
\[ 1.12 = \text{surface flaw correction at A} \]
\[ 3 = \text{stress concentration effect at A} \]
\[ Q = \text{elliptical flaw correction}=f(a/2c) \text{ obtained from standard graphs}\]
\[ \sqrt{\sec(pa/2b)} = \text{finite width correction accounting for relatively large a/b ratio.} \]

Two samples for each of the steels having a specific volume fraction of bainite are tested for fatigue crack initiation studies. Initial crack lengths are found to vary between 17 and 133 µm for specimens having different bainite contents. One of the major limitations of the adopted procedure is the uncertainty associated with the time of ‘detection of the initiated cracks’ due to discrete examinations of the specimen. As a result achieving very short initial crack lengths is uncertain in this procedure. The geometry of the notch that introduces the first observed crack has been recorded for each specimen and the \( K_{ini} \) values are estimated; these are shown in Table 2.

### 3.3. Short Crack Growth

The recorded short crack growth data on the investigated steels are compiled to obtain the variation of \( a \) versus \( N \), and some typical plots are shown in Fig. 6. Each plot in Fig. 6 exhibits some plateau regions. The plateau regions are typical characteristic of short crack growth behaviour. Several earlier investigators19,23,30–32) have also reported such plateau regions during the growth of short cracks for different materials. For example, such plateau regions have been reported in high strength steel by Lankford30) in 306LN austenitic steel by Liendstedt et al.,31) in titanium alloys (Ti–6Al–2Sn–4Zr–6Mo (mass%) and Ti–8Al (mass%)) by Ravichandran et al.,32) in plain carbon steel (C–0.25 mass%) by Ray and co-workers.19,23) The plateau regions in a \( a \) versus \( N \) curve typically represents the events of crack arrest and this phenomenon has been commonly attributed19,23,30–33) to the occurrence of decelerated crack growth or temporary stoppage of crack at microstructural barriers like grain boundaries.

The number of locations at which crack arrests are noted, is different for different specimens. The time duration for each crack arrest is also different. For example, the number of plateau regions in a \( a \) versus \( N \) plot for specimens having 50.3% and 90.3% bainite are two, whereas that for 72.7% bainite is three. The events related to crack arrests (plateau regions) are indicated by arrows in a \( a \) versus \( N \) plots (Fig. 6).

The crack length at which the last crack arrest took place is recorded during the short crack growth studies and these recorded values are 711.9, 513.9, 488.1, 506.9 and 519.9 µm for S50B, S62B, S72B, S82B and S90B specimens respectively. These crack lengths are considered as ‘transition crack lengths’ between short and long crack fatigue thresholds. The stress intensity factor range corresponding to the transition crack length is henceforth referred as near long crack fatigue thresholds (NLFTTH).
plateau regions in a versus N plot, at which crack arrests are prominent, indicate the existence of barriers due to short crack thresholds. Ray et al.\textsuperscript{19} have suggested that the duration of crack arrest is an indication for the possible presence of barriers or NLFTH. Short extents of plateau region usually imply crack arrest at barriers whereas a long extent usually indicates short crack threshold.\textsuperscript{19} In the investigated ferrite–bainite steels the plateau regions are, however, almost of similar duration and hence only the last plateau is considered as NLFTH. The various maximum crack lengths at which crack arrest occurred in different specimens can be attributed to the nature of the cracks, and this is an inherent characteristic of short crack growth behaviour. The occurrence of crack arrest at different lengths originate from different possibilities like local microstructural environment, extent of crack deflection, plasticity associated with crack tip, crack closure and local residual stresses.\textsuperscript{19,23,30,32,34}

The short crack growth rate (\(da/dN\)) has been calculated by measuring the increment in crack length (a) in a specific time interval and then dividing it by the number of fatigue cycles (N) the specimen has been subjected to in that interval. These data are next examined by plotting \(da/dN\) (in log scale) versus a. Typical plot of \(da/dN\) versus a for a FBDP steel is shown in Fig. 7. This plot, in general, indicates considerable fluctuations in crack growth rate; but the average growth rate can be considered to exhibit an initial decreasing trend followed by an increasing trend as shown by a dotted line. A number of inflections (shown by the points A, B and C) are observed in \(da/dN\) versus a plot. At each inflection, the magnitude of \(da/dN\) tends to zero and is not measurable; but in order to incorporate these points in the plots, \(da/dN\) has been arbitrarily kept at a very low value equal to \(10^{-11}\) m/cycle. Each inflection corresponds to some plateau region as shown in a versus N plot (Fig. 6). All crack length measurements are done in the primary direction of crack growth i.e. normal to the edge of the specimen containing the micro-notch, and the crack length measurements are done at a magnification of 500×.

Large fluctuations in the crack growth rate correspond to microstructural barriers like grain boundaries, or ferrite–bainite interfaces encountered during crack propagation. Similar types of observations are found reported for plain carbon steel.\textsuperscript{19} Figure 8 indicates the crack path through the microstructure along with the plot of \(da/dN\) versus a for a specimen containing 72.7% bainite. Arrows indicate different minima observed during the short crack growth, and the specific microstructure around the ‘transition crack length’ is shown in Fig. 9. The crack path in Fig. 9 exhibits significant deflection at ferrite–bainite interface prior to its passing inside a bainite colony, this phenomenon leads to virtual crack arrest or the occurrence of the minima in crack growth rate as discussed earlier. The magnitude or the order of the transition crack length for low carbon FBDP steel is not available in the existing literature, but it may be noted that the estimated values of the transition crack length in the investigated steel are similar to the magnitudes reported by Narasiah et al.\textsuperscript{23} in single and multiphase steels and that by Shademan and Soboyejo\textsuperscript{35} in titanium alloys.

[Fig. 7. Typical plot of short crack growth rate (\(da/dN\)) versus crack length (a) for the ferrite–bainite steel S73B containing 72.7% bainite. The points A, B, and C indicate plateau regions in the a versus N plot.]

[Fig. 8. (a) Variation of crack growth rate with crack length and (b) the corresponding microstructure exhibiting the crack profile. The arrows indicate locations where minimum crack growth is encountered. The microstructure presented in part (b) is a collage from different frames recorded on the crack path. The figures are recorded from a specimen of FBDP steel containing 72.7% bainite. The area indicated by black arrow has been used for microstructural identification in Fig. 9.]

[Fig. 9. Sharp crack deflection occurring at the short crack threshold in ferrite–72.7% bainite dual-phase steel. FG - ferrite grain, FF - ferrite–ferrite interface, B - bainite colony, FB - ferrite–bainite interface, and BB - bainite–bainite interface.]
The magnitude of the stress intensity factor \( (K) \) ahead of a crack tip depends on the geometry of the crack, specimen configuration and the nature of the applied load. The geometry of a crack plays an important role because the nature of loading remains unchanged during short crack growth testing. Thus crack geometry is defined from the examination of the fracture surfaces after short crack growth studies. The results indicate that the cracks may be considered as quarter elliptical corner cracks. The stress intensity factor for these cracks has been calculated using the relationship suggested by Tada et al\(^{29}\) as:

\[
\Delta K = (1.12)^2 \frac{2}{\pi} \sigma \sqrt{\pi a} \tag{2}
\]

where \((1.12)^2\) represents surface flaw corrections and \(\frac{2}{\pi}\) represents the correction for a quarter penny edge crack. The stress intensity factor range calculated using Eq. (2) gives the lower bound value. The stress \((\sigma)\) ahead of a crack under bend load \((P)\) has been calculated as:

\[
\sigma = \frac{6Pl}{WB^2} \tag{3}
\]

where \(l\) is the distance between ‘the point of application of load’ and ‘the location of a crack’, and \(W\) and \(B\) are the dimensions of the reduced section of the specimens (Fig. 4). The magnitude of stress calculated using Eq. (3), varies linearly from point N to M (Fig. 2) as 182.2 to 207.7 MPa for the initial imposed load of 130 N. The variation of stress between these points during crack growth studies is in the range of 124.7–142.2 MPa corresponding to the load of 89 N. The magnitude of the above mentioned stresses are for a specimen having \(W=11.0\) mm and \(B=5.0\) mm.

It may be mentioned that the position of the investigated cracks are usually either at location M or at location P (Fig. 2) which are symmetrical in nature with respect to the imposed load line. But the exact location of the crack with respect to the load line varied. This variation has been taken into account by ‘\(l\)’ in Eq. (3) to estimate the stress value. Thus the actual stress for each crack is not same but the stress values for the different cracks are found to remain almost within a narrow band. The exact stress values have been used to compute the value of \(\Delta K\) in each of the specimens. In addition it may be mentioned that all the investigated cracks are found to initiate in the flat region close to the fillet of the specimen. This phenomenon assists one to consider insignificant effect of stress concentration due to the curved region at the fillet of the specimen.

The recorded crack extension has been converted to \(\Delta K\) using the aforementioned procedure. The magnitude of \(\Delta K\) is taken as the value of \(K_{\text{max}}\) following ASTM standard\(^{30}\) since the experiments have been carried out at \(R=-1\). Plots of \(da/dN \ versus \ \Delta K\) for a few typical specimens having different bainite contents are shown in Fig. 10. The nature of these plots are similar to that of \(da/dN \ versus \ a\). The magnitude of \(\Delta K\) corresponding to the maximum crack length for a specimen at which a plateau in \(a \ versus \ N\) plot is observed, is considered as the near long crack fatigue threshold value (NLFTH) for short cracks and is referred here as \(\Delta K_{\text{thsc}}\) for the material.

3.4. Near Long Crack Fatigue Thresholds

The short crack fatigue threshold as discussed in the earlier part with respect to long crack fatigue threshold is schematically shown in Fig. 11.\(^{30}\) The short and long crack paths are indicated by the paths A–B–D/A–C–D and C–D–E respectively in Fig. 11. The magnitudes of \(\Delta K\) corresponding to points B and C indicate the fatigue threshold for short and long crack respectively. The point C or D represents the transition between short and long crack. The difference of \(\Delta K\) at points B and C depends on stress ratio \((R)\).\(^{30}\) Larger the stress ratio larger will be the difference of \(\Delta K\) between points B and C. The present investigation has been carried out at \(R=-1\). It is thus considered that crack growth would follow the path AB indicated by dotted line which merges at C. Thus the transition crack length which could be at point D is expected to shift to point B/C when one considers negligible or marginal difference between point B and point C. The fatigue threshold values of short cracks are shown in Fig. 12. The estimated values (5.2–5.8 MPa m\(^{1/2}\)) of short crack fatigue threshold, \(\Delta K_{\text{tusc}}\) in the investigated FBDP steels containing 50.3–90.3% bainite exhibit an increasing trend with increasing bainite content, but for all practical purposes the magnitudes of \(\Delta K_{\text{tusc}}\)
can be considered as almost independent of the amount of bainite.

Short cracks exhibit faster growth rate than long cracks, and these can even grow below the long crack threshold.\(^{17,37}\) The faster crack growth rate of the short cracks is attributed to the lack of crack closure at the early stages of their propagation due to limited length of crack wake.\(^{38,39}\) Blochwitz\(^{40}\) has reported that larger plastic zone size is associated with short cracks compared to long crack and this feature is responsible for the anomalous short crack growth behaviour. Riemelmoser et al.\(^{41}\) have reported that the plastic zone size ahead of short cracks at the applied stress of 364 MPa is almost 4 times larger than that of long cracks at the same value of stress intensity factor for an aluminium alloy exhibiting yield stress of 400 MPa.

### 3.5. Effect of Microstructure on Short Crack Growth Behaviour

The influence of microstructure on the rate of fatigue crack propagation has been examined by several investigators,\(^{20,42-44}\) but the co-relation between the segmental lengths of a crack and the specific microstructural feature (different phases/constituents or interfaces) through which it traverses, has been reported only by Ray and his co-workers.\(^{19,23}\) These investigators have quantitatively examined such co-relation in ferrite–pearlite plain carbon steels and reported that the amount of crack length passing through a microstructural feature is approximately proportional to the volume fraction of the constituent. Using the recorded crack paths as described in Sec. 2.1, the co-relation between the segmental lengths of a crack and the amount of ferrite/bainite or that of the interfaces through which it traverses has been examined here. The different microstructural features are ferrite grains, ferrite–ferrite grain boundaries, bainite colonies, ferrite–bainite interfaces and bainite–bainite interfaces. Typical relations between the total segmental lengths of a crack path and its associated microstructural constituents for short crack growth tests in FBDP steels are shown in Figs. 13(a) and 13(b). One can typically note from Fig. 13(a) that 17, 36 and 32% of crack length passes through ferrite grain, bainite colony and ferrite–bainite interface respectively in S62B specimen. On the other hand, Fig. 13(b) indicates that 58 and 25% of crack length passes through bainite colony and bainite–bainite interfaces respectively in S83B specimen. These results indicate that with increase in the volume fraction of bainite, the preference of the crack path to pass through microstructural constituents changes. The amount of crack lengths passing through the different microstructural constituents (ferrite and bainite) and through the different types of interfaces (ferrite–ferrite, ferrite–bainite and bainite–bainite) in FBDP steels having increasing amounts of bainite are examined in Fig. 14. The amount of the total segmental crack lengths passing through “ferrite grains+bainite colonies” initially decreases followed by an increase with increasing bainite. Similarly, crack lengths passing through “ferrite–ferrite+ferrite–bainite+bainite–bainite” interfaces first increases and then decreases with increase in bainite content in the investigated steels. Thus there exists a competitive process for the crack to be intra-granular or inter-granular depending on the amount of the bainite content in the investigated specimens. The amount of intra-granular crack path compared to inter-granular crack path is higher for specimens containing bainite upto 70%; however, the trend reverses for specimens containing bainite greater than 70% (Fig. 14). These observations infer that the affinity of a crack to pass through the interfaces depends on the relative amount of the microstructural constituents.

### 4. Conclusions

The effect of bainite content on the short crack growth
behaviour in a series of ferrite–bainite dual phase steels has been examined together with detailed characterizations of their microstructure, hardness and tensile properties. The following major conclusions are drawn from this investigation:

1. The stress required to initiate cracks ($\sigma_i$) in the investigated low-carbon ferrite–bainite dual-phase steels, containing different volume fractions of bainite, varies from 79.0 to 106.2 MPa. The estimated magnitude of $\sigma_i$ is highest for the steel containing approximately 50% bainite. The magnitude of $\sigma_i$ is between 14–19% of the tensile strength of the specimens.

2. The length of a crack at which its nature exhibits change from ‘short’ to ‘long’ crack behaviour, referred as transition crack length, is found to be in the range of 488 to 712 μm for the selected FBDD steels containing bainite between 50.3–90.3%.

3. The maximum values of short crack fatigue thresholds are found to be in the range of 5.2–5.8 MPa m$^{1/2}$ in the investigated steels with varying amounts of bainite. The short crack fatigue thresholds are thus almost independent of the amount of bainite in these dual-phase steels.

4. The fatigue crack path passes through ferrite grain, bainite colony, and through the interfaces of ferrite–ferrite, ferrite–bainite, and ferrite–bainite. Quantitative estimation of the different types of fatigue crack path indicates that the affinity of a crack to pass through the interfaces depends on the relative amount of the microstructural constituents and amount of the crack path through the interface is highest for the specimen with 72.7% bainite.

5. The fatigue crack path is found to be predominantly intra-granular for steels containing <70% bainite while it is predominantly inter-granular for steels containing >70% bainite.

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