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METALLURGICAL INVESTIGATION INTO THE ORIGIN OF CRACKS AT WELDED CONNECTIONS ON A HOT DIP GALVANISED FABRICATED STRUCTURAL STEEL PERIMETER WALKWAY PLATFORM FOR THE NEW KUSILE POWER STATION IN SOUTH AFRICA

For

ROBOR GALVANISERS

Attention*:*

Mr Riaan Louw

(Operations Director)

Report no. 220512

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SUMMARY AND CONCLUSION

1. Cracks were discovered at the highly restrained fillet welded connections on structural steel perimeter walkway platforms for the new Kusile power station after hot dip galvanising.
2. Similar cracks had been found after hot dip galvanising after the design of the highly restrained welded connections on the walkway platforms had been modified.
3. Metallographic and fractographic examination revealed that the cracks had developed by liquid metal assisted cracking (LMAC) during hot dip galvanising, an uncommon cracking mechanism for hot dip galvanising of welded structural steelwork.
4. The design of the walkway platforms did not satisfy the British Constructional Steelwork Association's guidelines published during 2005 for minimising the risk of LMAC during hot dip galvanising of welded structural steelwork.
5. The design of the walkway platforms resulted in excessive thermally-induced stresses being introduced at the highly restrained welded connections during hot dip galvanising.
6. Although other factors also contributed to the LMAC of the walkway platforms, it is concluded that a substantial deficiency in the design of the walkway platforms had been the main factor triggering LMAC at specific highly restrained welded connections on the platforms.

1. BACKGROUND

1.1 Mr Riaan Louw (Operations Director of Robor Galvanisers) informed Grobler that a number of cracks had been discovered at welded connections on a structural steel walkway platform after hot dip galvanising. Examining photographs of the cracks on the walkway platform provided by Mr Louw, Grobler found that:

1.1.1 Most of the cracks were at connections between 50 x 50 x 4 mm diagonal structural steel angle section chords welded to much larger section I-beams at T-joints between longitudinal and transverse chords (cf. Figure 1a to 1c).

1.1.2 Some of the angle diagonal chords had fractured completely (cf. Figure 1c).

1.1.3 Some of the fracture locations were some distance from the weld heat affected zones in the unaffected base metal (cf. Figure 1c).

1.1.4 Through-thickness cracks had also developed in the webs of some of the I-beams at the toes of fillet welds joining the angle section chords to the webs of the transverse chords (cf. Figure 1c).

1.1.5 Cracks had also developed from the relatively sharp 90° corners at T-joints between the flanges of I-beams (cf. Figure 1d).

1.1.6 Many of the angle section chords had distorted/buckled severely during hot dip galvanising (cf. Figure 1a).

1.2 Following the cracking of the first walkway platforms, the designers had changed the design of the angle section diagonal chord joint. The angle section diagonal chords were now welded to the webs of the transverse I-beam chords situated in between the longitudinal I-beam chords next to the T-joints between the transverse and longitudinal I-beam chords (compare the top image in Figure 1b with the bottom image in Figure 2d).

1.2.1 Cracks were discovered again at the angle section diagonal chord welded joints after hot dip galvanising of the first platform walkway fabricated to the new design (cf. Figure 2a to 2c).

1.2.2 Many of the angle section diagonal chords, restrained by large section longitudinal and transverse I-beam chords, had distorted/buckled severely during hot dip galvanising (cf. Figure 2d).

1.2.3 The severity of the cracking at and in the vicinity of the welded connections between the angle section chords and the I-beam chords appears to be less than on the original platform design.

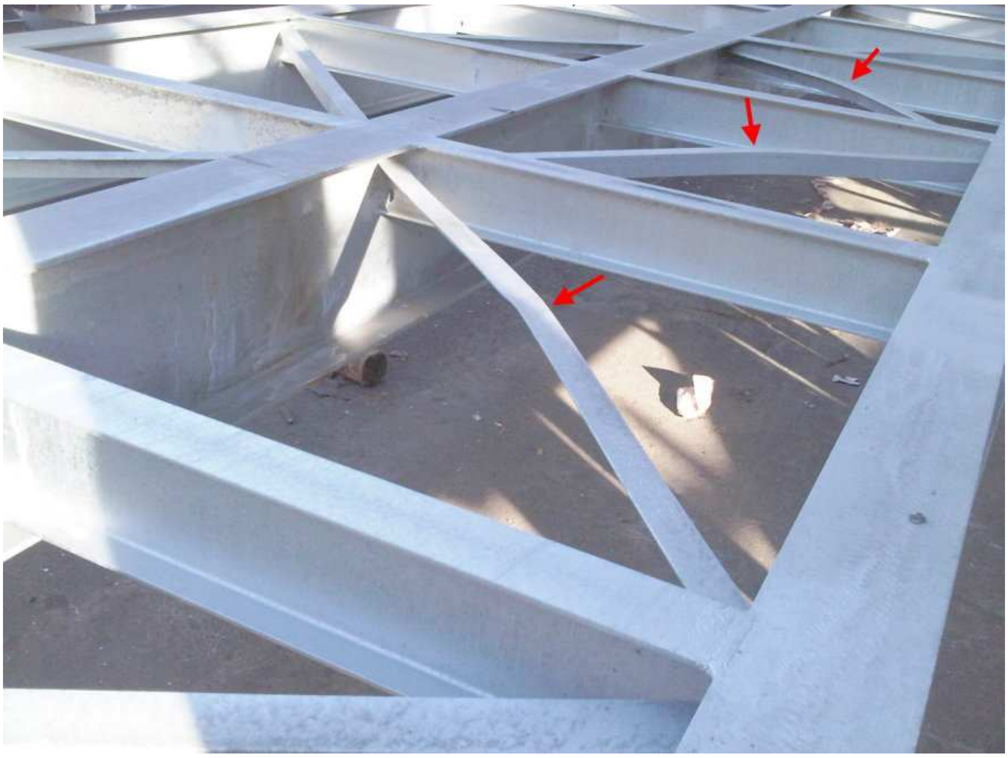


Figure 1a: Hot dip galvanised walkway platform with severely distorted 50 x 50 x 4 mm angle section chords. Cracks were discovered after hot dip galvanising at a number of the welded connections at the ends of the angle section chords. The angle sections had been welded to the 90° corner between the I-beam chords as shown in the top image in Figure 1b. (Images provided by Mr Riaan Louw and annotated by Grobler.)

Figure 1b: The top image shows the connection between the angle section chord and the two I-beam chords at a 90° T-joint. The arrows indicate the position of a crack in the angle section chord. The bottom image shows the same crack. The crack had developed in the unaffected base metal next to the weld heat affected zone of a fillet weld. (Images provided by Mr Riaan Louw and annotated by Grobler.)

Figure 1c: Some of the angle section chords had fractured completely in the base metal some distance from the fillet welds and weld heat affected zones. The bottom image shows cracks that had penetrated the web of an I-beam chord at the fillet welded connection between the angle section chord and web of the I-beam chord at the opposite side. (Images provided by Mr Riaan Louw and annotated by Grobler.) The failure of the angle section chord in the top image is similar to the LMAC failure of a diagonal chord on girder reported by CROSS[1] in the United Kingdom.

[1] *CROSS (Confidential Reporting on Structural Safety), "Liquid Metal Assisted Cracking (1)", Report ID: cross45, Published: Newsletter No 4-November 2006, http://www.structural-safety.org/view-report/cross46/.*

Figure 1d: Examples of cracks that had developed in I-beam flanges from 90° corners at T-joints between I-beam flanges. (Images provided by Mr Riaan Louw and annotated by Grobler.)

Figure 2a: The top image shows the new walkway platform with the design of the connections between the diagonal angle section chords and the I-beam chords modified. This is the first walkway platform that had been hot dip galvanised after the modification of the connection design. Cracks were discovered at a number of the welded connections between the 50 x 50 x 4 mm diagonal angle section chords and the webs of the transverse 160 x 82 mm I-beam chords at opposite sides of the middle longitudinal 406 x 178 mm I-beam.

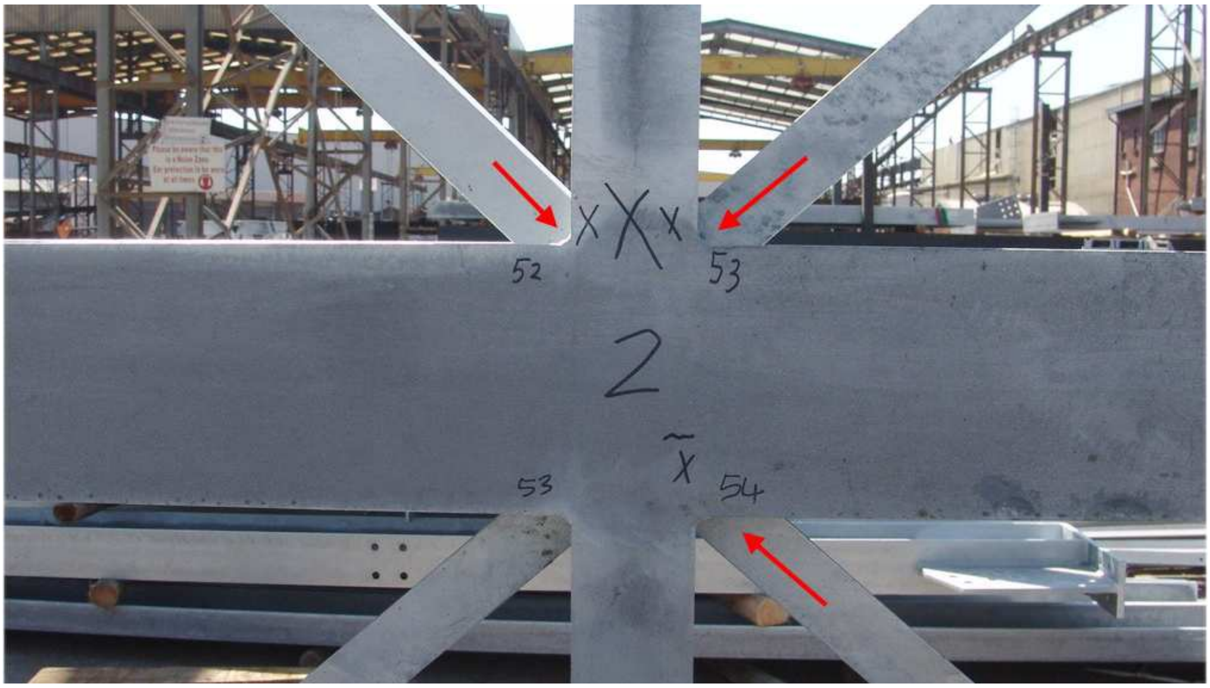


Figure 2b: Examples of cracks at welds in the web of the transverse I-beam chord at welded connections between the angle section chord and the transverse I-beam chord in the top image in Figure 2a. The cracks had developed at highly restrained welds.

Figure 2c: Examples of cracks in the web of a transverse I-beam chord at fillet welds at the connection between a diagonal angle section chord and transverse I-beam chord in the top image in Figure 2a. The cracks had developed at highly restrained welds.

Figure 2d: Examples of distorted/buckled angle section chords. The cracks were associated with the welded connections between these diagonal angle section chords and the webs of the transverse I-beam chords.

1.3 Christo Grobler Consulting Engineer CC was commissioned by Robor Galvanisers to determine the proximate cause of the cracks discovered after hot dip galvanising.

1.4 Robor had cut a portion from the walkway platform containing some of the welded connections with cracks for detailed examination by Grobler (cf. Figures 3a and 3b).

2. MAIN FINDINGS OF METALLOGRAPHIC AND FRACTOGRAPHIC EXAMINATIONS

2.1 Cracking mechanism

2.1.1 Four different cracking mechanisms can be triggered during hot dip galvanising, namely:

- Distortion Cracking,
- Hydrogen Embrittlement,
- Strain Age Embrittlement and
- Liquid Metal Assisted Cracking (LMAC).

2.1.2 **Distortion Cracking**

Although some of the angle section diagonal chords had become severely distorted/buckled as a result of differential heating during dipping of the walkway platform in the hot dip galvanised bath at approximately 450°C, the findings of this investigation confirmed the cracking mechanism not to be Distortion Cracking.

2.1.3 **Hydrogen Embrittlement**

Refer to the discussion in paragraph 2.3 below.

2.1.4 **Strain Age Embrittlement**

This form of cracking is associated with severely cold worked steel subjected to ageing or warm-working at temperatures less than 600°C. The cracking on the walkway platforms examined had not been associated with cold worked steel. The cracks had developed in hot rolled angle section chords and I-beam chords.

2.1.5 **LMAC**

Metallographic and fractographic examination of the cracks revealed that the cracks had developed by liquid metal assisted cracking (LMAC) (cf. Figures 3a to 3k and 4a to 4e).

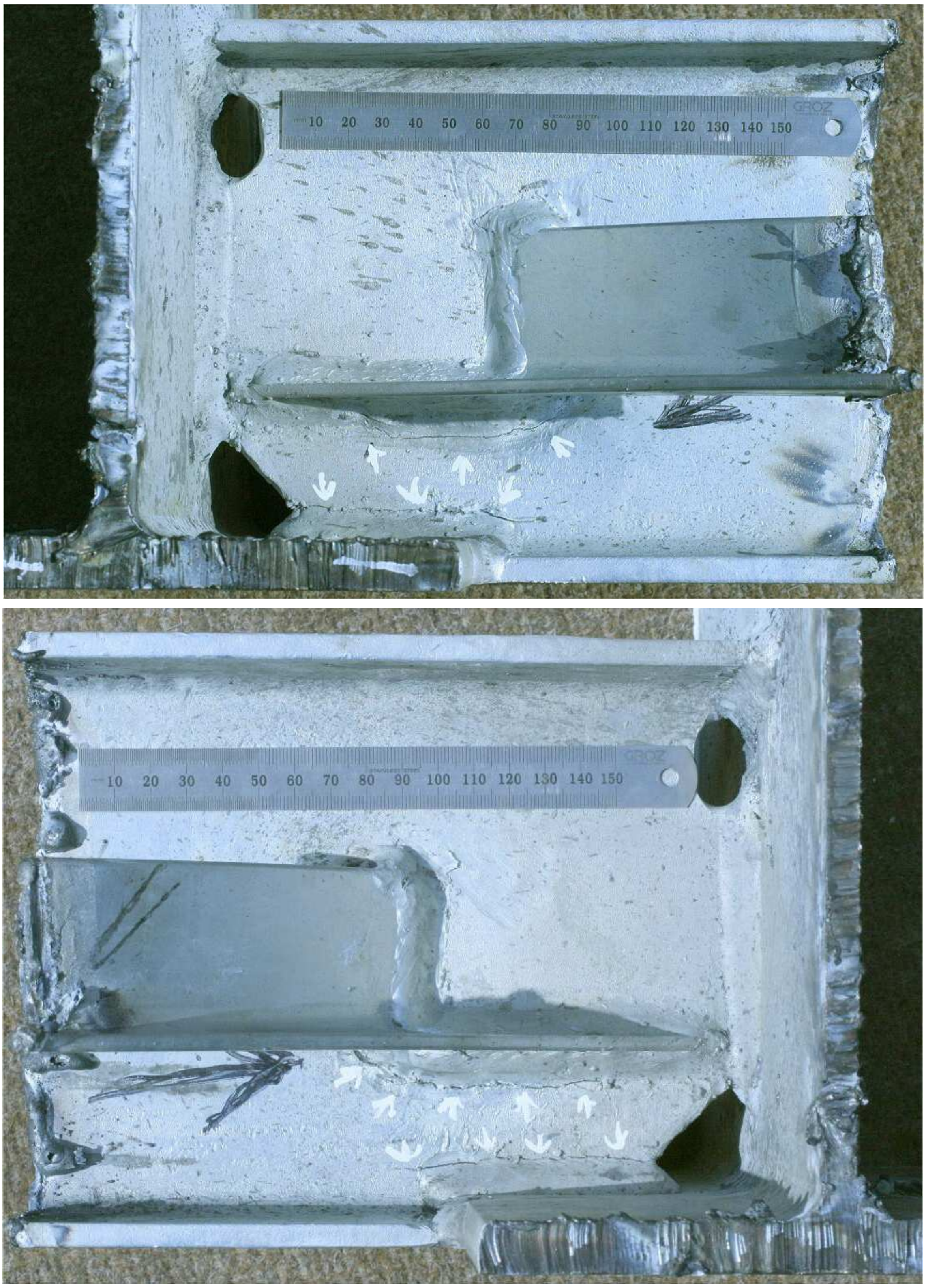


Figure 3a: Sample provided for examination by Grobler with cracks in the web of the transverse I-beam chord. The cracks had developed at both sides of the web at fillet welded connections between small angle section chords and the webs of much larger I-beam chords.

Figure 3b: Close-up views of cracks in the web of a transverse I-beam chord in Figure 3a. Note the grinding of the web at the fillet weld toe at the top crack in the top image. The findings of this investigation indicated that the grinding had probably been done by the fabricator to remove undercut at the fillet weld toe. Most of the cracks on the walkway platform were not associated with such fillet weld toe grinding.

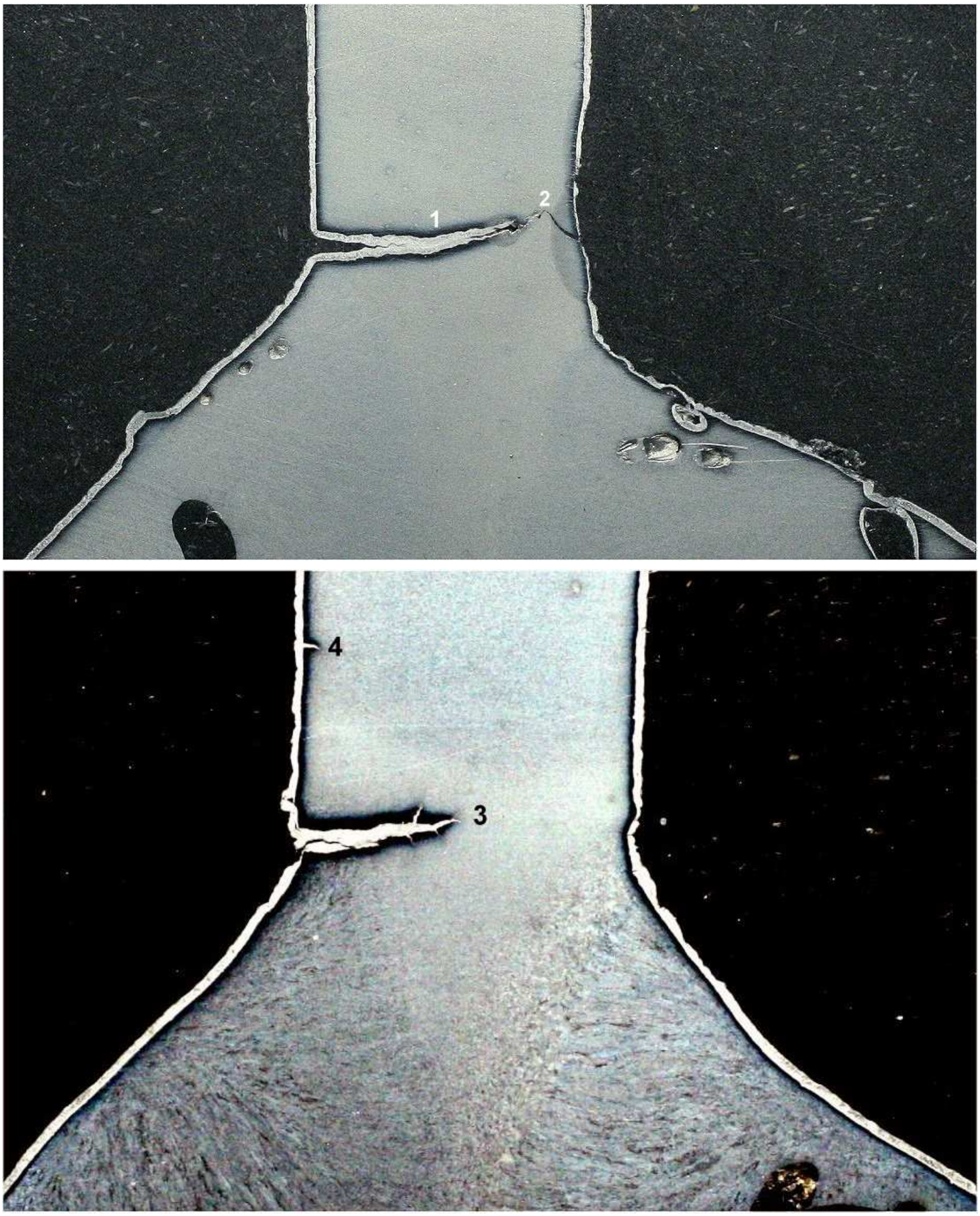


*Figure 3c: Polished and etched sections through one of the cracks with the section in the bottom image closer to the crack tip than the section in the top image. **Top image**: (1) Zink had penetrated most of the through-thickness crack, (2) the final end portion of the crack had developed by shear fracture during shrinkage during cooling after hot dip galvanising. **Bottom image**: (3) The crack had developed in the web of the I-beam chord from the fillet weld toe in the weld heat affected zone. Note the branching at the front end portion of the crack. (4) This crack had developed in the web base metal some distance from the toe of the fillet weld outside the weld heat affected zone and was also filled with zinc.*

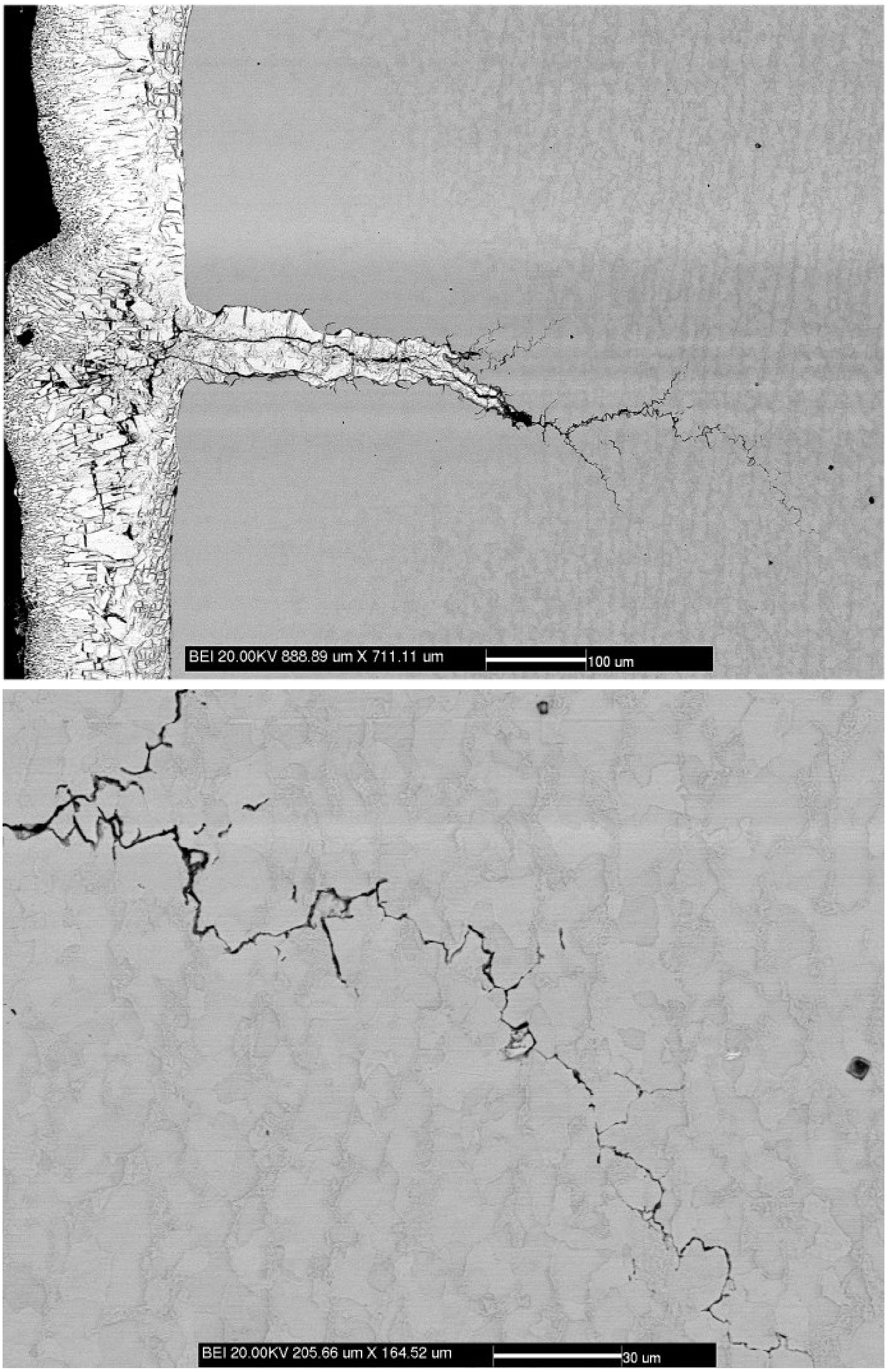


Figure 3d: Backscattered electron images of small surface crack (4) in the bottom image in Figure 3c that had developed in the base metal remote from the weld heat affected zone. The branching and intergranular crack paths are indicative of liquid metal assisted cracking (LMAC).

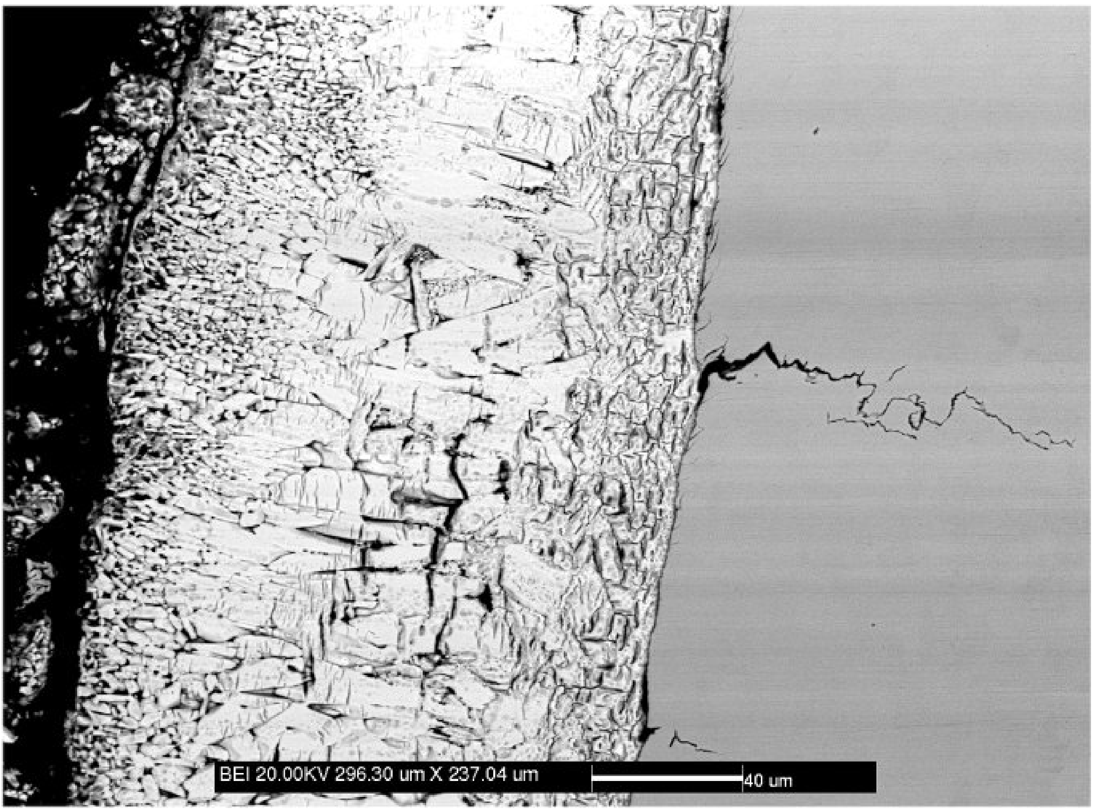


Figure 3e: Examples of small LMAC cracks at the surface of the web of the I-beam chord between the two large cracks in the bottom image in Figure 3c. These cracks had also developed in the base metal remote from the heat affected zone of the fillet welds.

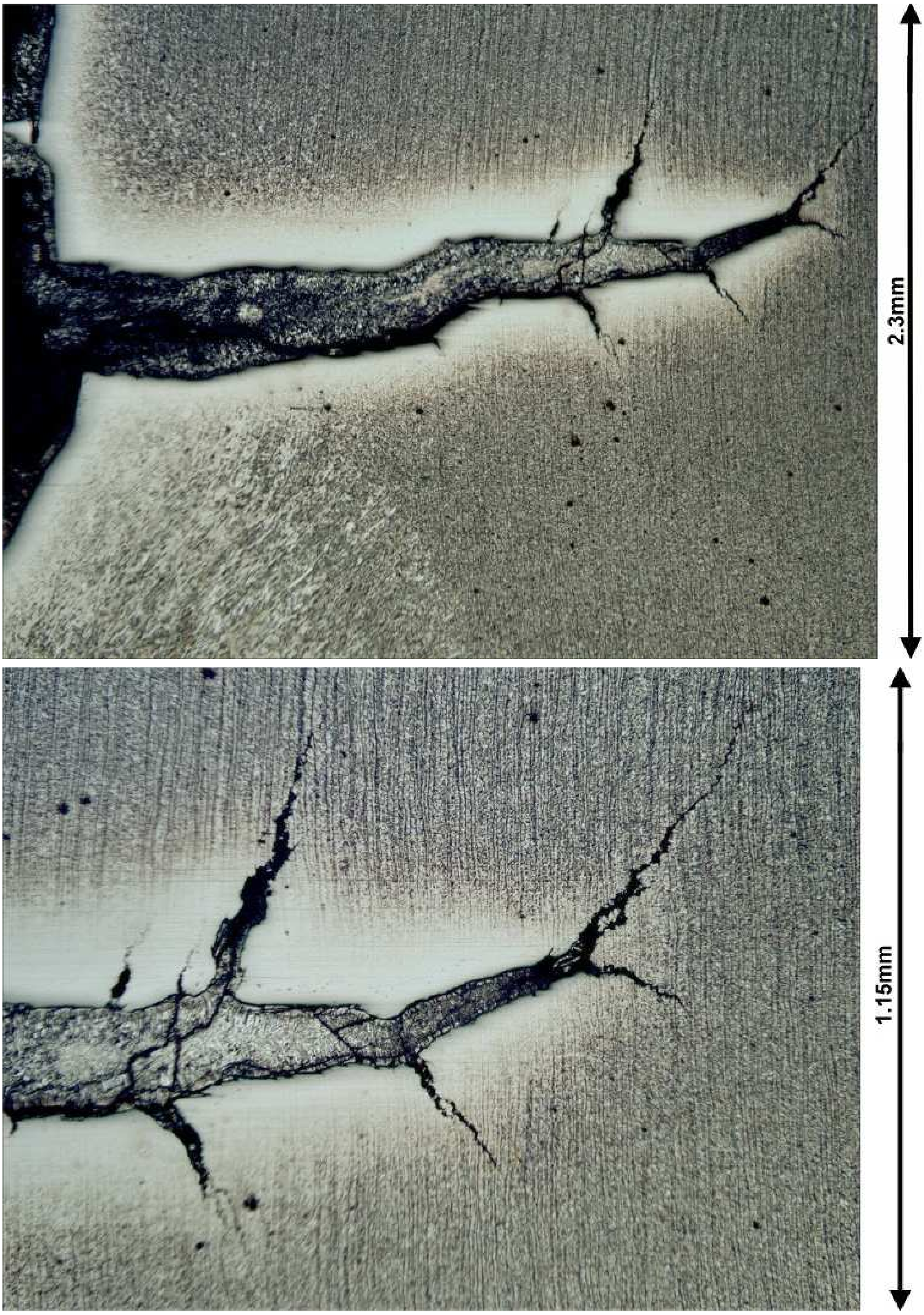


Figure 3f: Micrographs of the branched intergranular LMAC crack (3) in Figure 3c. This crack had originated at the toe of the fillet weld in the weld heat affected zone. It has, however, propagated into the unaffected base metal.

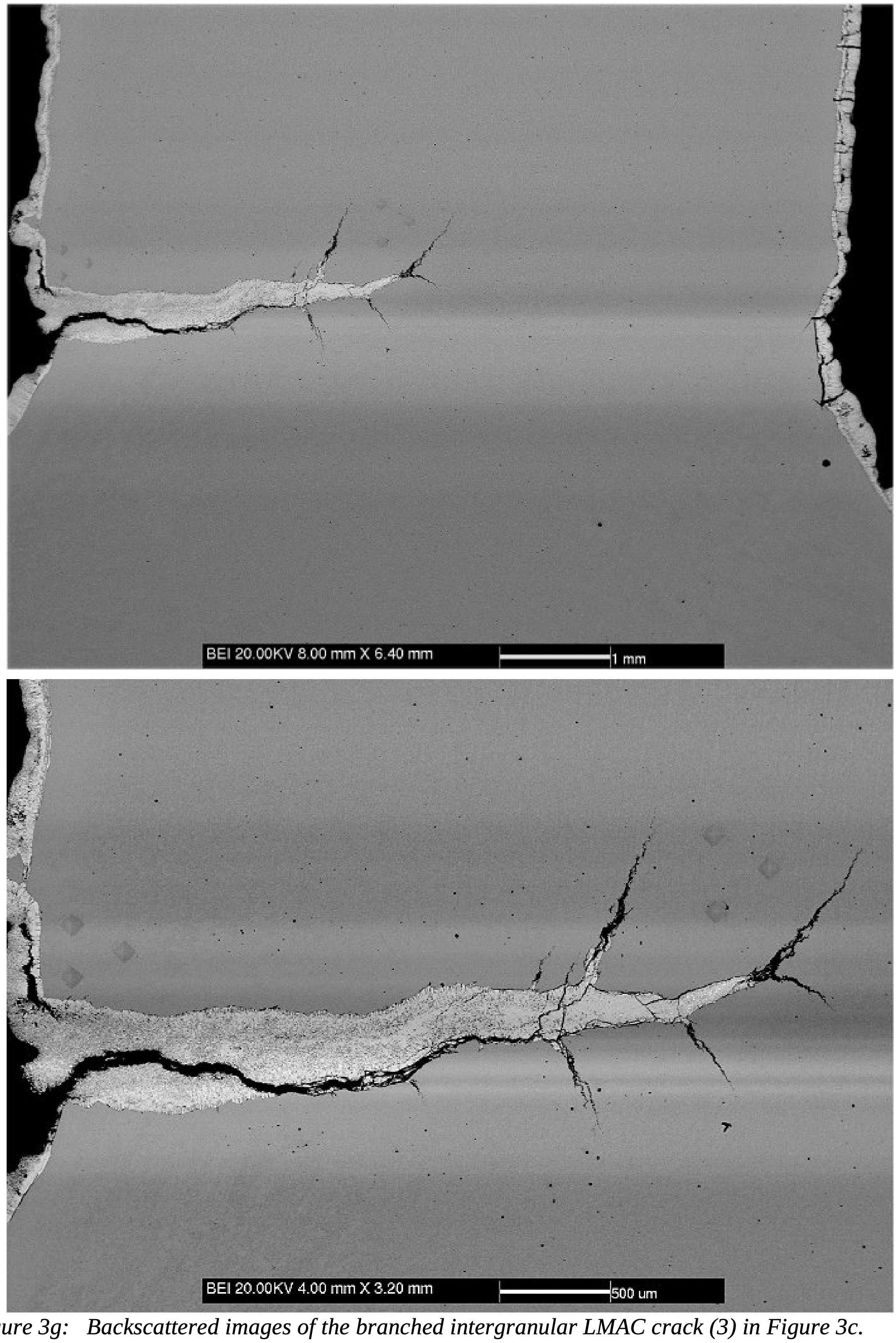


Figure 3g: Backscattered images of the branched intergranular LMAC crack (3) in Figure 3c.

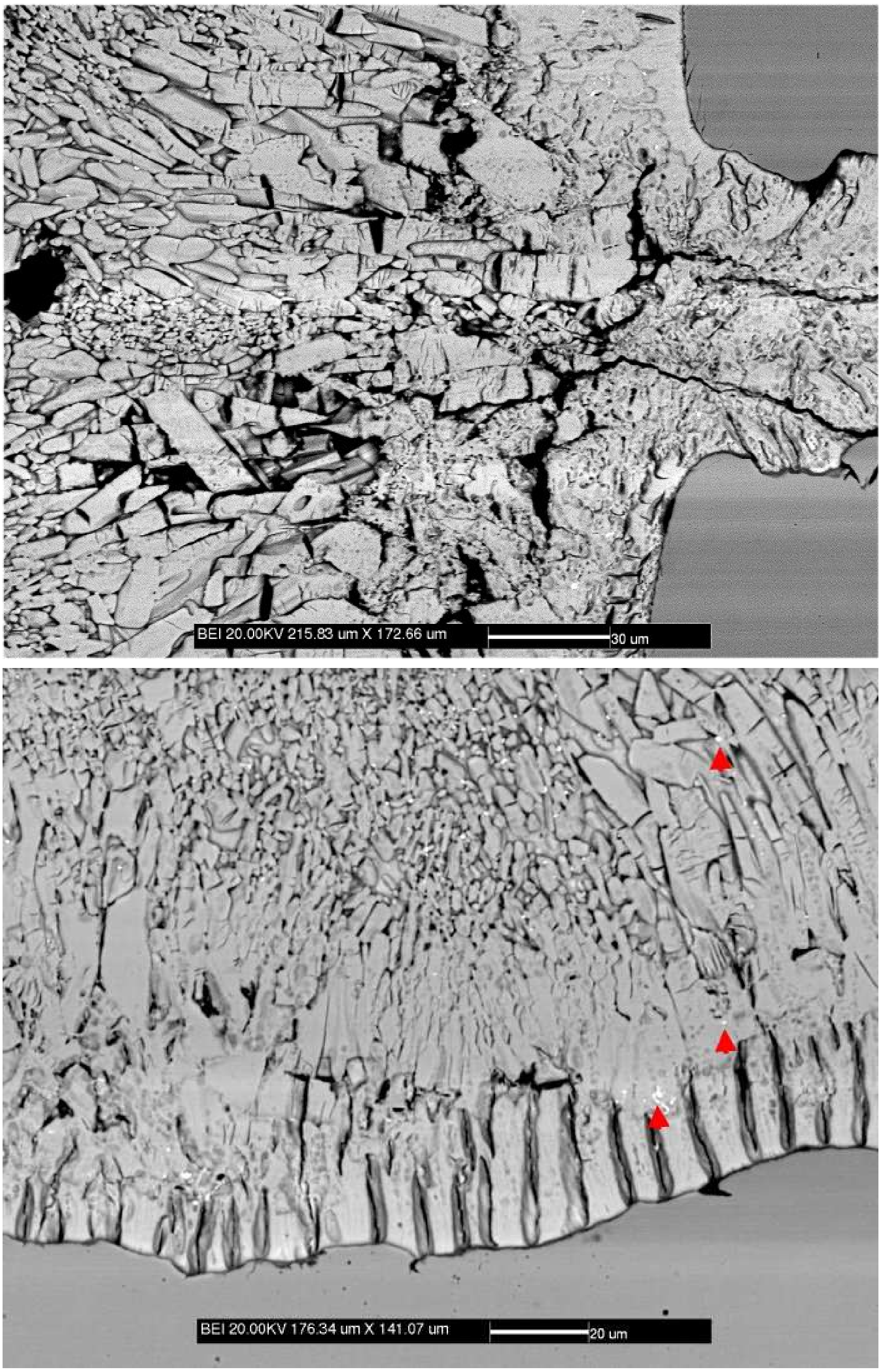


Figure 3h: Backscattered electron images showing small lead particles (white phase) in the zinc at the start of the large LMAC crack at the surface of the web at the left-hand side of the bottom image in Figure 3g.

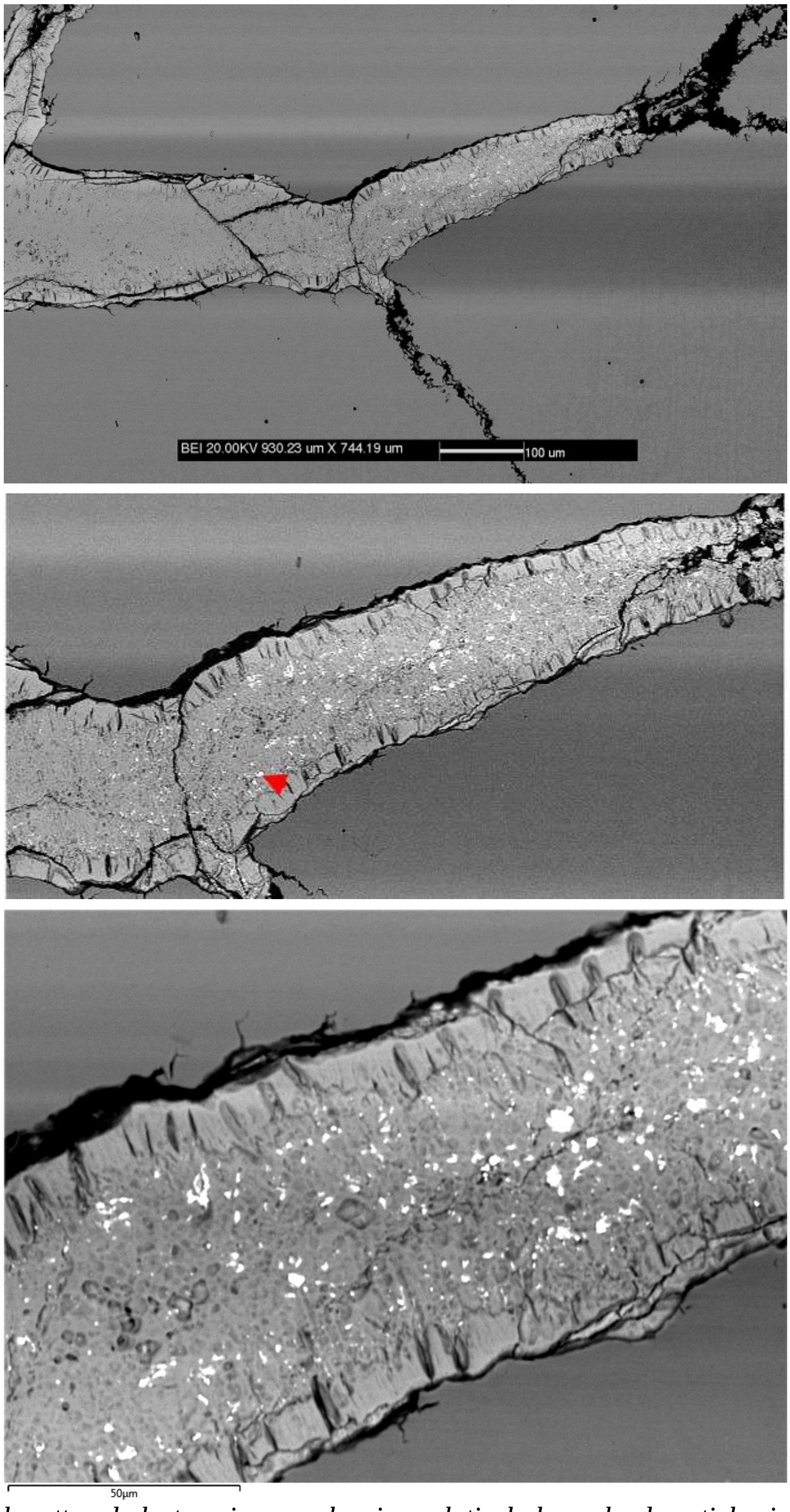
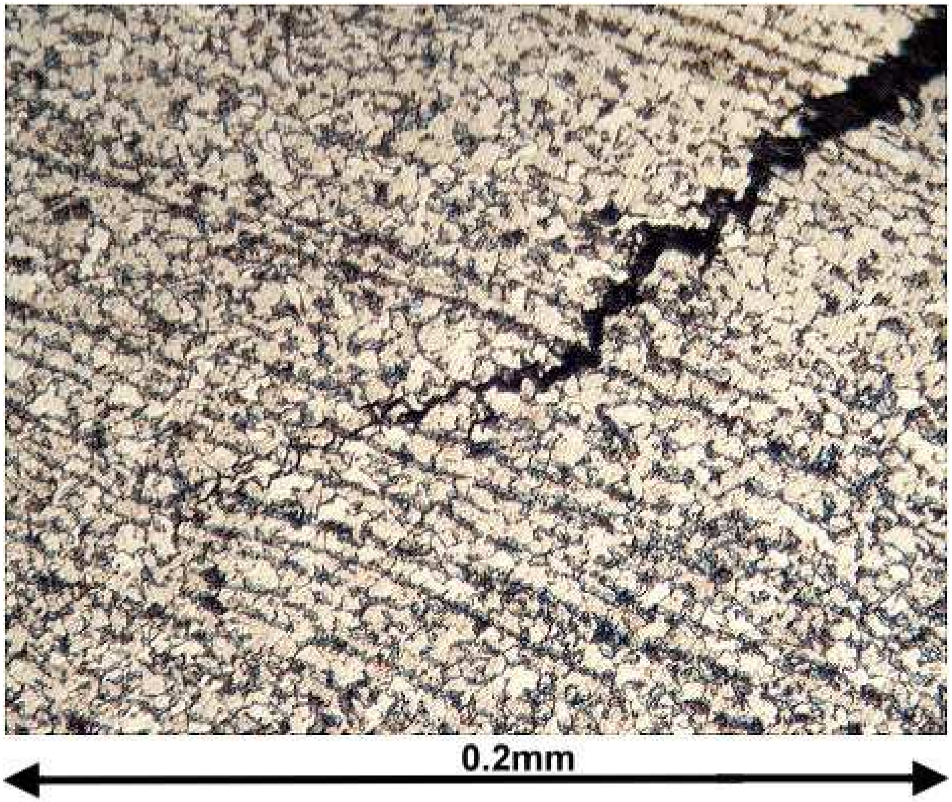


Figure 3i: Backscattered electron images showing relatively large lead particles in the zinc (white phase) in the right-hand side end portion of the LMAC crack in the bottom image in Figure 3g. The lead concentration increased towards the end of the crack.



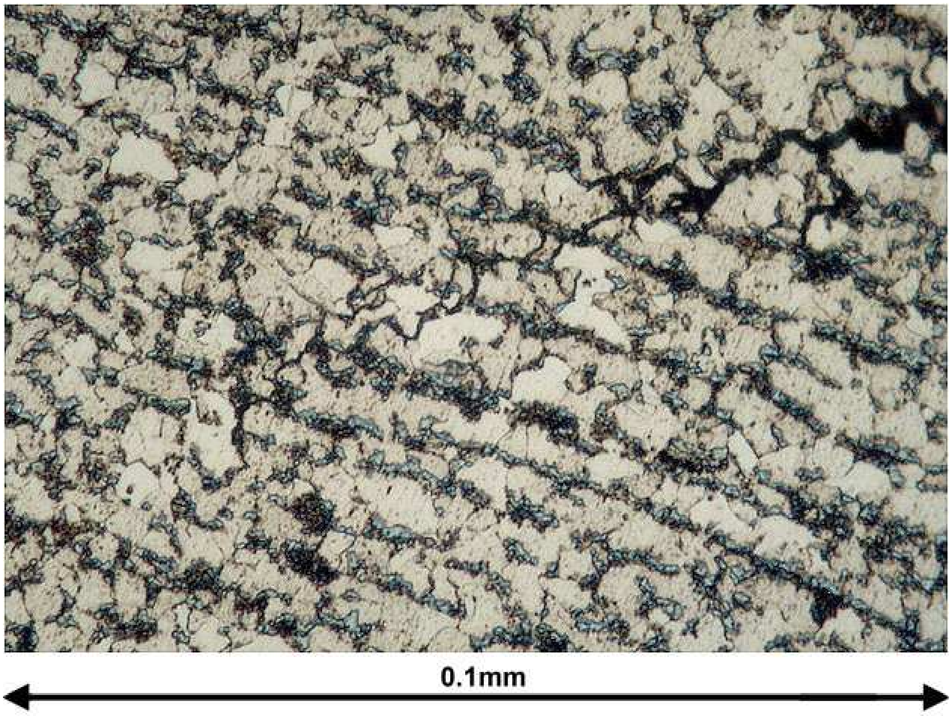


Figure 3j: Micrographs of the end portion of the bottom right-hand side branch of LMAC crack (3) in the bottom image in Figure 3f. Note the intergranular crack path and the banded ferrite-pearlite microstructure with the lighter phase ferrite and the darkish phase pearlite and the bands indicating the rolling direction.

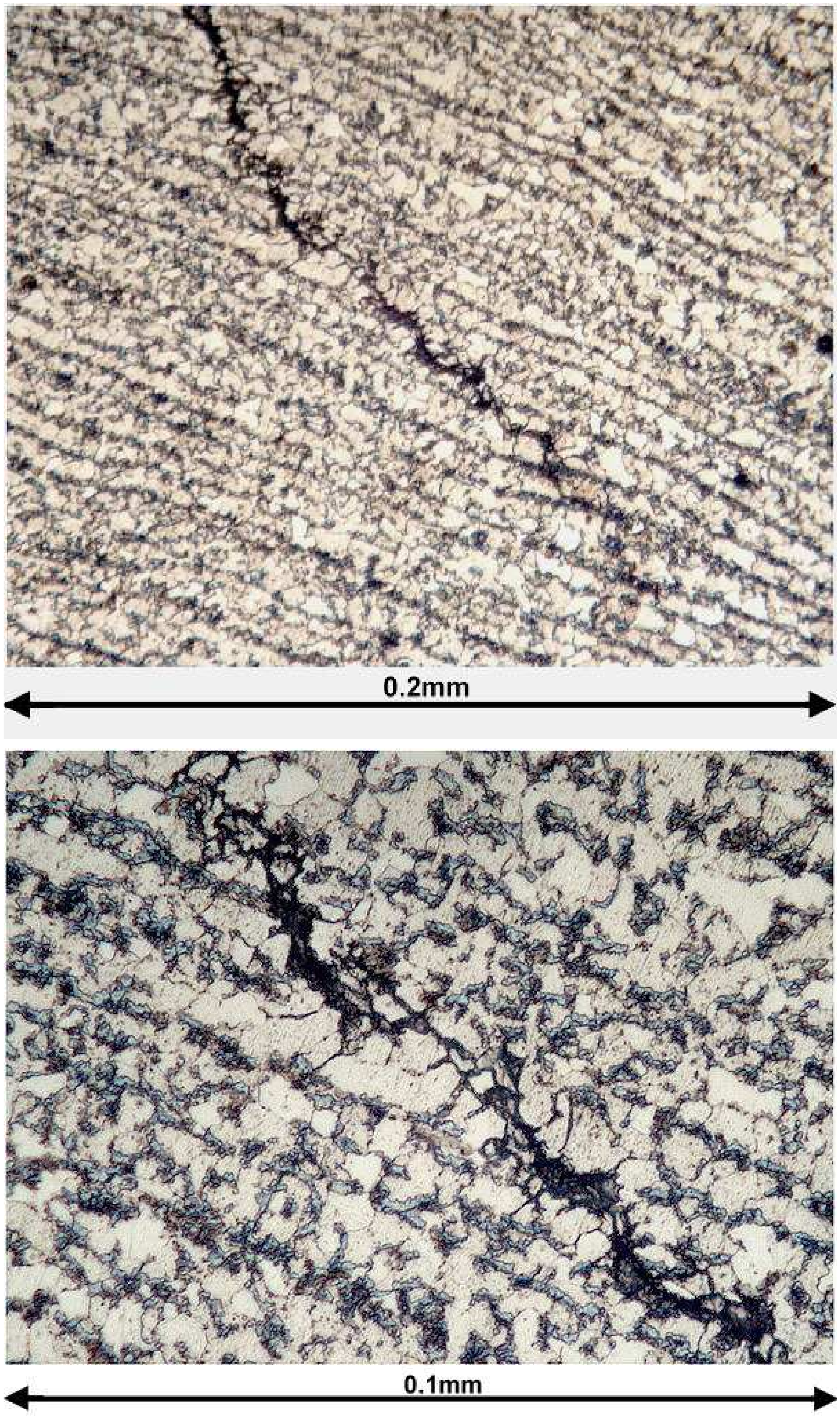


Figure 3k: Micrographs of the end portion of the top right-hand side branch of LMAC crack (3) in the bottom image in Figure 3f. Note the intergranular crack path and the banded ferrite-pearlite microstructure with the lighter phase ferrite and the darkish phase pearlite and the bands indicating the rolling direction.

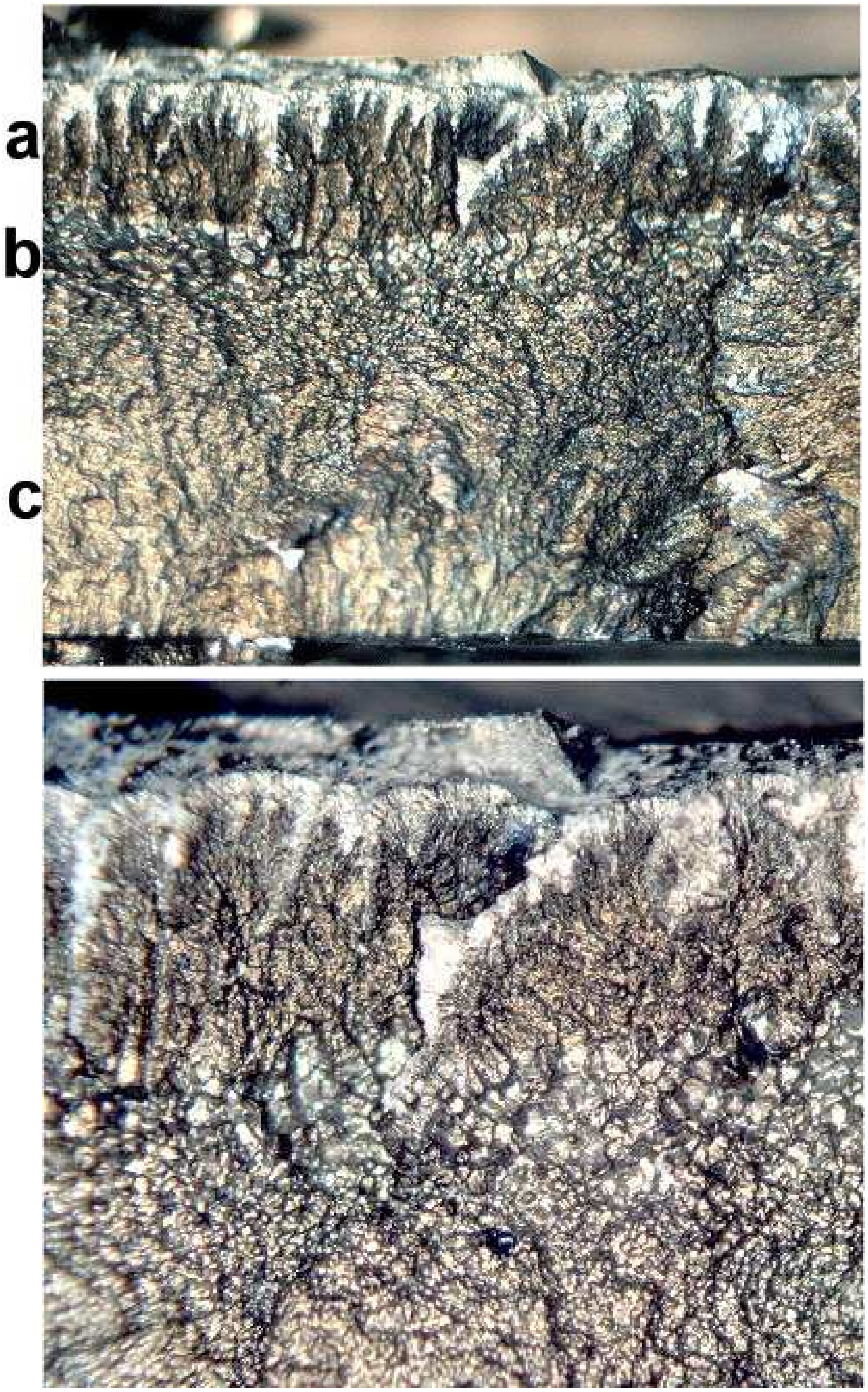


Figure 4a: Stereo microscopic images of a typical fracture surface of one of the LMAC cracks after stripping of the zinc layer with an inhibited hydrochloric acid solution with: (a) transgranular cleavage fracture through the weld metal, (b) an intergranular fracture through the heat affected zone with the grain size increasing towards the weld metal reaching a maximum at the fusion boundary, and (c) an intergranular fracture through the base metal.

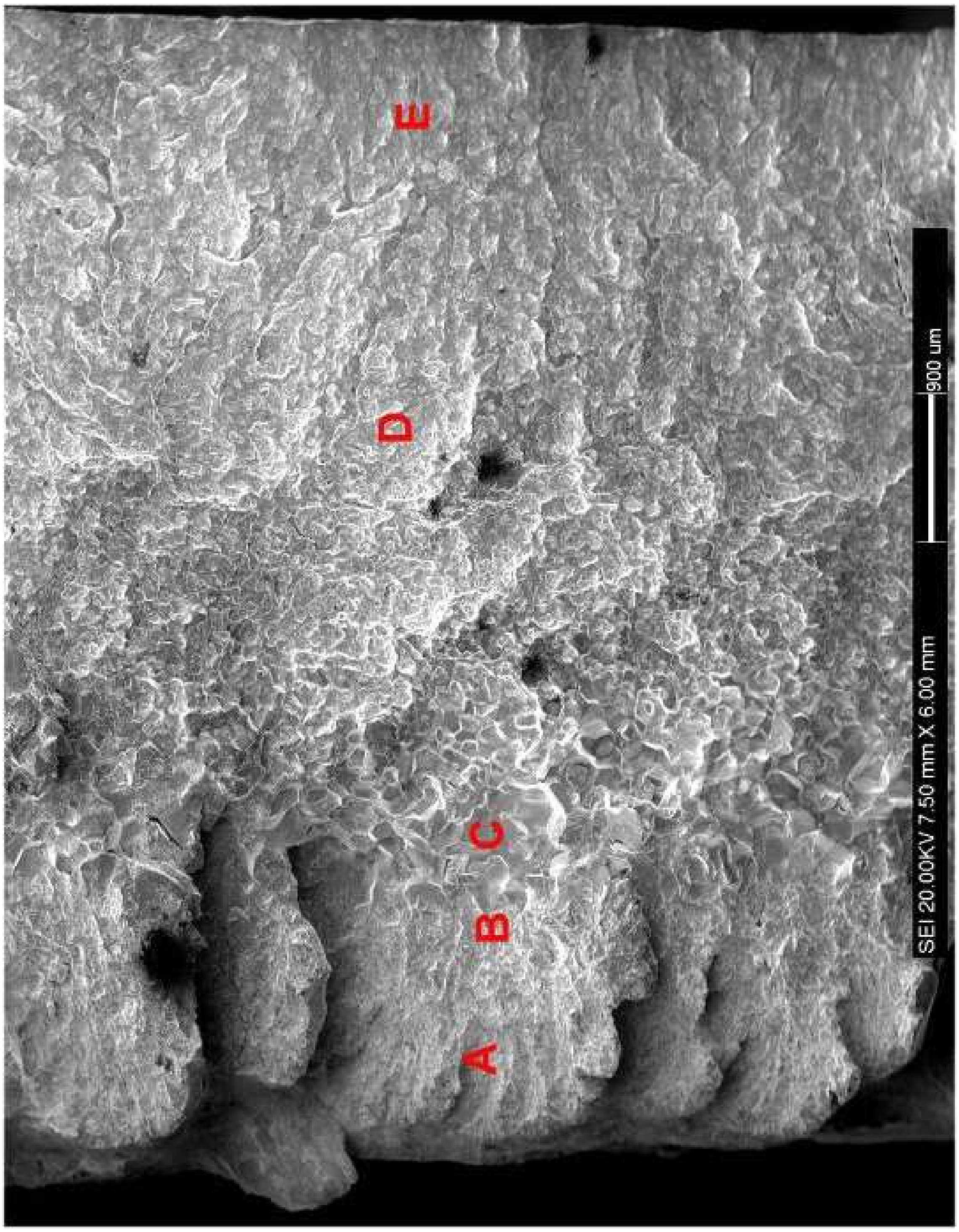


Figure 4b: Secondary electron image of the fracture surface in Figure 4a. Higher magnification images of the fracture surface at A to C are shown in the following figures.

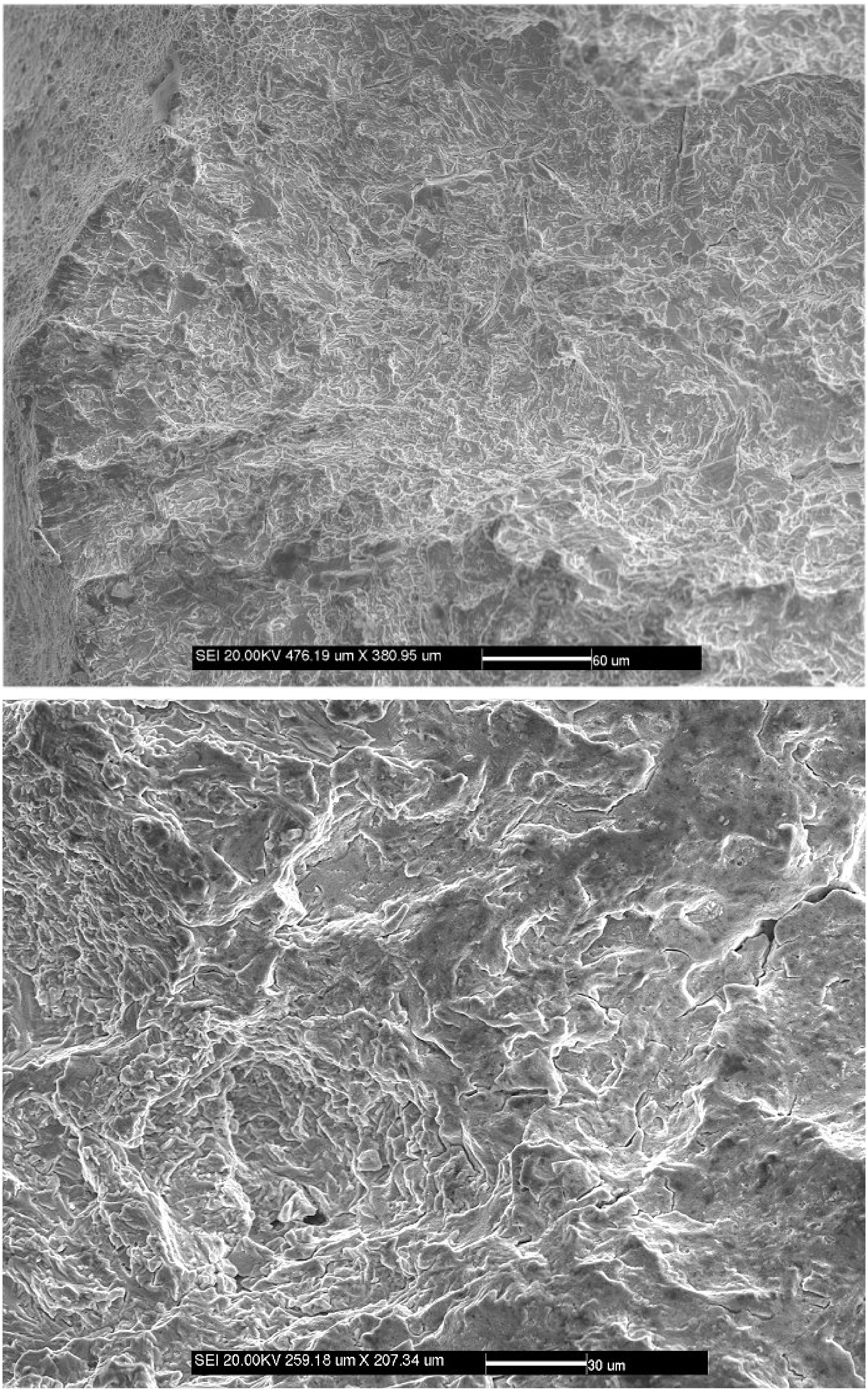


Figure 4c: Secondary electron images of transgranular quasi-cleavage fracture through the weld metal at A in Figure 4b.

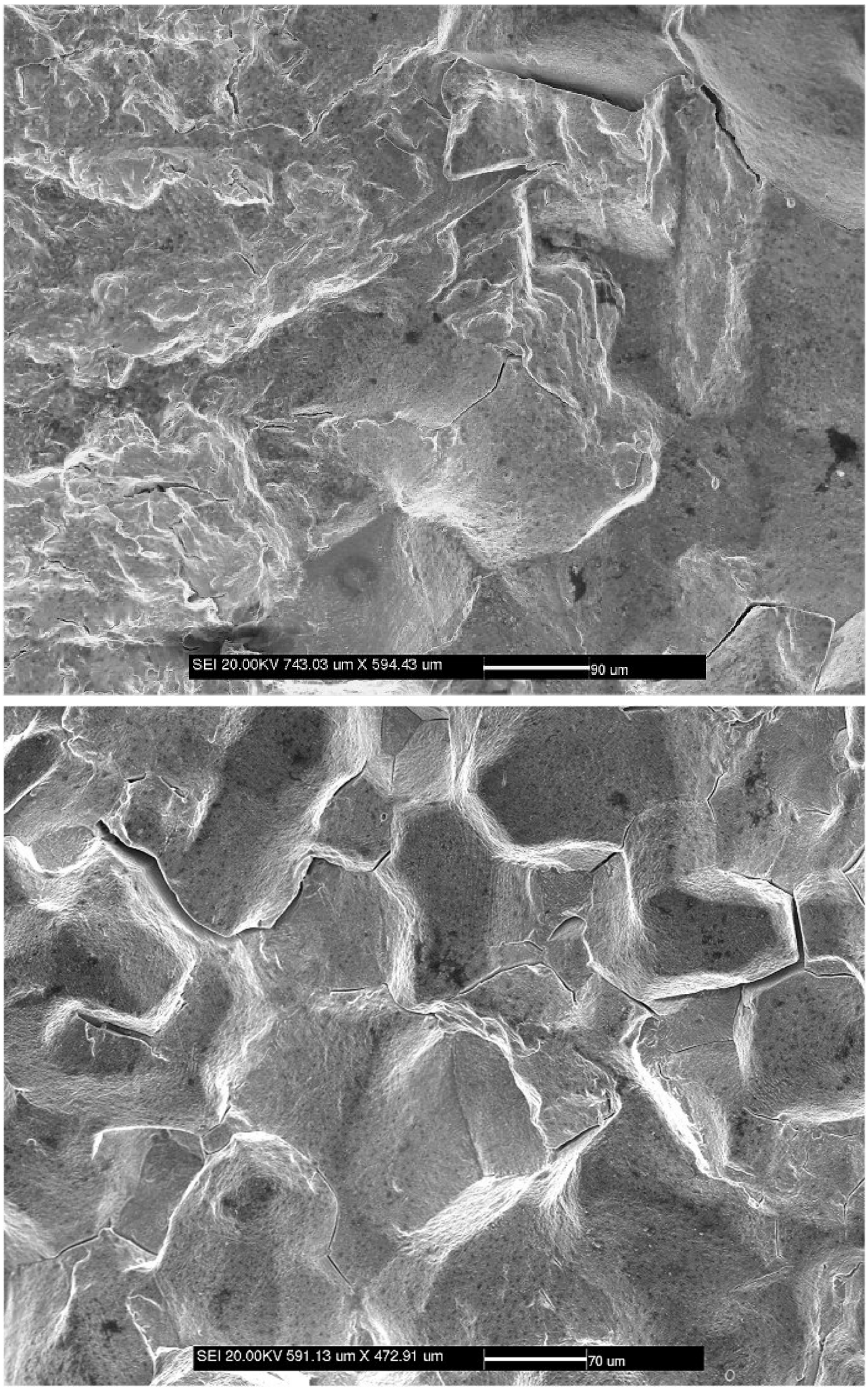
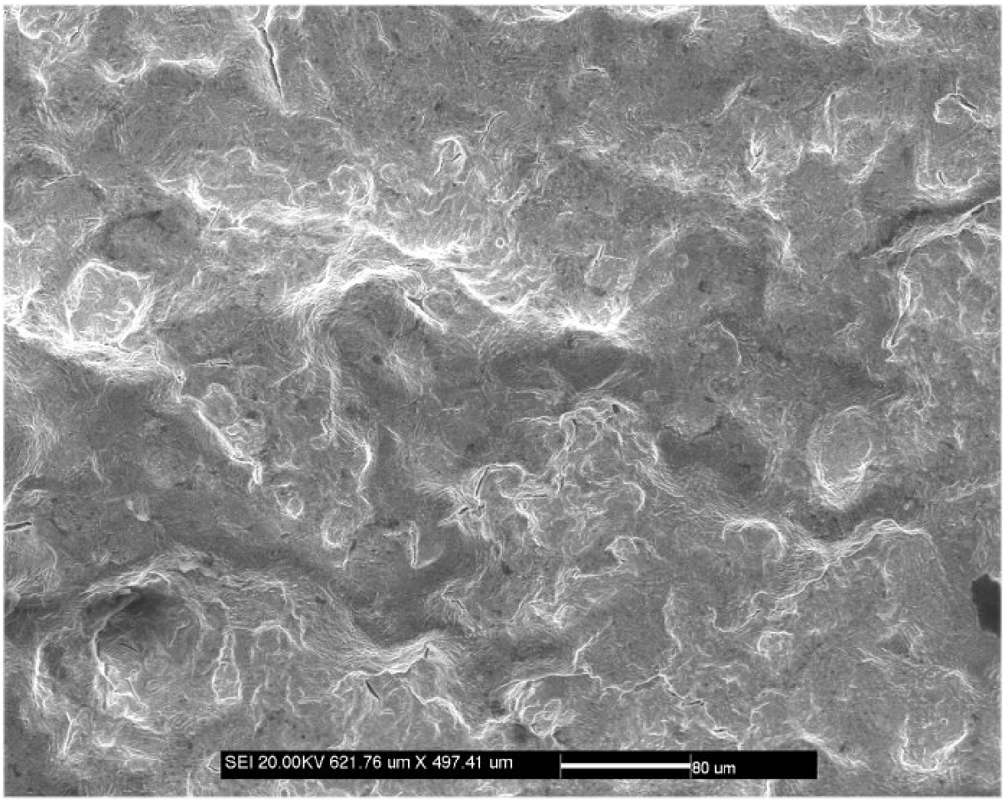


Figure 4d: Secondary electron images of an intergranular LMAC fracture at B (top image) and C (bottom image) through the heat affected zone in Figure 4b. The quasi-cleavage fracture through the weld metal is visible at the left-hand side of the top image.



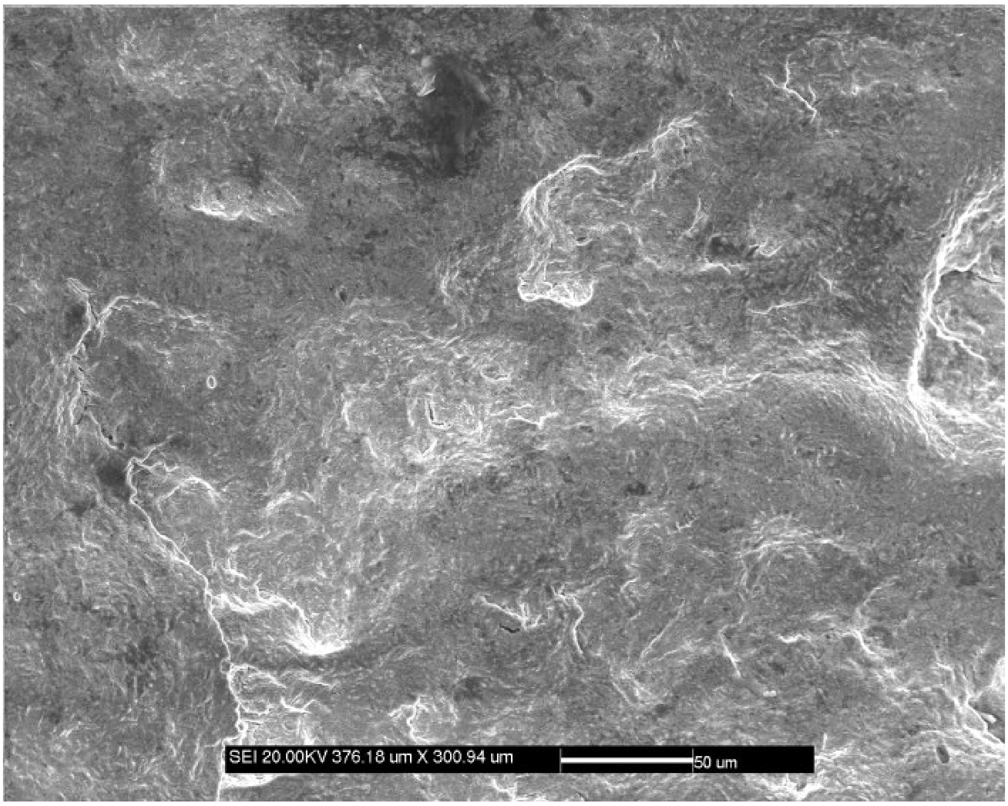


Figure 4e: Secondary electron images of an intergranular LMAC fracture at D (top image) and E (bottom image) through the base metal in Figure 4b. Refer also to the bottom images in Figures 3j and 3k.

2.2 Crack origin

2.2.1 Some of the cracks had initiated in the weld heat affected zones at the toes of some of the fillet welds. Because of a relatively low carbon content and relatively high-heat input during welding, the typical hardness of the heat affected zone at the crack origins was only 243 HV. The typical base metal hardness of the transverse I-beam web was 229 HV.

2.2.2 Some of the crack origins were in stress concentrations in the weld metal next to the fillet weld toes.

2.2.3 Some of the cracks had developed in the unaffected base metal remote from the fillet welds and the weld heat affected zones.

2.3 Crack path

2.3.1 The crack path was transgranular in the weld metal and intergranular in the fillet weld heat affected zones and unaffected base metal.

2.3.2 The development of cracks in the unaffected base metal remote from the fillet weld heat affected zones and intergranular fracture through the low-hardness ferrite-pearlite base metal clearly indicated the fracture mechanism not to be hydrogen-induced cracking, but liquid metal assisted cracking.

2.4 Locations of the cracks on the platform

2.4.1 Cracks had developed at the most highly restrained welded connections.

2.4.2 Cracks had developed at, and in the vicinity of, the connections between the small section size diagonal angle section chords and the much larger section size transverse I-beam chords.

2.4.3 Cracks had not developed at those T-joints between the transverse I-beam chords and longitudinal I-beam chords where diagonal angle section chords had not been welded to the transverse I-beam chords. The joint restraint at these connections was lower.

2.4.4 Many of the diagonal angle section chords had become severely distorted/buckled during hot dip galvanising because the thermal expansion of the angle section chords, having been heated faster than the surrounding larger section I-beam chords, had been restrained by the surrounding larger section transverse and longitudinal I-beam chords.

2.4.5 The welded connections between the diagonal angle section courts and the webs of the transverse I-beam chords had therefore been subjected to substantial additional and dynamic thermally-induced stresses, probably above the yield strength.

2.4.6 The LMAC cracks had therefore developed during hot dip galvanising at welded connections subjected to substantial additional thermally-induced stresses.

3. PROXIMATE CAUSE OF THE DEVELOPMENT OF THE LIQUID METAL ASSISTED CRACKS

3.1 Liquid metal assisted cracking (LMAC) during the hot dip galvanising of especially welded structural steelwork is uncommon and has not yet been addressed in any international specification for hot dip galvanising of welded structural steelwork.

3.1.1 It has been reported by hot dip galvanisers in the United Kingdom, Germany, Japan and the USA.

3.1.2 LMAC is also known as liquid metal embrittlement in the USA.

3.1.3 LMAC is the sudden and rapid brittle fracture of a normally ductile material when subjected to relatively high tensile stresses during direct contact with liquid metal.

3.1.4 After initiation, the cracks can propagate by brittle intergranular or brittle transgranular (cleavage) fracture at speeds of between 10 and 100 cm/second[2].

3.1.5 The fracture surfaces are usually covered with the liquid metal.

3.2 During 2005, the British Constructional Steelwork Association Ltd (BCSA) had published a guideline for managing liquid metal assisted cracking during hot dip galvanising of welded structural steelwork[2].

3.3 BCSA concluded that there are three main prerequisites for LMAC to occur during hot dip galvanising of structural steel, namely:

3.3.1 Relatively high stresses during hot dip galvanising.

3.3.2 A susceptible steel.

3.3.3 Liquid zinc at approximately 450°C.

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[2] *BCSA and GA Publication No. 40/05: "Galvanising Structural Steelwork, An approach to the management of Liquid Metal Assisted Cracking", British Constructional Steelwork Association Ltd, West Minister, London, 2005,*

3.4 Stress level

3.4.1 LMAC during hot dip galvanising is associated with local stresses exceeding the yield stress, i.e., it is associated with localised plastic deformation. The yield stress of structural steel is approximately 50% of the ambient temperature yield strength after being heated to the galvanising temperature of approximately 450°C.

3.4.2 Substantial changes in section size at welded connections are likely to be associated with large thermal stresses when the structure is dipped into the galvanising bath because the smaller section size elements will heat up much faster than the larger section size elements. The small section size diagonal angle section chords had been heated up much faster than the much larger section size longitudinal and transverse I-beam chords on the walkway platforms examined during this investigation.

3.4.3 The thermal expansion of the small section size diagonal angle section chords had also been restrained by the much larger section size longitudinal and transverse I-beam chords. Additional local stresses had therefore been introduced at the fillet welded connections as a result of the resultant distortion/buckling of the angle section chords on the walkway platforms examined during this investigation.

3.4.4 Unnecessary stress concentrations due to poor workmanship and undercut at the toes of fillet welds can also cause increased local stresses at welded connections during hot dip galvanising. The LMAC on the walkway platforms examined was not associated with poor workmanship or undercut at fillet weld toes. It would appear that excessive undercut at the toes of some of the fillet welds had been removed by grinding during fabrication before hot dip galvanising.

3.4.5 Both the first and the modified design of the walkway platforms examined offered a high risk of LMAC because the following features had resulted in abnormal thermally-induced stresses at some of the connection nodes during hot dip galvanising:

(1) The substantial difference between the section size of the diagonal angle section chords and the transverse I-beam chords to which these angle sections had been welded.

(2) The large section size longitudinal and transverse I-beam chords completely restraining the thermal expansion of the diagonal angle section chords.

3.4.6 The designs of both the first and modified walkway platforms did not comply with the guidelines in BCSA and GA Publication No. 40/05 for limiting the risk of LMAC during hot dip galvanising of structural steelwork.

Figure 5: The risk of LMAC at the welded connections associated with the diagonal chord is relatively low because the section size of the diagonal chord is similar to that of the adjacent horizontal and vertical chords and because the rate of heating of the diagonal chord during dipping in the hot dip galvanising bath is likely to be similar to that of the surrounding chords.

3.4.7 The design of the diagonal chord of the steel girder in Figure 5 satisfied the guidelines in document No. 40/05 for limiting the risk of LMAC during hot dip galvanising:

(1) The section size of the diagonal chord is similar to that of the horizontal and vertical chords.

(2) The rate of heating of the diagonal chord is likely to be similar to that of the horizontal and vertical chords during dipping of the girder in the hot dip galvanising bath.

Cracks had not developed at any of the welded connections in any of these girders that had been hot dipped galvanised in the same bath as the walkway platforms with the cracks examined in this report.

3.5 Material susceptibility

3.5.1 The following steel grades have a higher risk of LMAC during hot dip galvanising[2]:

- High-strength quench and tempered steels
- High-strength steel grades with a yield strength greater than 355 MPa
- Cold formed hollow steel sections
- Weathering steels

3.5.2 The walkway platforms had been constructed with low-strength hot-rolled structural steel members with a low risk of LMAC.

(1) The hardness of the I-beam base metal (229 HV) was substantially lower than the recommended threshold value of 270 HV[1]. Even the hardness of the weld heat affected zones was less than 270 HV.

(2) The carbon equivalent of the transverse I-beam (0.40) where the cracks had developed was less than 0.44[3].

[3] *MetLab certificate number 12-2675 A dated 21 May 2012*

3.6 The galvanising process

3.6.1 Double dipping

(1) For very deep components dipping from one side and then from the other side is often necessary, i.e., double dipping. Double dipping can exacerbate thermal stresses or reduce them.

(2) The walkway platforms were very deep components. They had to be galvanised by double dipping with the diagonal angle section chords at the one side of the middle longitudinal I-beam chord completely submerged in the bath during the first dip and the diagonal angle section chords at the opposite side of the middle longitudinal I-beam chord only partially submerged in the bath.

(3) The diagonal angle section chords at the one side of the middle longitudinal I-beam had therefore been subjected to two hot dip galvanising thermal cycles.

(4) The LMAC cracks on the walkway platforms had, however, been associated with diagonal angle section chords at both sides of the middle longitudinal I-beam.

(5) The LMAC of the walkway platforms cannot therefore be attributed to the inevitable double dipping of the relatively deep platforms.

(6) Because the platforms had to be subjected to double dipping during hot dip galvanising, it had been crucial for the design engineer to design the platforms in accordance with international guidelines to ensure a minimum risk for LMAC during hot dip galvanising.

3.6.2 Some researchers are of the opinion that the risk of LMAC can be reduced by limiting the Tin, Lead and Bismuth concentrations in the galvanising bath[4].

(1) The total Tin-and-Lead and Bismuth in the galvanising bath is limited to $\leq$ 1.3% and $\leq$ 0.1% (weight percentage) respectively in Germany.

(2) Using one of the latest energy dispersive x-ray microanalysis spectrometers recently installed on a scanning electron microscope in South Africa, Grobler could not detect any Tin in the Zinc that had penetrated the LMAC cracks.

(3) The average Lead concentration of the Zinc coating on the walkway was found to be less than 1.3%. The high Lead particle content of the zinc in the LMAC crack close to the end of the crack detected during back scattered imaging (cf. Figure 3i) is attributed to the fact that the lead in the liquid zinc had not reacted with the steel surface and that it had therefore accumulated as a result of the reaction of the zinc with fracture surfaces of the propagating crack.

3.6.3 Robor Galvanisers had galvanised large tonnages of structural steelwork for many years without LMAC. A large amount of structural steelwork had also been galvanised during the period between the first LMAC of the first walkway platform and the second walkway platform with the modified design. Had the composition of the galvanising bath, or the galvanising method been the main cause of the LMAC of the walkway platforms, many of the structural steelwork hot dip galvanised before and after these walkway platforms in the same galvanising bath should also have incurred LMAC.

[4] *BCSA and GA Publication No. 40/05: "Galvanising Structural Steelwork, An approach to the management of Liquid Metal Assisted Cracking", British Constructional Steelwork Association Ltd, West Minister, London, 2005*

3.7 Proximate cause of LMAC of specific connection nodes on the walkway platforms

3.7.1 The evidence indicates the design of the perimeter walkway platforms to be the main factor triggering LMAC during hot dip galvanising.

3.7.2 The large difference in this section size of the diagonal angle section chords and the surrounding I-beam chords had resulted in abnormal thermally-induced stressing of the welded connections between the angle section chords and transverse I-beam chords of the platforms.

3.7.3 The design of the walkway platforms did not satisfy international guidelines for minimising the risk of LMAC during hot dip galvanising of structural steelwork.

(This is an electronic transmission and is therefore left unsigned)

Dr Christo Grobler Pr Eng