

Corrosion fatigue crack growth mechanisms in offshore monopile steel weldments

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ABSTRACT Offshore structures are generally fabricated of welded joints, which are considered as potential spots for crack initiation owing to the degree of stress concentrations imposed by the weld geometry and the effects of residual stresses introduced by welding processes. There are significant numbers of the current and anticipated offshore installations coupled with the use of newer materials and fabrication techniques. It is therefore important to understand the crack growth mechanisms in these structures accompanied with the effects of mean or residual stresses for a safe estimation of their service lives. In this paper, crack growth results of HAZ and weld materials similar to those used for offshore installations are presented. Tests were conducted in air and in simulated free-corrosion conditions at loading frequencies of 0.3 Hz in seawater, 5 Hz in air and at loading ratios of 0.1, 0.5 and 0.7. Results showed that crack growth rates were influenced by mean stresses, materials microstructure accompanied by welding procedure and environment. Crack growth results showed good agreement when compared with those obtained from other steels used for offshore structures.

Keywords crack growth rates; free-corrosion; HAZ; mean stress; weld.

NOMENCLATURE

- a = crack length.
- B = specimen thickness.
- W = specimen width.
- ΔK = stress intensity factor range
- ΔP = applied cyclic load range

INTRODUCTION

There has been a significant increase in the use of medium strength steels for offshore structures such as oil and gas platforms and structures for renewable energy applications. These structures experience millions of load cycles in service and are also exposed to harsh marine environments, which may result in corrosion fatigue failures if inspection and maintenance strategies are not carefully deployed. Offshore structures are fabricated from welded steel sections, and owing to the phase changes, which occur during welding, there are possibilities for weld induced residual stresses that can significantly influence the degree of mean stresses under cyclic loading. Several sources of mean stresses have been classified in the literature as stresses owing to dead weight

loading, weld induced stresses and residual stresses accompanied by fabrications.¹ The phase changes that occur during welding may influence not only the microstructure of the material but also the pattern of crack growth such as crack branching. This has been described by Xiong and Hu,² as crack closure induced crack propagation that resulted in higher resistance to crack growth in Q345 steel.

Studies relating to corrosion assisted crack growth in representative steel materials used for offshore monopile fabrications have shown some appreciable level of importance towards the need for the structures to satisfy their design requirements. Recently, some interesting results were published on corrosion fatigue crack growth in parent material,³ and few results were presented on crack growth behaviour in the heat affected zone (HAZ)

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materials at lower stress ratios.⁴ These results have shown that crack growth rates have been enhanced in seawater than in air regardless of the material types. However, Adedipe *et al.*⁵ mentioned that corrosion fatigue damage mechanisms may not be adequately understood using only parent material for testing. Owing to welding induced residual stresses in HAZ and weld materials, newer material and plate thickness similar to those used in structures for renewable energy applications, accompanied by specimens that are designed for through thickness crack growth measurements.⁴ It is therefore important to include the crack growth behaviour in HAZ and weld material in estimating the fatigue lives of such structures in service.

The available data in the literature on fatigue crack growth in weld and HAZ materials were not obtained from the type of material and specimen fabrication procedure described in Ref. ⁴. These include the data published in Ref. ^{6–9}. Crack growth rates in weld and HAZ materials have been attributed to several factors. In the Thompson and Fukuda *et al.* works,^{10,11} crack growth rates in HAZ and weld materials fabricated from BS4360 50D steel were attributed to hardness variation between parent, HAZ and weld materials. However, in Healy *et al.* and Trudel *et al.* works,^{10,11} crack growth results were explained with respect to preferred crack growth direction accompanied with microstructure variations in the materials, while in Ref. ^{2,8,9,12}, crack growth behaviour in weldments were related to residual stresses induced crack closure. Further explanations can be found in Ref. ⁵. Mean stress effects on crack growth rates have been described as the ratio of the minimum to the maximum stresses used for testing.¹³ However, it was mentioned by Burnside *et al.*¹⁴ that mean stress effects on crack growth rates in 50D steel depend on material, environment and crack growth region. This can be argued considering the investigations that have shown different crack growth behaviour in similar materials with respect to increasing mean stresses.^{15–17} Thorpe *et al.*¹³ found that at free-corrosion potential, crack growth rates in BS 4360 50D steels were significantly enhanced as the mean stress was increased from 0.5 to 0.7. However, Appleton¹⁷ found that there was no marked effect of increasing mean stress in seawater environment. The differences in temperature and seawater environments have been suggested as the possible reasons for the crack growth behaviour in the materials.⁵ The effects of stress ratio have also been reported to have appreciable influence on crack growth rates in X70 pipeline steels in seawater.¹⁸ However, the results reported in Ref. ^{15–18} were obtained from parent plates.

Irrespective of the costs involved in conducting crack growth tests at higher stress ratios, it is still important

to fully understand the crack growth mechanisms in structures that are subjected to high mean stress particularly in thicker plates with dimensions close to those used for monopile fabrications. This is to represent the loading conditions similar to those encountered in service as close as possible. In simulating tensile residual stresses in welds, high stress ratio tests such as *R*-ratio of 0.5 or higher have been suggested by Havn and Osvoll.¹⁹ However, this assumption may be limited to near surface tensile residual stresses, but for a through thickness case, the crack growth behaviour may be different due to the overall magnitude of the residual stresses accompanied by the welding procedure. Although, offshore support structures particularly those used for renewable energy applications are now being manufactured using improved welding procedures and design methodologies, but it must be mentioned that the effects of residual/mean stresses in welded structures cannot be eliminated completely owing to their complexities. Therefore, it is important to study the fatigue crack growth behaviour in these structures with respect to mean stresses so that existing database can be updated and results that may assist the development of new offshore design standards can be generated. It has been established that limited data have been obtained from weld and HAZ materials extracted from newer types of steels that are used for monopile fabrications,⁵ especially for tests conducted on HAZ materials at higher stress ratios. Apart from the ones that are discussed earlier, some HAZ data were obtained by Mecozzi *et al.*²⁰ at lower stress ratios and therefore may not be representative of high mean stress conditions.

In this paper, the fracture mechanics approach is employed to study the crack growth rates in weld and HAZ materials that are fabricated from monopile steels in air and simulated free-corrosion environments. Results are presented with respect to high mean stresses in HAZ and are compared with those obtained from parent and weld materials. Interpretation of the results with respect to microstructure examination of the crack path, fractographic analysis of the fracture surface and the variations in hardness values of the materials was also achieved.

MATERIAL AND SPECIMENS EXTRACTION

The material used for testing was a 90 mm thick welded plate manufactured from S355 J2 + N steel. The welding was carried out in accordance with the DNV-OS-C401 recommendations using the SWA-Twin/Tandem-twin process and a 4 mm filler material designated as S466 FB S3Si. In order to ensure that the direction of crack growth in circumferential welded monopile support

structures is reproduced as close as possible, a methodology was developed in Cranfield University for the extraction of the specimens that are used for testing. Three slices of 10 mm thick specimens that encompass the welded area were machined from the edges and the middle sections of the plate in order to establish uniform HAZ and weld dimensions and for polishing and etching. Grinding of the specimens was achieved using 120-, 240- and 1200-grit silicon carbide abrasive papers in ascending order, while the polishing was carried out using the polisher cloth of the appropriate size mounted on the rotating wheel of the Metaserv polishing machine. The polishing was accompanied with the applications of alcohol, diamond paste and colloidal master polisher until a surface finish of 0.5 μm was achieved. The extracted slices were etched by applying a 2% Nital solution in order to reveal the weld runs and the HAZ. After characterising the geometry and dimensions of the weld region in three slices extracted from the welded plate, 16 mm thick compact tension, CT, specimens were designed according to the specifications set out in the ASTM E647²¹ and extracted from the plate, with their notches perpendicular to the rolling direction of the plate. The dimensions of the specimens have been given in Ref. ³. The specimens' notches were prepared by spark erosion and were positioned at the HAZ and weld areas of the plate as shown in Fig. 1. Further details can be found in Ref. ²².

EXPERIMENTAL PROCEDURES

All the crack growth tests were carried out as recommended in the ASTM E647 using two 100 kN capacity servo-hydraulic fatigue testing machines. The tests were carried out at loading frequencies of 0.3 Hz in seawater, 5 Hz in air and at loading ratios of 0.1, 0.5 and 0.7. The reason for the choice of the loading frequency used for testing, particularly in seawater, was subject to the frequency sensitivity analysis that was conducted in a previous study.³ Crack lengths were measured in air using digital camera and in seawater

using back face strain and direct current potential drop techniques. The seawater used for the investigations was prepared according to the ASTM D1141.²³ Details of the experimental procedure have been provided in Ref. ^{3,4} including the method used to determine crack lengths from back face strain readings. A test method, which was an extension of the sinusoidal waveforms that are commonly used for fatigue testing, was developed using the wavematrix software and was applied for fatigue crack propagation testing. The method tagged 'loop type waveform' in this paper was developed to allow stable strain gauge readings during the seawater tests so that reliable crack length measurements could be determined.

In the loop type waveform, each loop consists of four steps. The steps are repeated a number of times based on the anticipated number of cycles for the test and each of the waveforms has a start and end envelope of 20 seconds. The number of cycles in each loop is a subject of the number of desired data points with respect to the total number of cycles for the tests. This was based on trial tests. In step one, the waveform was programmed to ramp to the test minimum load at duration of 20 seconds, while in step two, the sinusoidal waveform was applied at the desired number of cycles with respect to the defined start and end envelopes respectively. In step three, the wavematrix was programmed to ramp to the test mean load to allow measurements to be taken from the strain gauge and direct current potential drop, while in step four, the WAVEMATRIX was defined to hold at the mean load for 20 s to allow enough time for measurements. After step 4, the counter would return to step 1 to commence a new loop.

After testing, the macro examinations of the crack directions were conducted using the Nikon SMZ745T microscope equipped with an AxioCam ERC5S camera, while the micro examinations were conducted using the Nikon eclipse ME600 optical microscope with magnifications $\times 5$ and $\times 20$, respectively. Analysis of the fracture surfaces was conducted on selected areas using the Philips XL 30 SFEG Oxford EBSD system at magnifications $\times 200$, $\times 1000$ and $\times 4000$. Hardness tests were carried out using a load of 200 g on the Zwick

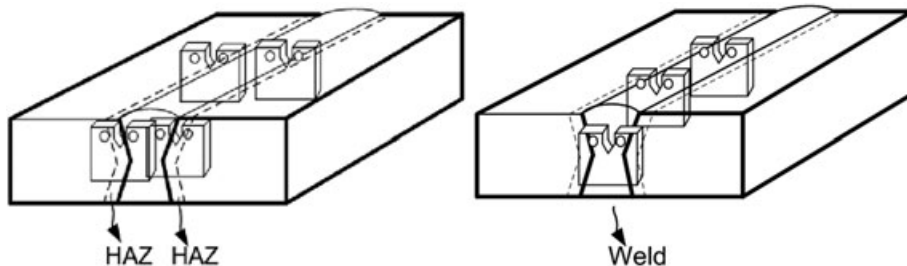


Fig. 1 Compact-tension (CT) specimens extracted from HAZ and weld regions of a 90 mm thick plate.

computer assisted Vickers micro-hardness tester with diamond indenters. Hardness measurements were taken in two sets: from the parent material to weld material and along the HAZ.

FATIGUE CRACK GROWTH ANALYSIS

Crack growth rates were determined from the results of crack lengths and number of cycles using 7-point incremental polynomial method. Cyclic crack tip stress intensity factor range ΔK was determined by the function of the form^{21,24}:

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \frac{(2 + \frac{a}{W}) (0.886 + 4.64(\frac{a}{W}) - 13.32(\frac{a}{W})^2 + 14.72(\frac{a}{W})^3 - 5.6(\frac{a}{W})^4)}{(1 - \frac{a}{W})^{1.5}} \quad (1)$$

where ΔK is the stress intensity factor range, ΔP is the applied cyclic load range, B is the specimen thickness, W is the width of the specimen and a is the crack length.

RESULTS AND DISCUSSIONS

Fatigue crack growth tests on different specimens were conducted under the loading conditions specified in Table 1.

Fatigue crack growth rates in air and seawater at an R -ratio of 0.1

The fatigue crack growth rate per cycle obtained from the tests performed at R -ratio of 0.1 in HAZ in air are correlated with the stress intensity factor range, and the results are shown in Fig. 2. It can be seen that the crack growth curves are similar over the entire ΔK tested,

Table 1 Loading conditions and material constants for parent plate, HAZ and weld materials

Environment	Material	R -ratio	P (kN)	C	m
Air	Parent	0.1	9	7.1×10^{-12}	3.0
Air	HAZ	0.1	9	7.0×10^{-13}	3.5
Air	Weld	0.1	9	5.0×10^{-13}	3.6
Air	Parent	0.5	7	2.1×10^{-12}	3.4
Air	Parent	0.7	5.25	2.1×10^{-11}	2.6
Air	HAZ	0.5	7	7.0×10^{-13}	3.7
Air	HAZ	0.7	5.25	2.1×10^{-12}	3.4
Seawater	Parent	0.1	9	4.1×10^{-13}	4.2
Seawater	HAZ	0.1	9	6.0×10^{-14}	4.7
Seawater	Weld	0.1	9	3.0×10^{-15}	5.7
Seawater	Parent	0.5	7	3.1×10^{-14}	5.6
Seawater	HAZ	0.5	7	8.0×10^{-13}	4.0
Seawater	HAZ	0.7	5.25	1.1×10^{-12}	4.0

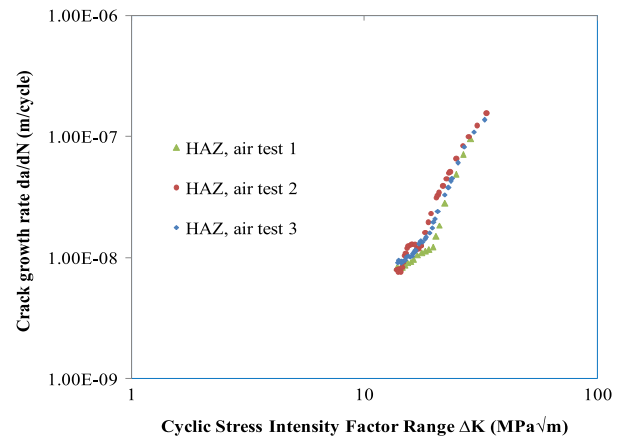


Fig. 2 Crack growth rates in heat affected zone (HAZ) materials in air. [Colour figure can be viewed at wileyonlinelibrary.com]

resulting in bi-linear relationships. However, it can be seen that test 1 produced a steeper crack growth curve at lower ΔK range compared with the other two tests. Analysis of the crack length versus number of cycles revealed a difference of approximately 190 000 cycles between test 1 and tests 2 and 3. From metallographic examination of the specimen surfaces, it was observed that the starter notch tip of specimen 1 was aligned in the coarse grain region of the HAZ close to the weld material, while in specimens 2 and 3, the notch tips were positioned at the middle regions of the HAZ. Therefore, the difference in loading cycles would have been influenced by different crack initiation sites, propagation pattern, variations in microstructure along the crack paths and the degree of crack branching during propagation. Because cracks initiate at the weld HAZ and propagate in the unaffected parent material,²⁵ it is expected that the degree of crack branching towards the parent material would be more if the cracks initiate near the weld compared with near the parent material; and this may be responsible for the difference in loading cycles. Also, crack deviation from the coarse grain region towards the region closer to the parent material suggests that crack deviation was a factor of the region having a lower resistance to crack growth. A similar crack branching phenomenon accompanied with crack closure and higher crack growth resistance was also reported in weld materials extracted from Q345 steel.² Interpretation of the results with metallographic examination of the crack surfaces will be discussed further in a later section.

It can be seen from Fig. 2 that there is no marked difference in the curves particularly at higher ΔK , which provides an appreciable level of repeatability in the experimental data. The delayed crack growth particularly at lower ΔK followed by the accelerated crack growth as the crack propagates has been explained by crack closure induced by mean or compressive residual stresses ahead

of the crack tips.^{2,4,8,9} In Austin's work,¹ it was mentioned that the damaging tensile portion of residual stress field in welded plate is approximately a quarter of the plate thickness such that the beneficial (i.e. compressive) segment of the stress field is the mid-section of the plate. However, from the data plotted in Fig. 2, the transition from the delayed to the accelerated crack growth regime occurred at ΔK less than $19 \text{ MPa} \sqrt{m}$, a point where the crack length was approximately 11.25 mm from the notch and about 47.5 mm through the thickness of the weld plate. Considering the specimens' orientation as schematically shown in Fig. 1, this depth was found to be approximately at the mid-section of the 90 mm plate where the specimens were extracted from. Therefore, the crack growth behaviour of the HAZ materials in air (Fig. 2) appears to be consistent with the explanations given by Austin and may be used to interpret the data.

The crack growth rates in HAZ materials in air and seawater are compared in Fig. 3. It can be seen that the seawater curves are similar over the ΔK ranges tested. Crack growth rates were found to be slightly higher in the seawater test 2 than in test 1, but the difference was insignificant. The type of crack growth patterns that were obtained in the HAZ materials in air was not evident in seawater probably because of the time dependent behaviour of corrosion fatigue damage and the interaction of the crack tip with the seawater environment compared with the fatigue crack growth mechanisms in air that is considered to be purely mechanical. Because residual stresses are released as fatigue crack progresses, their effect under a corrosive environment may be marginal, thus leading to the environment being more dominant in seawater compared with residual stresses. However, this proposal was only limited to the observed

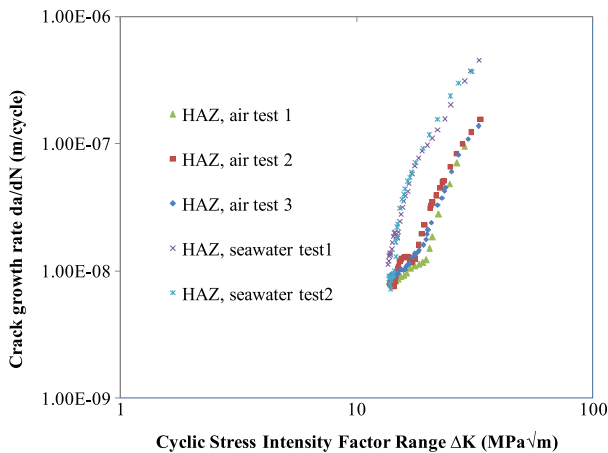


Fig. 3 Crack growth rates in heat affected zone (HAZ) materials in air and seawater. [Colour figure can be viewed at wileyonlinelibrary.com]

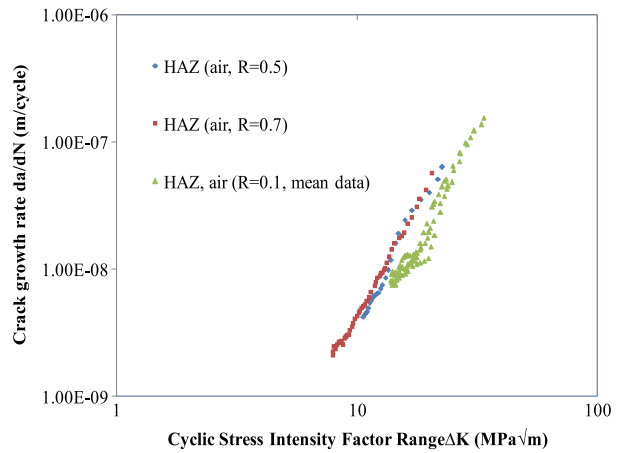


Fig. 4 Crack growth rates in heat affected zone (HAZ) materials in air at R -ratios of 0.1, 0.5 and 0.7. [Colour figure can be viewed at wileyonlinelibrary.com]

crack growth behaviour of the HAZ in seawater. Also, owing to microstructural changes in the HAZ and weld materials, their corroded surfaces were more severe than in the parent material tested under the same environmental and loading conditions. Therefore, it may also be implied that crack growth rates in the HAZ materials are significantly influenced by these microstructural variations, accompanied by rates of material removal.

Crack growth rates were found to be higher in seawater than in air over the range of ΔK examined. The Paris-law constants, C and m , derived from the line of best fits through the mean data in air and seawater are presented in Table 1. It can be observed that the seawater environment has enhanced the fatigue crack growth rate per cycle by an order of magnitude. At lower ΔK , below $15 \text{ MPa} \sqrt{m}$, crack growth rates were found to

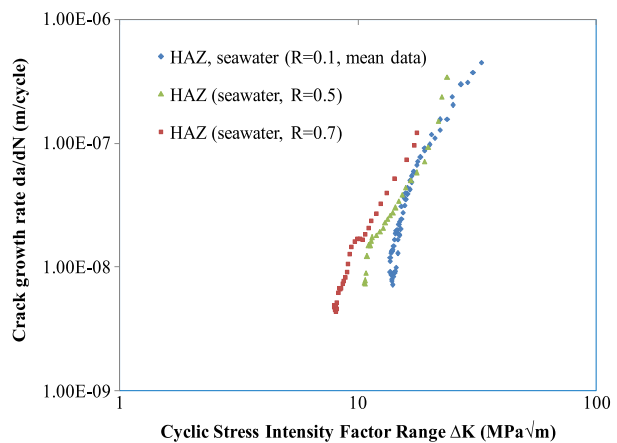


Fig. 5 Crack growth rates in heat affected zone (HAZ) materials in seawater at R -ratios of 0.1 to 0.7. [Colour figure can be viewed at wileyonlinelibrary.com]

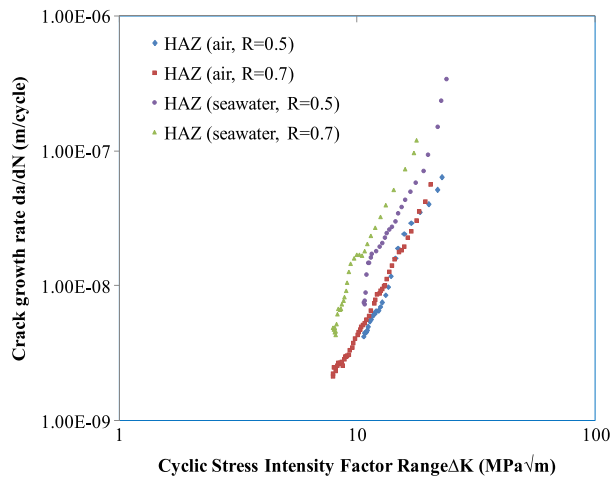


Fig. 6 Air and seawater data in heat affected zone (HAZ) at R -ratios of 0.5 and 0.7. [Colour figure can be viewed at wileyonlinelibrary.com]

be twice higher in seawater than in air. Beyond the ΔK of $15 \text{ MPa} \sqrt{m}$, crack growth rates in seawater were approximately five times higher than in air. This was due to the environmentally enhanced crack growth mechanisms in seawater that are expected to be significant at higher crack opening displacement. However, at higher ΔK , crack growth rates in seawater were four times higher than in air. It can also be observed in Fig. 3 that at higher ΔK , the seawater curves have similar slopes to those obtained in air.

Fatigue crack growth rates in air and seawater at different R -ratios

In order to understand the effects of mean stress on crack growth rates in the HAZ material and to eliminate the

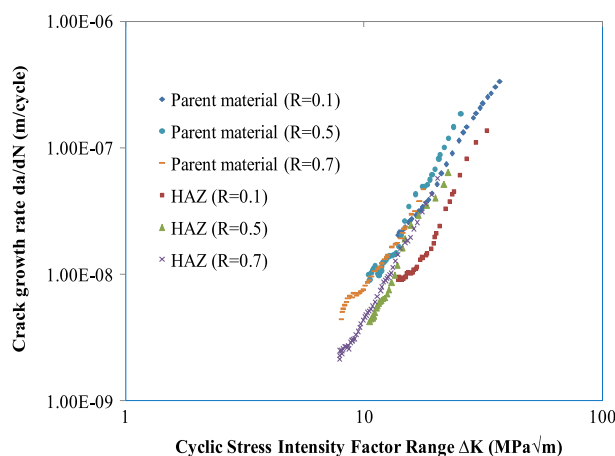


Fig. 7 Crack growth data comparison in heat affected zone (HAZ) and parent material in air. [Colour figure can be viewed at wileyonlinelibrary.com]

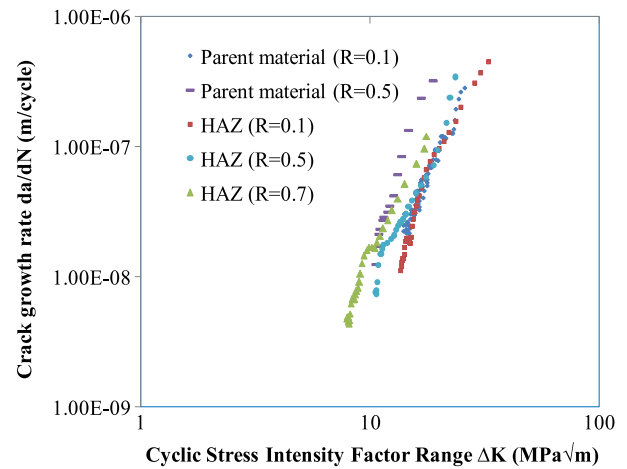


Fig. 8 Crack growth data comparison in heat affected zone (HAZ) and parent material in seawater. [Colour figure can be viewed at wileyonlinelibrary.com]

possible effects of residual stress induced crack closure⁴ that had been used to explain the bi-linear crack growth relationships observed in the tests on HAZ material in air shown in Fig. 2, some tests were conducted in air at R -ratios of 0.5 and 0.7. The results are compared with the mean data of those obtained at R -ratios of 0.1 in Fig. 4. It can be seen that for tests conducted at higher R -ratios the bi-linear relationships that were evident at R -ratios of 0.1 are absent. The implication of this is that for tests conducted at higher stress ratios, crack closure effects are not significant owing to the degree of crack tip opening. A similar mechanism was reported by Trudel *et al.*²⁶ It can also be observed from the figure that the crack growth responses at R -ratios of 0.5 and 0.7 are similar, which implies that the effects of mean stresses are not significant in air. It can be seen in Fig. 4 that lower

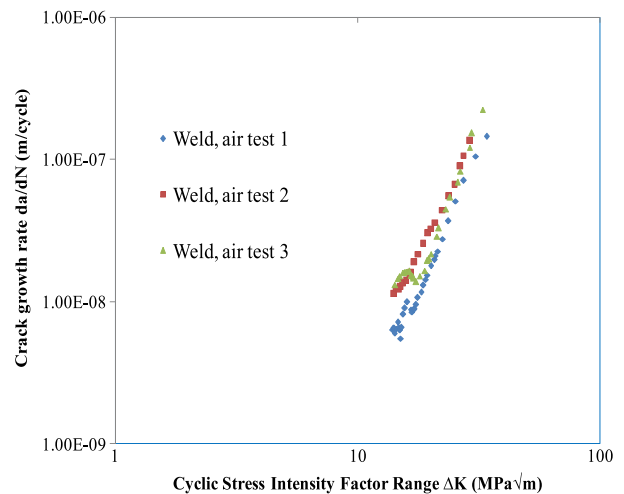


Fig. 9 Crack growth rates in weld materials in air. [Colour figure can be viewed at wileyonlinelibrary.com]

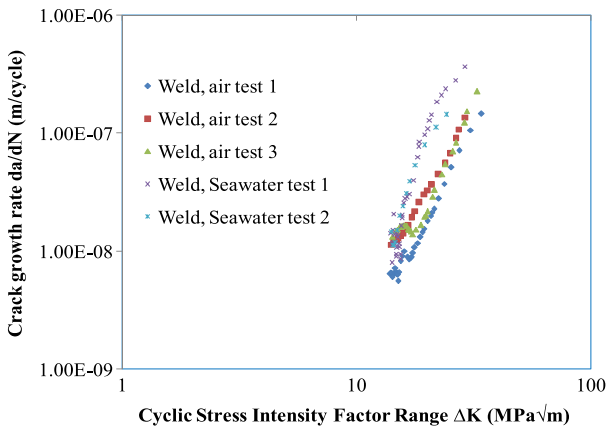


Fig. 10 Crack growth rates in weld materials in air and seawater. [Colour figure can be viewed at wileyonlinelibrary.com]

ΔK values were obtained at an R -ratio of 0.5 compared with those obtained at an R -ratio of 0.1, due to the effects of load range. However, two effects were revealed from the comparison made with the R -ratio of 0.1 tests: first, at all the tested ΔK ranges, crack growth rates were found to be higher at higher R -ratios than at an R -ratio of 0.1 but this was not more than twice the crack growth rates at an R -ratio of 0.1 and second, there were reductions in the ΔK values at higher R -ratios compared with the R -ratio of 0.1 test.

In Fig. 5, crack growth rates obtained in free-corrosion conditions at R -ratios of 0.5 and 0.7 are compared with the mean data of those obtained at an R -ratio of 0.1. Crack growth rates were generally found to increase at higher stress ratios compared with those obtained at an R -ratio of 0.1. It can also be seen that the effect of the test environment accompanied with

higher R -ratios has marked effects on crack growth behaviour in the materials. At ΔK between 13 and 18 $\text{MPa}\sqrt{m}$, crack growth rates were found to be twice higher at an R -ratio of 0.7 than at an R -ratio of 0.5 and approximately four times higher than those obtained at an R -ratio of 0.1. At higher ΔK ranges, beyond 18 $\text{MPa}\sqrt{m}$, the R -ratio of 0.7 curve deviated towards the R -ratio of 0.1 curve. Similarly, it can be seen that at higher ΔK , the crack growth curve obtained at an R -ratio of 0.5 approached the one obtained at R -ratio of 0.1. These trends could be explained in terms of the degree of corrosion debris within the crack accompanied by rates of material removal by corrosion in the HAZ material. In Appleton's work,¹⁵ the extent of corrosion products in the crack was also reported to be dominant under free-corrosion conditions, thus restricting appreciable access of the corrosive environment to the crack tip.

The effects of higher stress ratios on crack growth rates in air and seawater are compared in Fig. 6. Over the range of ΔK values examined, the crack growth rates in seawater were significantly enhanced at higher stress ratios and were found to be in the order of two to three times faster than the equivalent air data obtained at R -ratios of 0.5 and 0.7, respectively. It can also be seen that the acceleration in crack growth in seawater is more rapid at lower ΔK values compared with the air data. This was due to the effect of the seawater environment, which is expected to be dominant under a fully open crack, leading to a reduction in resistance to crack growth at lower ΔK . The trends of the data plotted in Fig. 6 clearly show the significance of environmental interaction with mean stress effects on crack growth rates in seawater compared with in air.

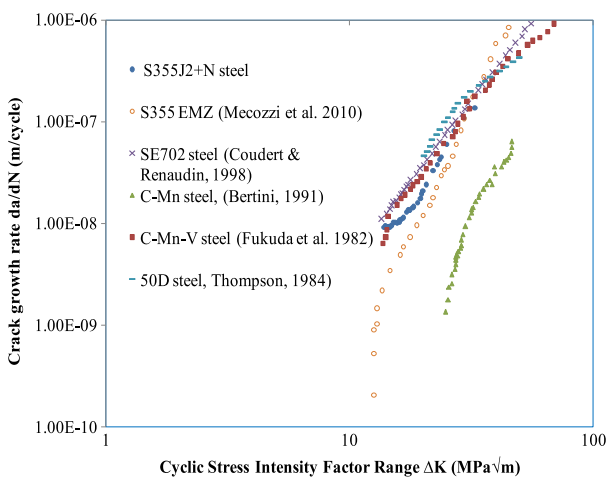


Fig. 11 Comparison of crack growth rates in heat affected zone (HAZ) material in air with literature data. [Colour figure can be viewed at wileyonlinelibrary.com]

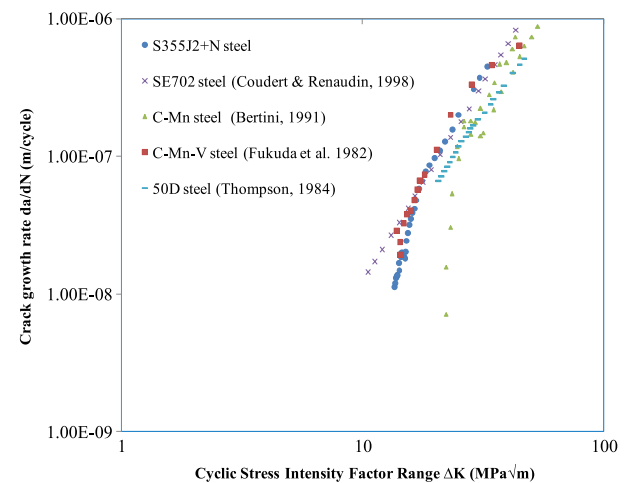


Fig. 12 Comparison of crack growth rates in heat affected zone (HAZ) material in seawater with literature data. [Colour figure can be viewed at wileyonlinelibrary.com]

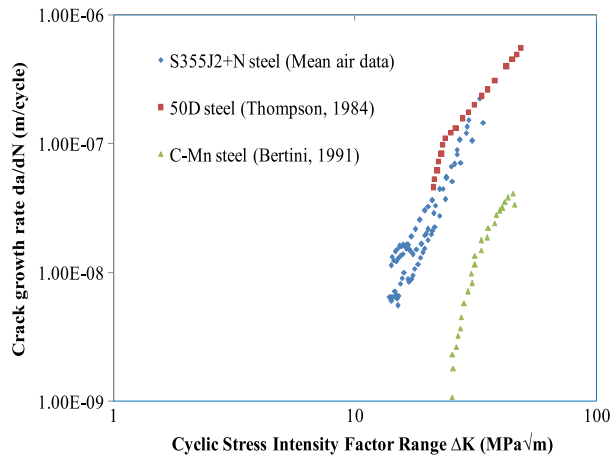


Fig. 13 Comparison of crack growth rates in weld material in air with literature data. [Colour figure can be viewed at wileyonlinelibrary.com]

Comparison of fatigue crack growth behaviour in HAZ and parent material

Crack growth rates at lower and higher R -ratios in parent material in air are compared with the HAZ data in Fig. 7. At lower values of ΔK , for tests conducted at an R -ratio of 0.1, crack growth rates in parent material were higher than the HAZ data by a factor of 4, compared with higher ΔK where crack growth rates in parent material were higher than in HAZ material by a factor of approximately 2. However, at ΔK above 25 $\text{MPa}\sqrt{m}$, the HAZ and parent material curves are similar and the two curves almost converged. In Fig. 7, it can also be observed that the crack growth behaviour in the HAZ material at R -ratios of 0.5 and 0.7 is similar to those obtained in parent material at the R -ratio of 0.1. For the cases considered in this paper, this implies

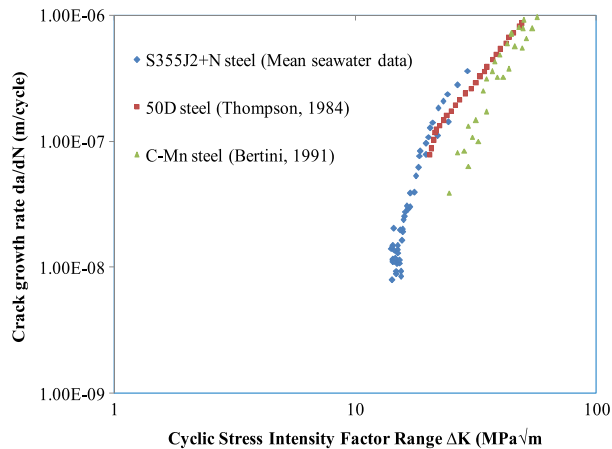


Fig. 14 Comparison of crack growth rates in weld material in seawater with literature data. [Colour figure can be viewed at wileyonlinelibrary.com]

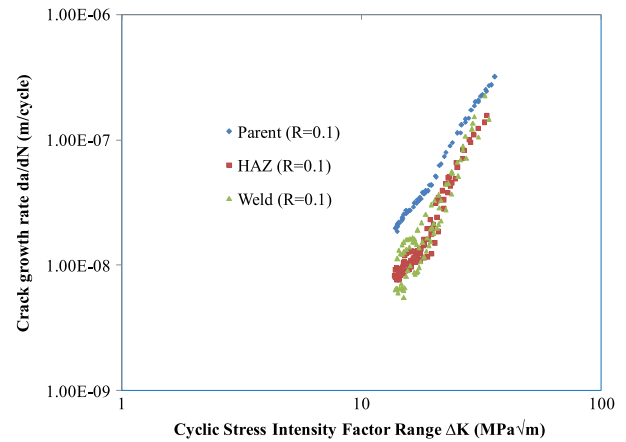


Fig. 15 Crack growth rates in parent, heat affected zone (HAZ) and weld materials in air at an R -ratio of 0.1. [Colour figure can be viewed at wileyonlinelibrary.com]

that the crack growth data obtained in parent material at an R -ratio of 0.1 in air may be used to represent HAZ crack growth behaviour in air at higher R -ratios. More experimental data are required to confirm these observations and examine the repeatability of these trends.

The HAZ and parent material seawater data obtained at an R -ratio of 0.1 and higher R -ratios are compared in Fig. 8. It can be observed that at the R -ratio of 0.1 the HAZ and parent material crack growth data are similar. However, at ΔK below 15 $\text{MPa}\sqrt{m}$, crack growth rates in HAZ material were found to be slightly lower than in parent material, but beyond this point, the crack growth behaviour in both materials were nearly the same. This is similar to the crack growth response in a similar material used for offshore

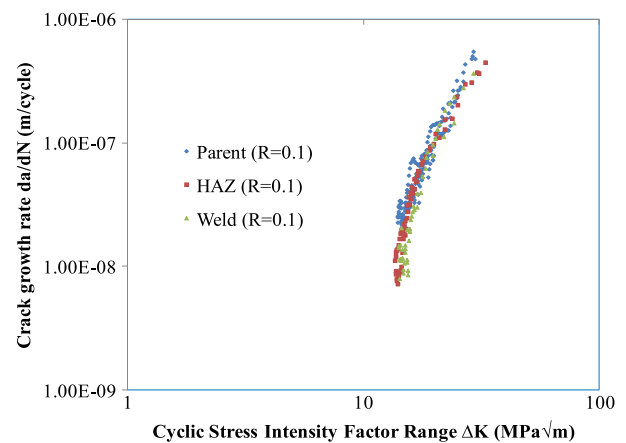


Fig. 16 Crack growth rates in parent, heat affected zone (HAZ) and weld materials in seawater at an R -ratio of 0.1. [Colour figure can be viewed at wileyonlinelibrary.com]

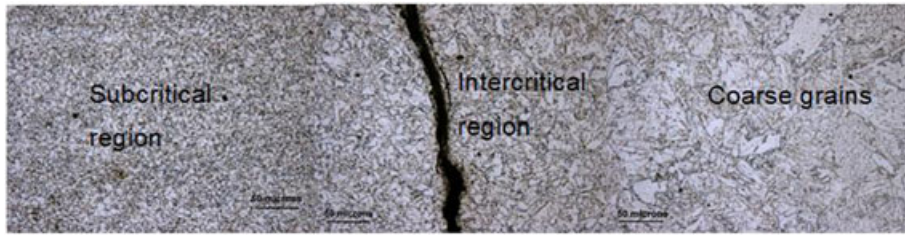


Fig. 17 Crack growth in the intercritical heat affected zone (HAZ) region (×5). [Colour figure can be viewed at wileyonlinelibrary.com]

installations.⁶ It appears from the present observation at an *R*-ratio of 0.1 that the material data of parent material in seawater can also be used to estimate the corresponding HAZ crack growth behaviour. However, crack growth rates in parent material in seawater at the *R*-ratio 0.5 were also found to be higher than in HAZ materials tested using the same *R*-ratio but were found to be similar to those obtained from HAZ material at an *R*-ratio of 0.7 at lower ΔK . At higher ΔK , crack growth rates in the parent material were found to be about three times higher than in HAZ material, with the HAZ curves converging with the *R*-ratio of 0.1 ones. Considering the presence of possible weld fabrication defects and HAZ microstructure sensitivity to corrosion assisted fatigue crack growth, crack growth accompanied by deposits of layers of corrosion products within the crack is the most likely explanation of the HAZ crack growth rates at higher ΔK in seawater.

Fatigue crack growth rates in weld metal in air and seawater

Crack growth data obtained from weld material at the *R*-ratio of 0.1 in air and seawater are compared in Figs 9 and 10, respectively. The reasons for generating the weld crack growth data in this work were to examine the possibility for cracks initiating from welds and to also compare crack growth rates in welded zones with those in HAZ and parent material. Therefore, the data obtained from weld materials in this work are only limited to tests conducted at the *R*-ratio of 0.1.

It can be observed from Fig. 9 that the crack growth trends are similar. The curves deviated at ΔK below 20 MPa \sqrt{m} with delayed crack growth rates in test 1, beyond which the crack growth behaviour is similar. The crack growth mechanism in the weld materials at lower ΔK , particularly in test 1 may be due to material variation coupled with possibility of improvement in the

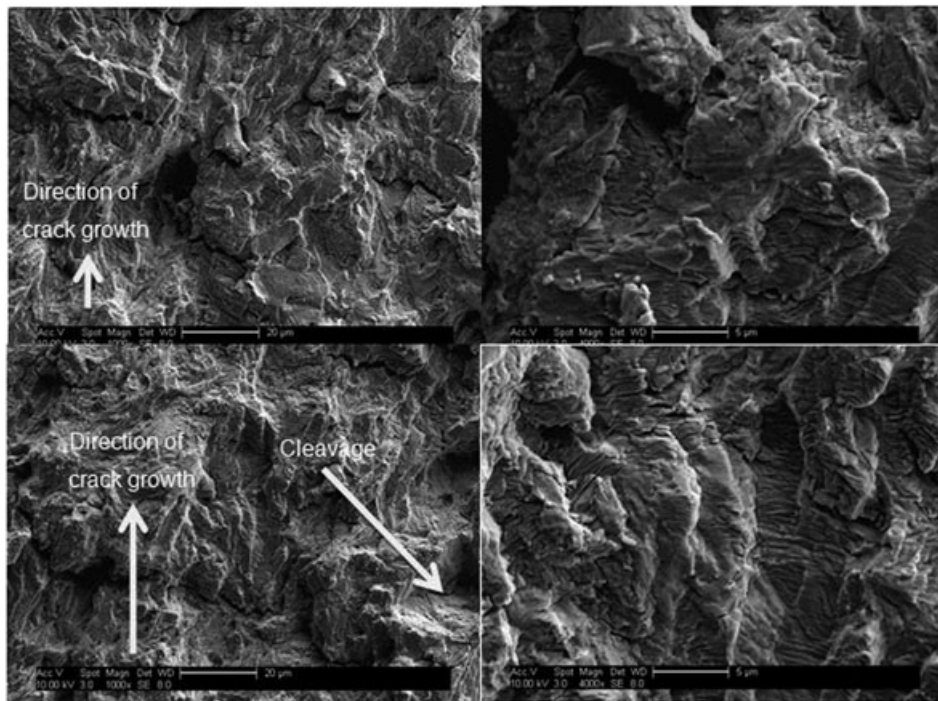


Fig. 18 Transition region in HAZ material in air at *K* between 18 and 19 MPa \sqrt{m} .

weld toughness as a result of grain refinement by the subsequent weld layers. Therefore, in test 1, the crack may be propagating through the weld region having more resistance to crack growth compared with tests 2 and 3. Microstructure examination of the weld materials' crack surfaces revealed that the degree of crack deviation in an attempt to propagate through a preferred path was marginal compared with what was observed in HAZ material.

Crack growth rates in weld materials in air are compared with those obtained in seawater in Fig. 10. It can be observed in the Figure that the data trends are similar. Crack growth rates in air were found to be similar to the seawater ones at lower ΔK particularly when compared with the weld air tests 2 and 3. This was due to the time dependent mechanism of seawater effect within the crack that is not expected to be dominant at lower ΔK . However, at ΔK less than $17 \text{ MPa } \sqrt{m}$, crack growth rates in seawater were approximately three times higher than in air. Subsequently, crack growth rates in seawater were found to be about five to six times higher than in air. At about the ΔK range of $20 \text{ MPa } \sqrt{m}$, the seawater curves began to approach the air ones and the resulted crack growth rates were measured to be three times higher in seawater than in air. This can be explained by the effects of the deposit of corrosion products at the crack tip at the higher ΔK as previously mentioned.

Crack growth comparison with literature data

Crack growth data obtained from HAZ materials were collected from the literature^{6,7,20,8,27} and are compared with the present data in Figs 11 and 12. It must be mentioned that the existing corrosion fatigue studies and database that were obtained more than 30 years ago are quite large; however, almost no data had been obtained from S355 J2 + N steel material used for the present investigation, particularly at higher stress ratios, with respect to the weld plate thickness and tests

conditions similar to what is experienced by monopile support structures. In Fig. 11, it can be seen that the present data are between those obtained from Coudert and Renaudin, Fukuda *et al.* and Thompson^{6,7,27} and those obtained from Mecozzi *et al.*,²⁰ while Bertini's²⁶ data are below the other data plotted in the figure. The most likely reason to explain the shift in Bertini crack growth curves to the bottom of the other curves is the differences in the applied test loads. The type of crack growth trend obtained from the material used for this work, the delayed crack growth at lower ΔK and the transition to a higher crack growth regime at higher ΔK were not evident in the other data regardless of some similarities in the crack growth curves. This can be explained with respect to the differences in material, welding sequence, welding procedure, material thickness and specimen geometry etc. Details of the welding procedure, thickness and specimens' geometry of the materials whose data are compared with those obtained from the present materials in Fig. 11 can be found in the literature.^{6,7,20,8,27}

The data obtained in free-corrosion conditions are compared with those obtained in the literature in Fig. 12. The data that are compared with the present results were mostly obtained under free-corrosion potential. Thompson⁷ observed the possibilities of hydrogen-induced crack growth even under a free-corrosion potential. The mechanism of environmental enhancement in crack growth rates in BS4360 50D steel in seawater was also explained by hydrogen embrittlement for all the applied potentials including free-corrosion potential.¹⁶ This implies that crack growth data derived under a free-corrosion potential may not absolutely represent the real effects of free-corrosion conditions on fatigue crack growth, as investigated in previous studies. However, from the comparisons made in Fig. 12, it was found that only the data obtained by Fukuda *et al.* are similar to those obtained from the present HAZ materials. In their work, a loading frequency of 0.133 Hz corresponding to sea

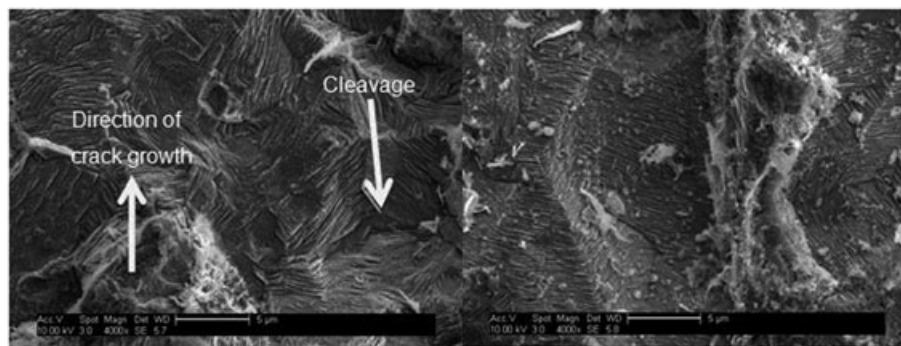


Fig. 19 Ductile striations on parent material in seawater $K = 19 \text{ MPa } \sqrt{m}$.

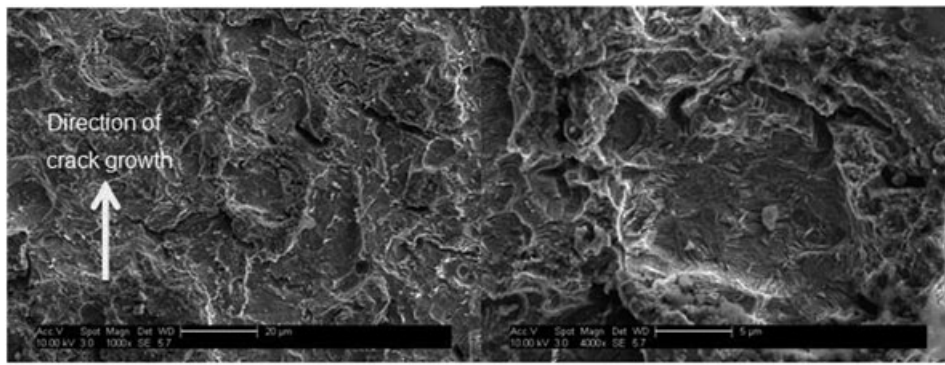


Fig. 20 Mixture of brittle and ductile striation in heat affected zone (HAZ) materials in seawater $K = 20 \text{ MPa } \sqrt{m}$.

wave frequency was used for testing, and it is expected that crack growth rates would be higher than those reported in the present study owing to the longer time the crack tip is exposed to the corrosive environment. The probable explanation for this is difference in material with respect to material composition, and mechanical properties accompanied with the type of welding procedure used for fabrication. Thompson’s data did not agree with the present data, as shown in Fig. 12, probably owing to the higher load frequency of 0.5 Hz used for testing with the intention of reducing the test duration. It should be noted that a higher load frequency in seawater would result in lower crack growth rates owing to the shorter crack tip opening time. This had also been proved by Vosikovsky²⁸ and in Ref. ³. There is a good agreement between the present HAZ data and those obtained from SE702 as shown in the figure particularly at ΔK above $14 \text{ MPa } \sqrt{m}$. This is also in agreement with the comparisons made for parent material fabricated from S355 J2 + N and SE702 steels.³ Mecozzi *et al.* did not obtain any crack growth results in seawater; their data are therefore not included in the comparisons made in Fig. 12.

In Fig. 13, the mean data obtained from weld material at the R -ratio of 0.1 in air are compared with those

obtained by Thompson⁷ and Bertini⁸ for BS4360 50D and C-Mn steels. Bertini’s data did not agree with the present data probably because of the differences in the test load range, specimen geometry, material composition and the yield strength of the welded zone that was investigated, which was reported to be 490 MPa. However, in seawater (Fig. 14), comparisons revealed that the crack growth behaviour of the present data is quite similar to Thompson’s data but dissimilar to Bertini’s data. When the data were analysed, it was found that Thompson’s data were obtained from 20 to 50 $\text{MPa } \sqrt{m}$, while Bertini’s data were obtained from 25 to 71 $\text{MPa } \sqrt{m}$. The present data were measured at ΔK between $14 \text{ MPa } \sqrt{m}$ and approximately $30 \text{ MPa } \sqrt{m}$. This implies that higher test loads were used in Bertini’s and Thompson’s tests compared with this work. Therefore, the data were compared based on the crack growth rates within the range of the present results. These were found to be slightly higher than Thompson’s data particularly at ΔK between 22 and $30 \text{ MPa } \sqrt{m}$.

Comparison of parent, HAZ and weld materials

The data obtained in air at the R -ratio of 0.1 in parent, HAZ and weld materials are compared in Fig. 15. Data

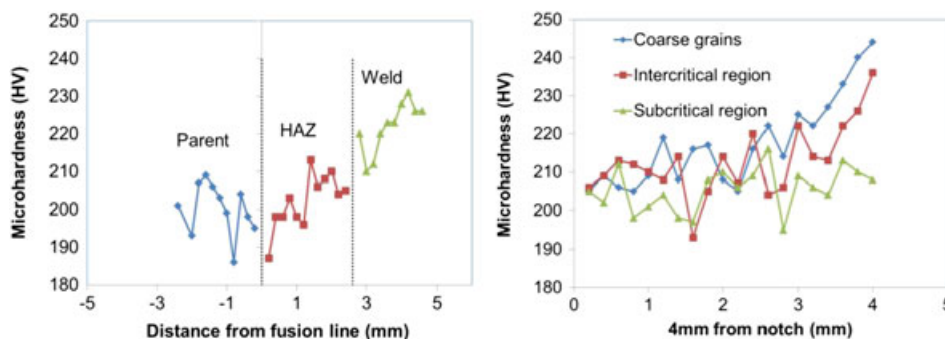


Fig. 21 Vickers hardness values, left: parent to weld, right: along heat affected zone (HAZ). [Colour figure can be viewed at wileyonlinelibrary.com]

analysis revealed that crack growth rates were generally higher in parent material than in HAZ and weld materials respectively. It can also be seen that the crack growth trends in HAZ and weld materials are similar particularly at higher ΔK . However, in free-corrosion conditions, crack growth rates were found to be similar in the three materials, as shown in Fig. 16. There was a slight difference in crack growth rates in parent material and those obtained in the HAZ and weld materials. The material constants resulting from the lines of best fit through the data obtained in parent, HAZ and weld materials are set out in Table 1. The C and m values in parent, HAZ and weld materials are those derived using the mean data. Regardless of the parallel relationships in the crack growth rates in air and seawater at the R -ratio of 0.1, the material constants vary from the parent, HAZ and weld materials. The implication is that the effects of environment and material variation still contributed to the crack growth rates in the materials. However, data analysis generally revealed similarities in crack growth rates in parents, HAZ and weld materials. This was also reported for high-strength steels weld and parent material with yield strength between 500 and 600 MPa.²⁹ It was recommended that suitable screening of the parent material crack growth data may be applied to evaluate the suitability of weldments. In Table 1, the material constants of the higher R -ratio tests also vary from parent, HAZ and weld materials. However, it can be observed that the R -ratios of 0.5 and 0.7 tests in HAZ have same m values but different C values. This implies that R -ratio effects in this case only have a significant effect on C values but marginal effects on m values.

Discussion of results with microstructure observation and analysis of the fracture surfaces

The microstructure variation in HAZ material is shown in Fig. 17. It can be seen that the crack propagated in the middle region of the HAZ, at the left of the coarse grains and later deviated towards the finer grains closer to the parent material due to its lower resistance to crack growth accompanied by microstructure induced crack growth. Xiong and Hu² also reported a similar crack branching phenomenon in Q345 steel weldments at lower stress ratios, leading to a reduction in crack growth. Crack branching was also observed in stainless steel welds,²⁶ and in the Healy *et al.* work,¹⁰ it was found that crack path in the HAZ of CSN3:8 steel was influenced by microstructure. It may therefore be implied that the data presented in Fig. 2 (HAZ, air) are also influenced by microstructure variations in the HAZ materials. It was also observed during the investigation that changes in crack path were more in

the HAZ microstructure than in the weld material. This would have also contributed to the difference in crack growth patterns in the two materials.

The examined fracture surfaces of the specimens tested at R -ratio of 0.1 are shown in Figs 18–20. Crack growth results of parent material have been discussed in a previous study.³ Analysis of all the fracture surfaces with respect to ΔK was not in detail. However, the areas of interest were only examined particularly in the HAZ materials owing to the data trend plotted in Fig. 2.

In HAZ materials, as previously mentioned, the change in the slopes of the data plotted in Fig. 2 occurred at ΔK below 19 MPa \sqrt{m} ; therefore, the fracture surfaces corresponding to ΔK between 18 and 19 MPa \sqrt{m} were only examined. The results are shown in Fig. 18. At ΔK of 18 MPa \sqrt{m} , the bottom right of the figure, it can be seen that the degree of fatigue striations is significantly higher than those at the top right of the figure that corresponds to ΔK of 19 MPa \sqrt{m} . The amount of striations in the bottom right may be due to the delayed crack growth prior to ΔK below 19 MPa \sqrt{m} , and the surface appearance shown at the top right may also be related to the change in slope in Fig. 2 prior to transition to the faster crack growth region.

The fracture surface of the parent and weld material tested in air generally revealed a mixture of ductile and brittle striation mechanisms, but these are not presented here. In seawater, at ΔK of 19 MPa \sqrt{m} , the fracture surface of the parent material shown in Fig. 19 revealed uniform cracking mechanism particularly at the right of the figure. Some cleavage features of the surface are also evident at the left of the figure accompanied with some corrosion products. The appearance of the fracture surface may be related to a minimum level of corrosion-enhanced damage in the parent material's microstructure compared with in HAZ (Fig. 20) and weld materials. This implies that fracture surfaces accompanied by the type of striations are material dependent, as mentioned in Ref. ³⁰.

The features of the fracture surface of the HAZ material is shown in Fig. 20. It can be observed that the damage features are significantly enhanced by corrosion compared with in parent material (Fig. 19). The degree of the corrosion-enhanced damage in the surfaces increased with an increase in ΔK . At ΔK of 20 MPa \sqrt{m} , the crack growth mechanism showed mainly brittle form of failure. The HAZ material fracture surface was also found to exhibit corrosion pits more severely than in parent material. A similar surface appearance was also observed in the weld material during the investigation. The implication of this is that both material microstructure variation and environmental factors are responsible for the crack growth mechanisms in seawater.

Discussion of results with hardness measurements

The hardness measurements taken from the parent material are compared with those measured in HAZ and weld zones as shown in the left of Fig. 21. It can be observed that the hardness values of the HAZ decrease from the weld towards the parent material with a mean hardness value of 209 HV. However, in the parent material, the mean hardness value was found to be 200 HV. It can also be seen from the right of the figure that the hardness values decrease from the coarse grain to the finer grain microstructure. The data plotted in the figure imply that the crack deviated from the harder region of the HAZ to the weaker region closer to the parent material. The variation in HAZ hardness values was also in agreement with what was reported for a similar material⁷ and in other types of steel.^{8,9,26,31}

CONCLUSIONS

The crack growth behaviours in HAZ and weld materials fabricated from S355 J2 + N steel were investigated in air and in a laboratory simulated seawater environment similar to what is experienced by offshore installations in service. The following conclusions can be drawn from the study.

- 1 The methodology developed for conducting crack growth tests in seawater has proved reliable. Small-scale specimens extracted from relatively thick weld plate with similar dimensions to those used for monopile fabrications have been used to reproduce the crack growth behaviour in the structures as close as possible.
- 2 The air tests conducted on HAZ materials at the R -ratio of 0.1 revealed delayed and accelerated crack growth at lower and higher applied stress intensity factor ranges respectively, resulting in a bi-linear relationship of the da/dN versus ΔK plots. However, at higher R -ratios bi-linear crack growth trend was eliminated.
- 3 On the basis of the limited test data obtained from this study, HAZ and weld materials showed higher resistance to crack growth than in parent material for tests conducted in air. However, in free-corrosion conditions, crack growth rates in HAZ, weld and parent material were found to be similar.
- 4 Crack growth rates in HAZ and weld materials were significantly enhanced in free-corrosion conditions, at all the stress ratios studied than in air environment. The HAZ and weld materials showed good resistance to crack growth when compared with other types of steels used for offshore structures.

- 5 Crack growth rates in HAZ materials were not only influenced by environment, material microstructure accompanied by welding process but by crack closure induced by possible effects of residual stresses.
- 6 Mean stress effects on fatigue crack growth depend on environment, material and loading conditions. Improvement in welding procedures accompanied with welding sequences can reduce the effects of high mean stress (i.e. damaging tensile residual stress) in offshore structures.

Acknowledgments

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