Appendix K: Metallographic Examination of Samples from GRW Tanker J3564

1 Overview

In order to provide experimental measurements and observations to supplement the analytical calculations and engineering critical assessment of the GRW circumferential seam welds, TWI has undertaken macro- and microscopic examination of several samples taken from GRW tankers.

2 Objectives

- Non-destructively examine sections to determine the presence and extent of lack of fusion indications.
- Destructively examine sections in order to:
  - Characterise the defect morphology (eg volumetric or crack-like) at the locations of lack of fusion indications;
  - Measure the defect lengths and depths;
  - Measure the local joint geometry to provide additional measurements for the ECA calculations;
  - Observe and measure any evidence of fatigue crack growth or ductile tearing;
  - Provide comprehensive post-mortem examination of sections from tankers subjected to topple testing by HSL.

3 Scope of Work

TWI received weld samples from various tankers: J3910, J2580, J3564 and J3217. The location where each sample was extracted from (and the associated TWI ID) is shown in Table K1.

All samples were photographed on arrival and subjected to radiography. When appropriate, dye penetrant examination was also undertaken. Metallographic examination was performed for each sample and the exact actions performed are listed in the sections below.

This appendix specifically addresses the examination of sections from J3564.

4 Samples from J3564

4.1 Description of samples

Sections from the cradle position of bands C, D and G of GRW tanker J3564 were removed and sent to TWI. These samples are located in positions where the fatigue stresses are likely to be relatively high and therefore the main objective of the examination of these samples was to identify whether there was any evidence of fatigue crack growth. Additionally, the circumferential length of these specimens means that they could be subjected to impact under a roll over event. Each of the three sections was sectioned at approximately 100mm intervals and macros were prepared of the cross-section. Table K2 describes the positions of each of the macros that are presented. This table can be cross-referenced with Table K1 for reference to the specific band from which the section was obtained.

In addition to the cradle weld sections, a large section (approximately 1800mm long) from the nearside rear weld was removed and sent to TWI.

4.2 Sample J3564 W03-04 Band C

For this sample, W03 refers to the front-side weld (left hand side in the figures) and W04 refers to the rear-side weld (right hand side in the figures). All prepared macro samples are shown in Figures K2-K9.

Figure K5 is of particular interest. The weld on the left side shows a 2.19mm crack-like, surface-breaking defect is present. This is a significant defect and arises purely as a result of lack of fusion and not fatigue. The right hand side (rear-side weld) shows a 1.62mm crack-like, surface-breaking flaw is present. Again, this defect arises purely as a result of lack of fusion and not fatigue.

These defects are present in slice 4, but either side of this macro (slice 3 and slice 5), only a gas pore is present where the crack-like defect appears in slice 4. Further sectioning of the macro-section was undertaken and the results are shown in Figure K6. In this figure, it can be seen that, up to a 10mm resolution of the length, both flaws are at least 40mm in length and no more than 50mm in length. Additionally, the further sectioning revealed that on the side containing the 1.62mm deep flaw, there was a deeper point along the length, with the maximum observed depth equal to 2.04mm.

These crack-like defects are not located directly at the positioner lip, as was the defect that led to rupture in J2580. An additional study to clarify the acceptability of these defects was undertaken and is described in Appendix M.

4.3 Sample J3564 W05-06 Band D

For this sample, W05 refers to the front-side weld (right hand side in the figures) and W06 refers to the rear-side weld (left hand side in the figures). All prepared macros are shown in Figures K10-K17.

The samples prepared from Band D did not contain any significant crack-like defects such as those found in the samples prepared from Band C. However, there are several lack of root fusion and lack of side wall fusion, embedded-type defects and some significant porosity. Although porosity is expected when welding the specific aluminium alloys in this joint, some of the gas pores have diameter nearly equal to the fillet weld throat thickness, which may negate the strengthening influence of the internal fillet weld under rollover. Additionally there are some macros that exhibit large amounts of misalignment.

4.4 Sample J3564 W07-08 Band G

For this sample, W07 refers to the front-side weld (left hand side in the figures) and W08 refers to the rear-side weld (right hand side in the figures). All prepared macros are shown in Figures K18 to K25.

The samples prepared from Band G did not contain any significant crack-like defects such as those found in the samples prepared from Band C. However, there are several lack of fusion, embedded-type defects and some significant porosity.

4.5 Sample from the rear end weld

The large section of the rear end weld provided to TWI is shown in Figure K1. The objectives of the metallographic examination of samples removed from this section were to:

- Analyse the circumferential weld to identify additional finite length flaws.
- Analyse the rim joint weld (further described in Appendix O).

The macrographs prepared from samples 01 to 05 from the rear weld are shown in Figures K26 to K30. Of particular significance are the following:

- The micrograph taken of the rim joint root in Figure K26 (micrograph "A") shows evidence of a similar lack of root fusion defect as discussed in Appendix O. This has the potential to lead to rupture of the rim joint weld throat during topple test conditions.
- The micrograph taken of the positioner lip in Figure K26 (micrograph "B") shows the existence a previous weld bead or evidence of a similar external tack weld that gave rise to the finite length flaw previously discussed. Whilst this external tack weld is not adjacent to an additional internal fillet weld, there is better fusion/penetration at this joint (compared to Figures K5 and K6) and therefore there is no offset surface-crack. The positioner lip defect is still present, but is small.
- The micrograph taken of the rim joint root in Figure K29 shows another lack of root fusion defect. There is some evidence of potential fatigue crack growth from the defect

4.6 Conclusions from examination

The following conclusions were reached following analysis of the samples prepared from sections removed from J3564

- One section exhibited crack-like, surface-breaking defects, 1.62mm and 2.19mm in height. Further sectioning revealed that the lengths of these defects were between 40mm and 50mm. The additional sectioning revealed that on the side containing the 1.62mm defect, there was a deeper point of the flaw, with the maximum observed depth equal to 2.04mm.
- A large number of samples exhibited significant porosity. The fillet weld joining the internal bulkhead to the extrusion band typically contained the largest gas pores. However, the internal fillet welds also contained large gas pores. In some cases, the diameter of the gas pores was nearly equal to the weld throat thickness. Such a pore could considerably weaken the beneficial influence of having the internal fillet weld present under rollover.
- A large number of lack of side wall fusion flaws were observed. These were either isolated lack of fusion, embedded-type defects or occurred in the vicinity of other lack of side wall fusion defects or gas pores.
- Examination of the rear weld showed some evidence of potential fatigue crack growth from a lack of root fusion defect in the rim joint weld.

5 Analysis of Weld Dimensions

The weld cap height and misalignment were measured on all macros prepared from J3564 and J3910. Additionally, HSL provided laser scan data for all bands (both offside and nearside) for J3910. A scatter data plot, showing the pairs of weld cap height and misalignment measurements is shown in Figure I99. There is no clear trend present in this figure. That is, there does not appear to be a strong relationship between weld cap height and misalignment. The non-dimensional geometry parameter, β, as described in the main report, is shown in Figure I100. This histogram was developed from the J3910 and J3564 measurements shown in Figure I98. There is a near-Gaussian type distribution of β-values, with approximately 40% of the values falling between 0.35 and 0.4. Using the fatigue life look-up table in the main report (and taking into consideration the built-in conservatism due to membrane-only loading), the estimated fatigue life would be in excess of 15 years.

Table K1 Samples received

TWI Sample ID	Tanker	Position	Weld length (mm)
W02	J3910	Band A O/S (impacted)	1450
W03	J3564	Band C O/S front weld	745
W04	J3564	Band C O/S rear weld	745
W05	J3564	Band D N/S front weld	840
W06	J3564	Band D N/S rear weld	840
W07	J3564	Band G O/S front weld	820
W08	J3564	Band G O/S rear weld	820
W09	J2580	Band H O/S (impacted)	1650
W10	J2580	Band H N/S	1660

Table K2 J3564 macro slice positions

Macro	Location (approx. distance from top of sample in mm)
W03-01	50
W03-02	160
W03-03	250
W03-04	350
W03-05	450
W03-06	550
W03-07	650
W05-01	50
W05-02	150
W05-03	250
W05-04	350
W05-05	450
W05-06	550
W05-07	650
W05-08	750
W07-01	50
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W07-03	250
W07-04	350
W07-05	450
W07-06	550
W07-07	650
W07-08	750

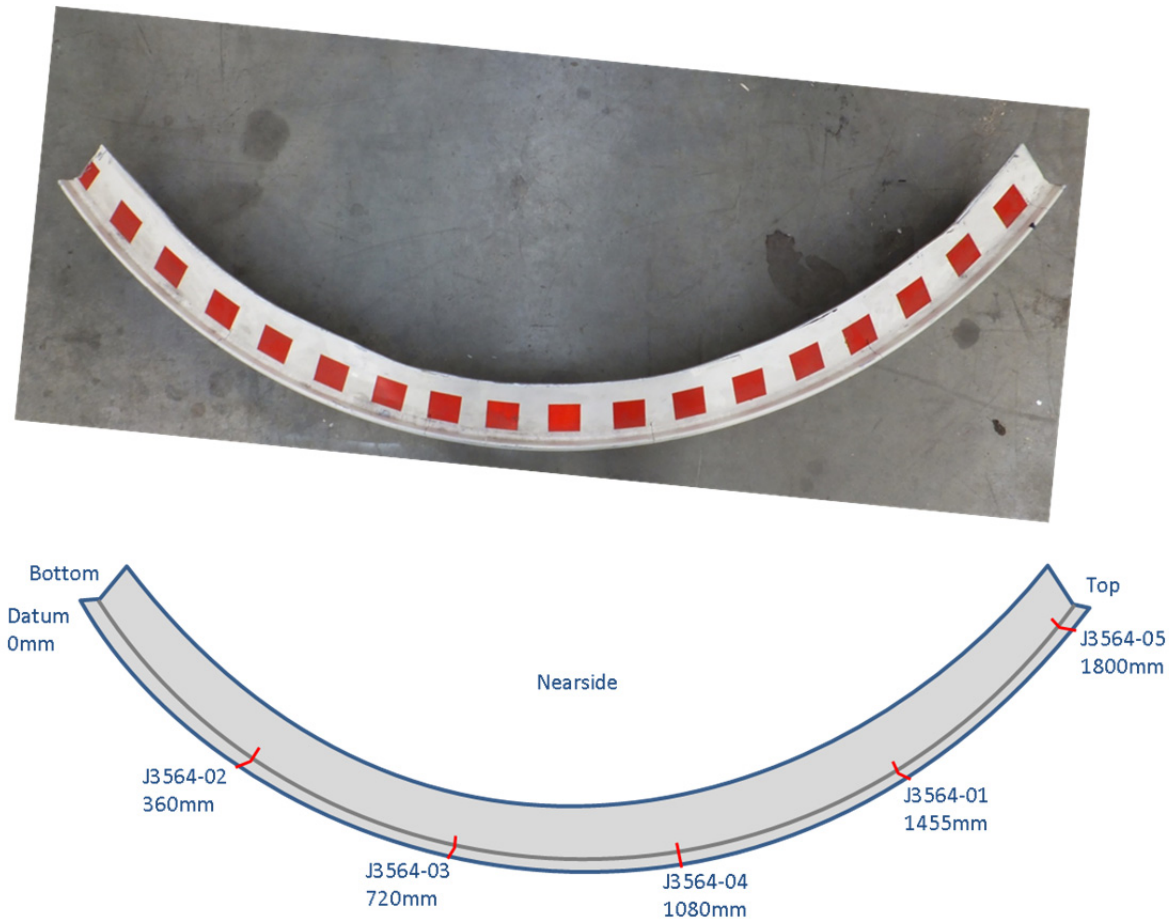

Figure K1 Image of the rear weld section sent to TWI and a diagram showing the location of additional sampling.

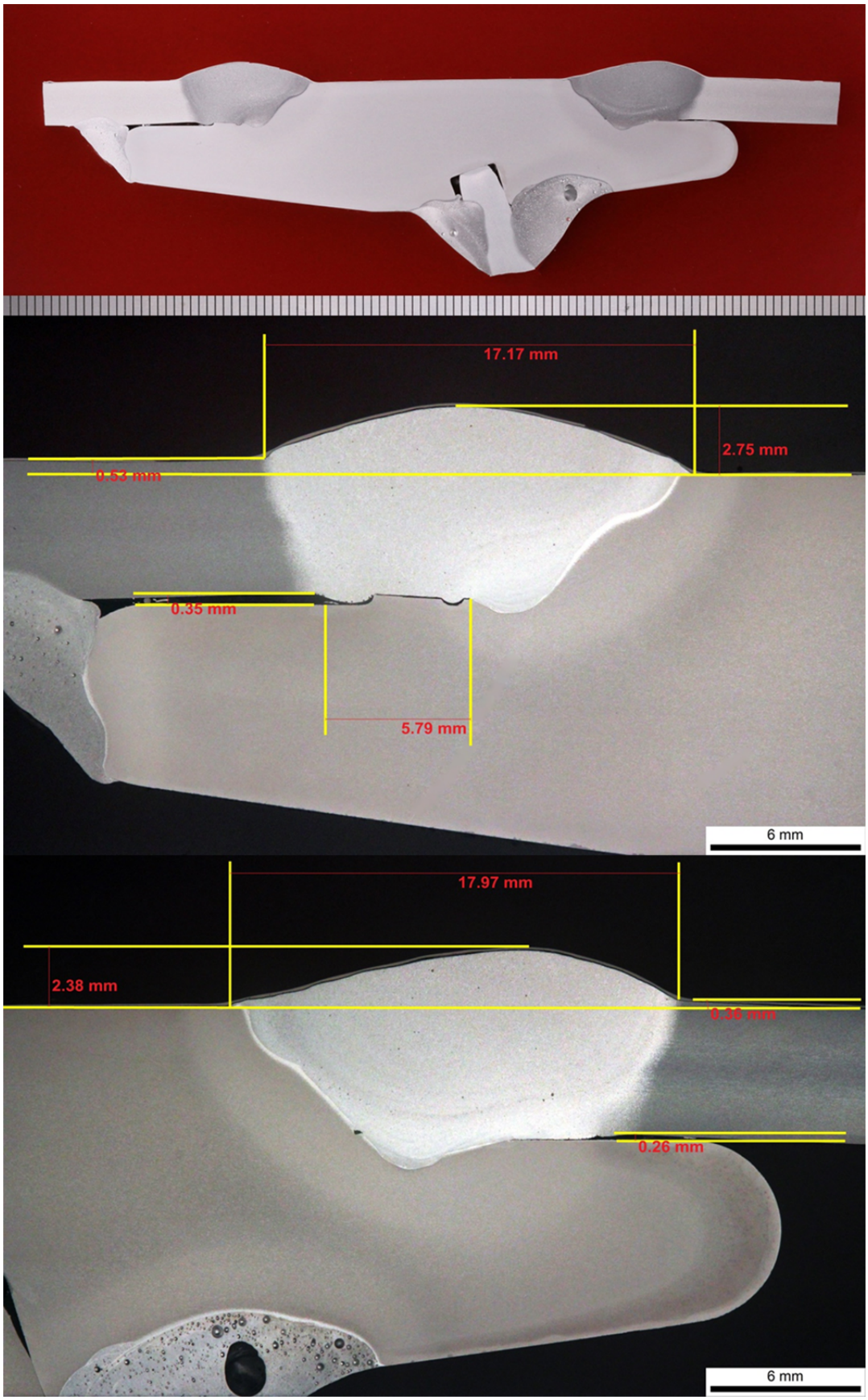

Figure K2 J3564 sample W03-04, slice 1.

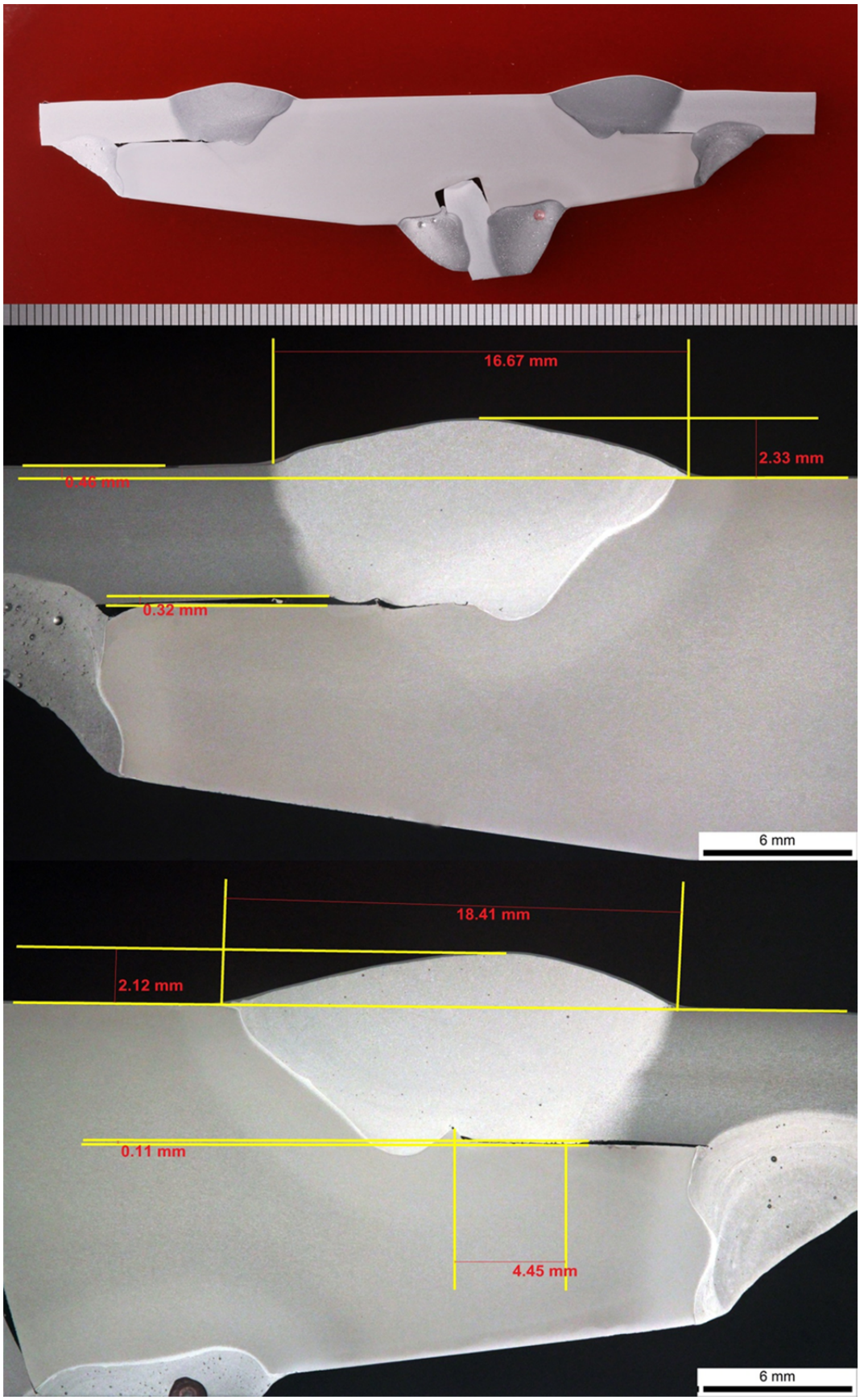

Figure K3 J3564 sample W03-04, slice 2.

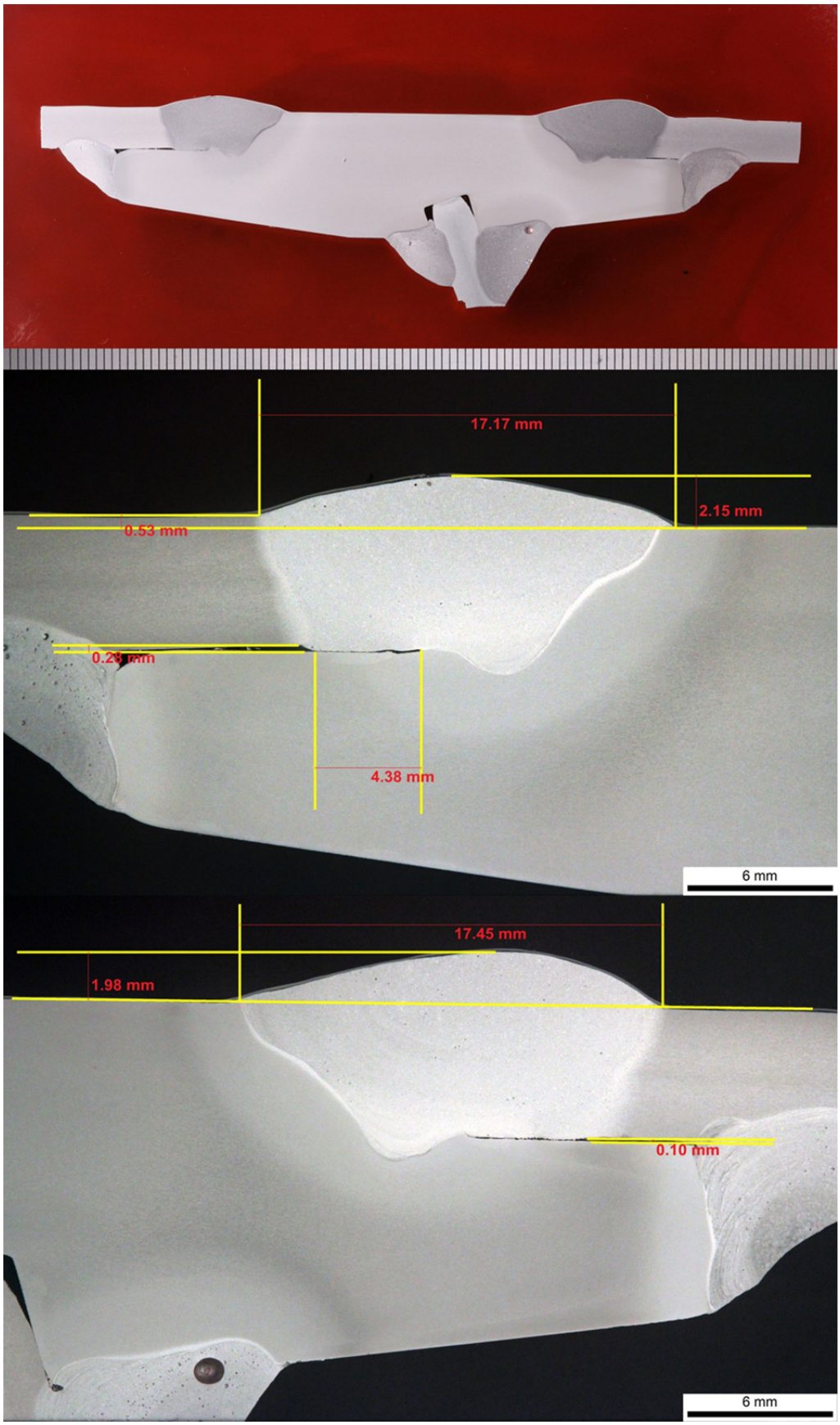

Figure K4 J3564 sample W03-04, Slice 3.

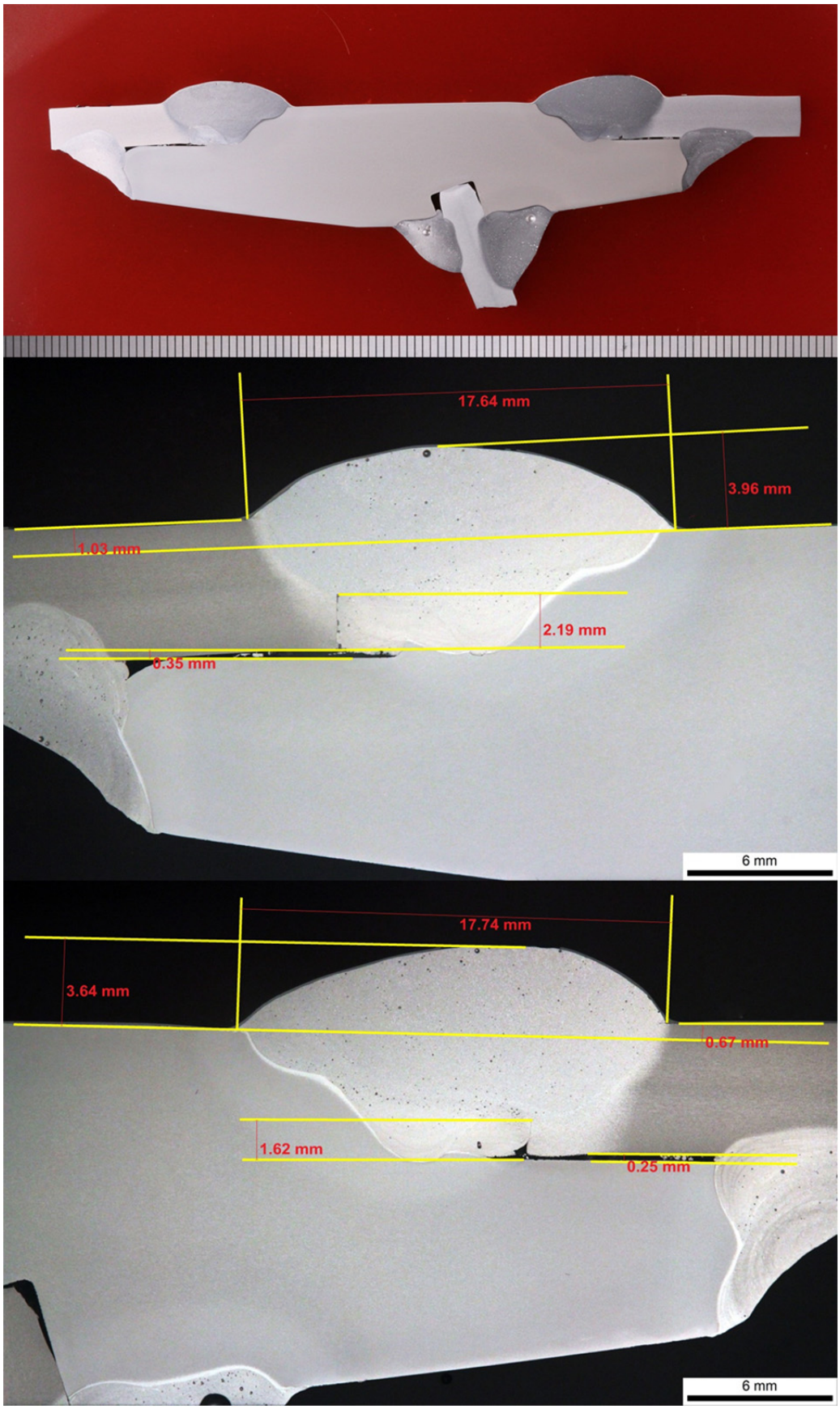

Figure K5 J3564 sample W03-04, slice 4.

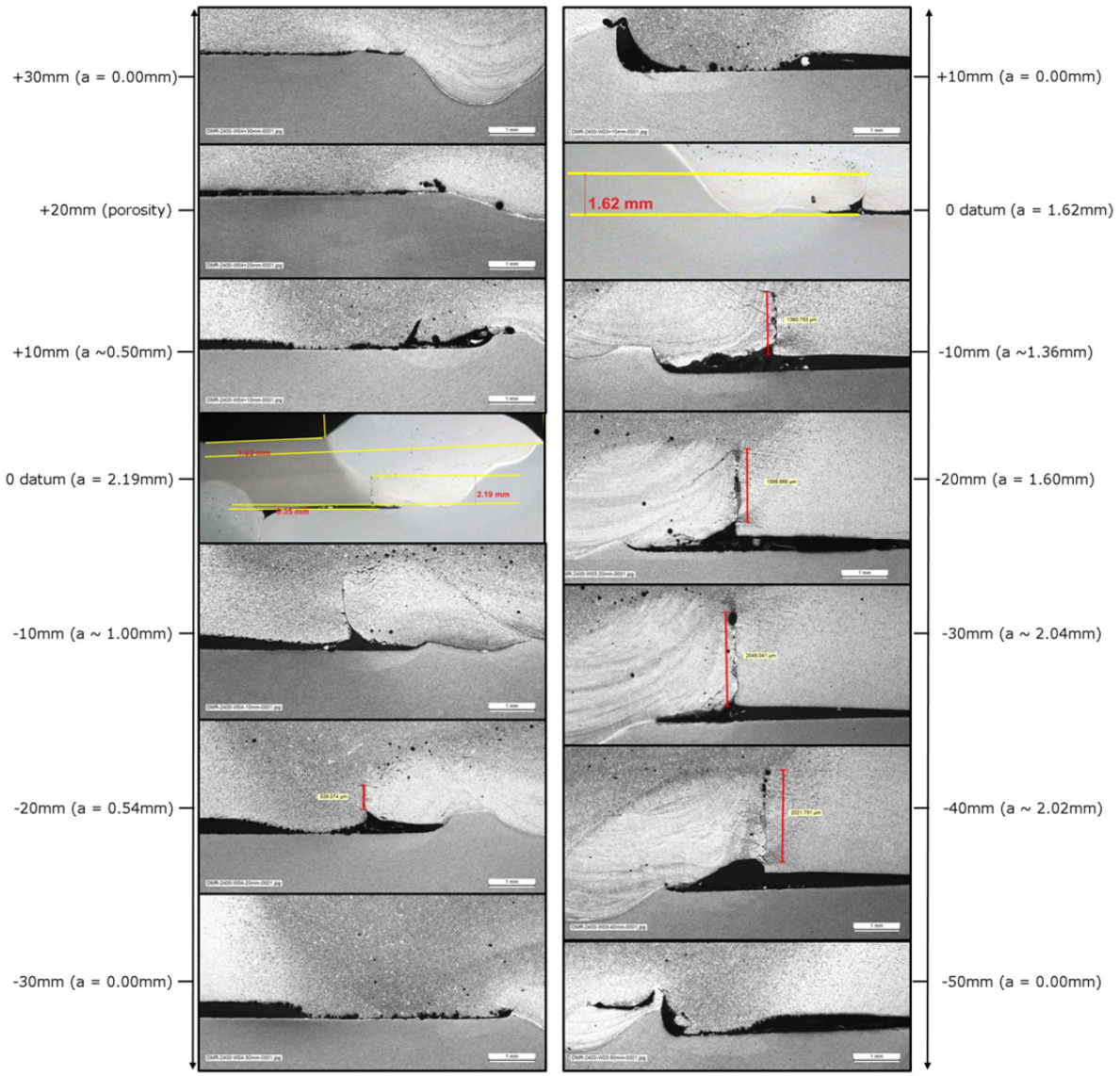

Figure K6 Illustration of the additional sectioning of the sample from J3564 that contained the 2.19mm and 1.62mm defects.

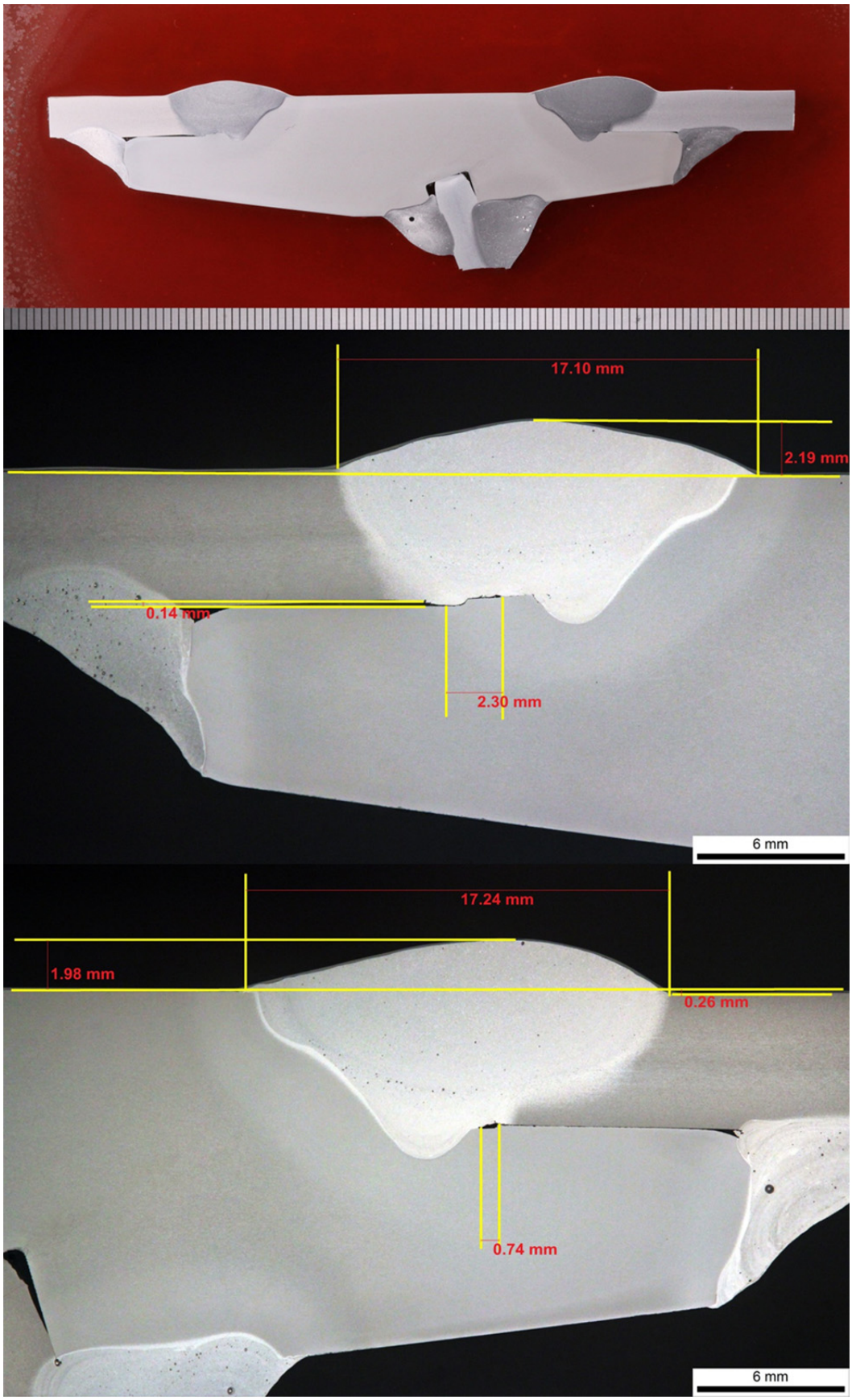

Figure K7 J3564 sample W03-04, slice 5.

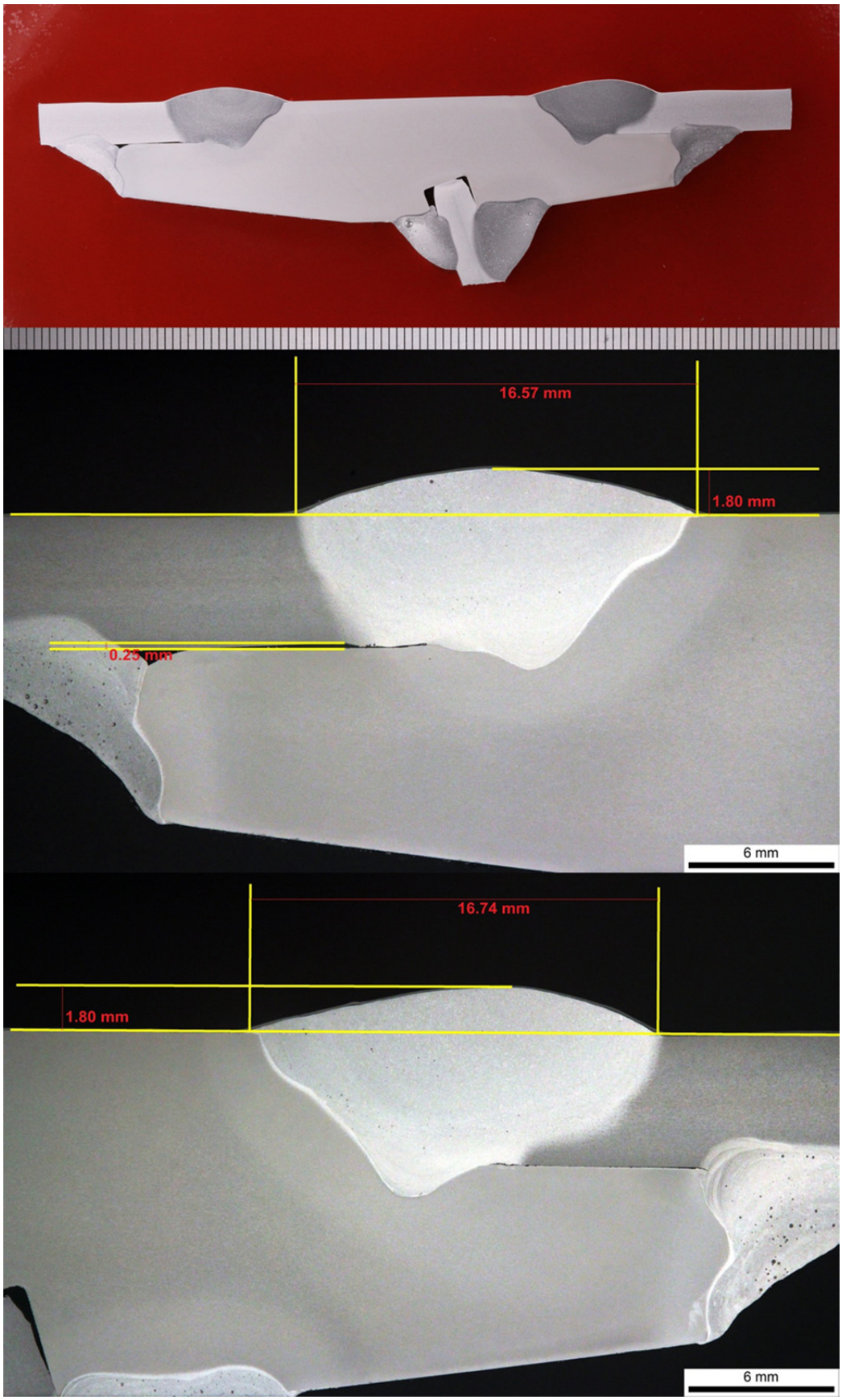

Figure K8 J3564 sample W03-04, slice 6.

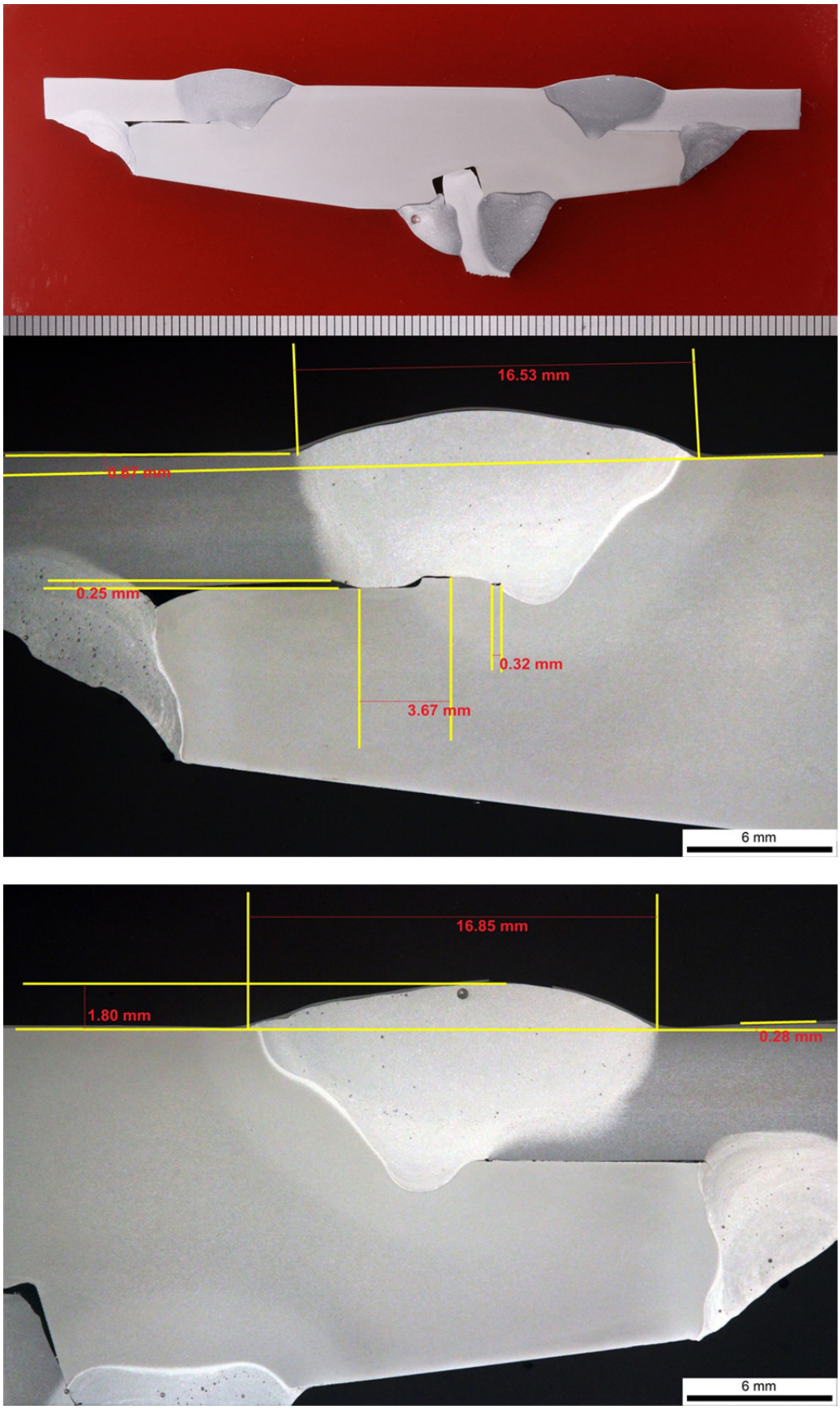

Figure K9 J3564 sample W03-04, slice 7.

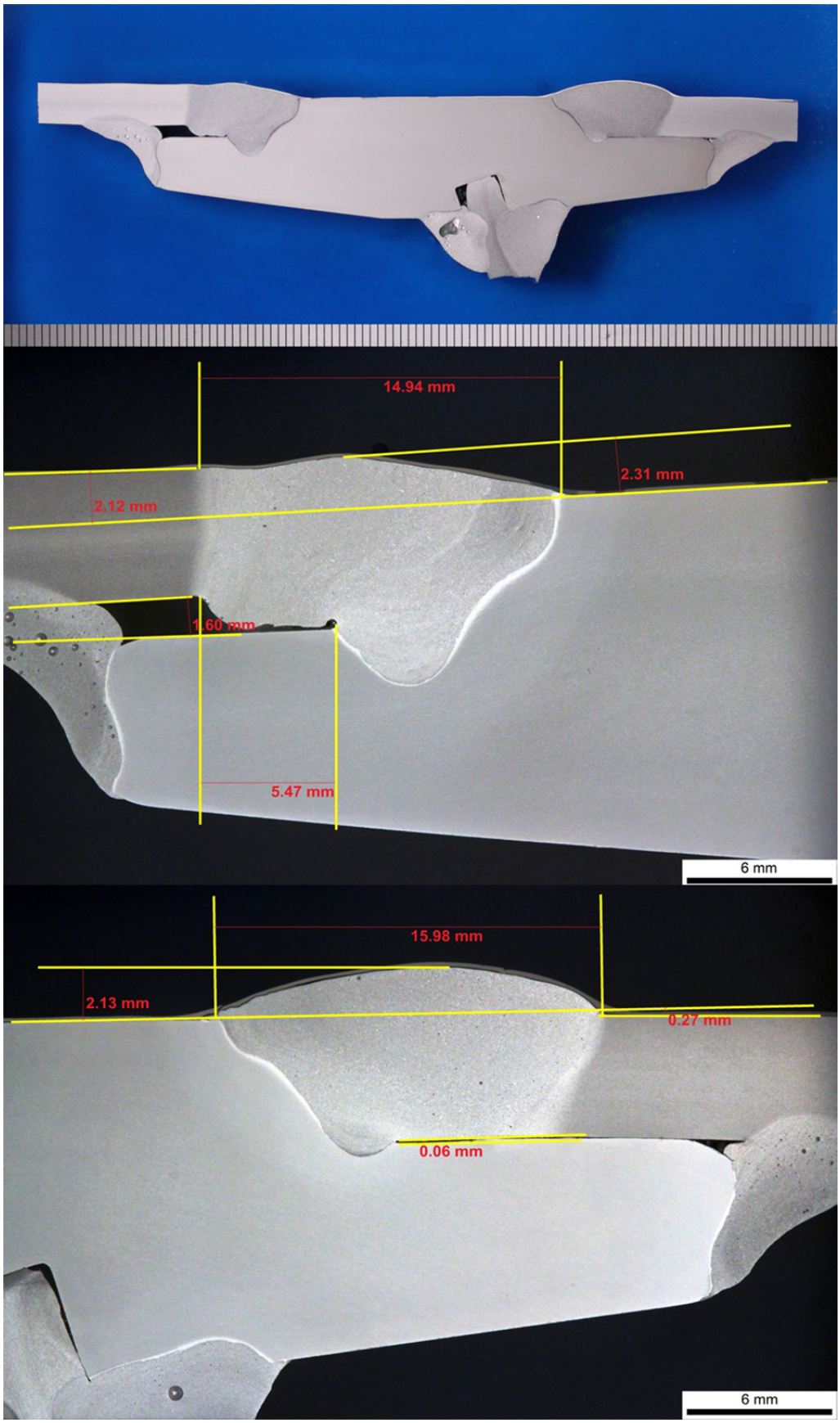

Figure K10 J3564 sample W05-06, slice 1.

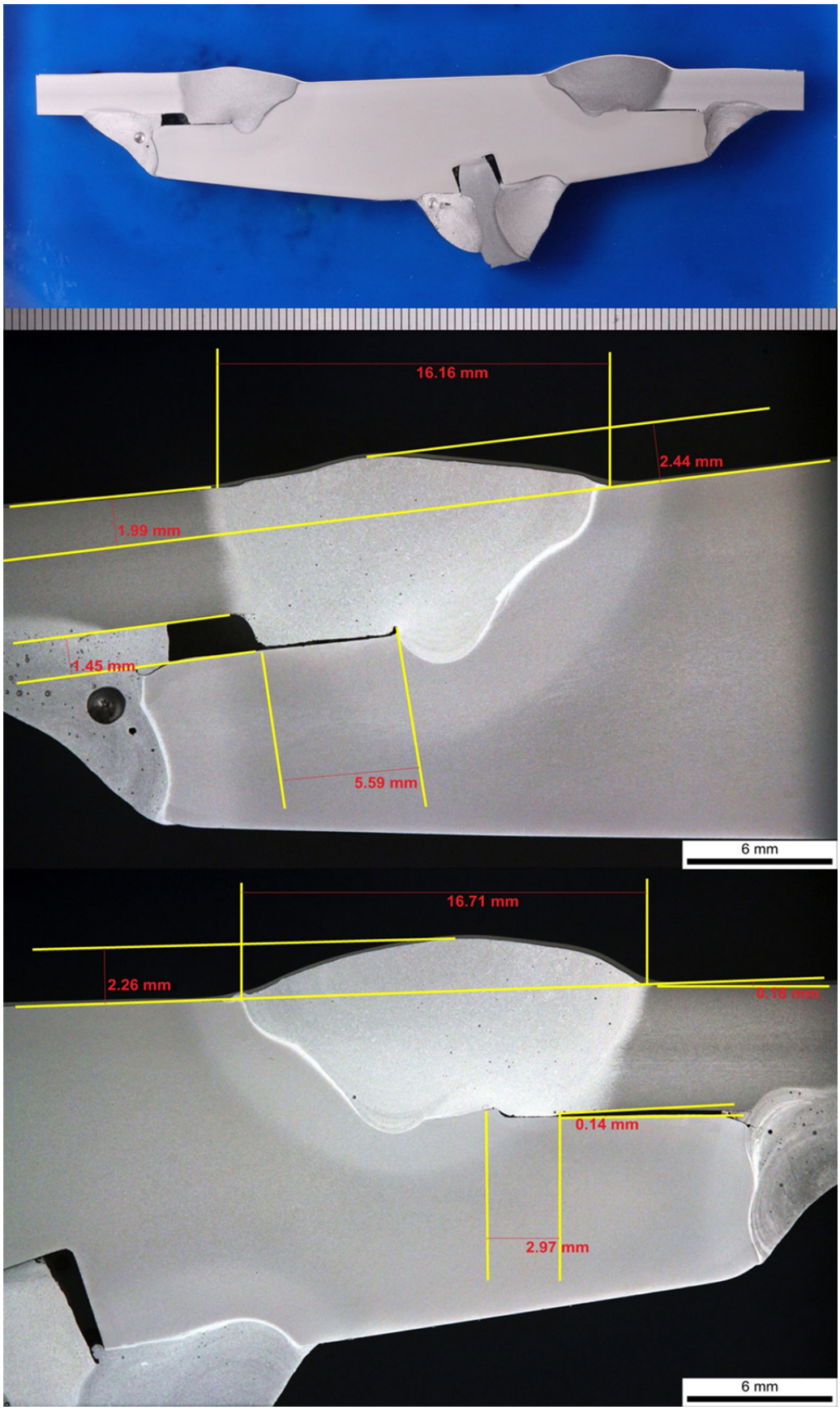

Figure K11 J3564 sample W05-06, slice 2.

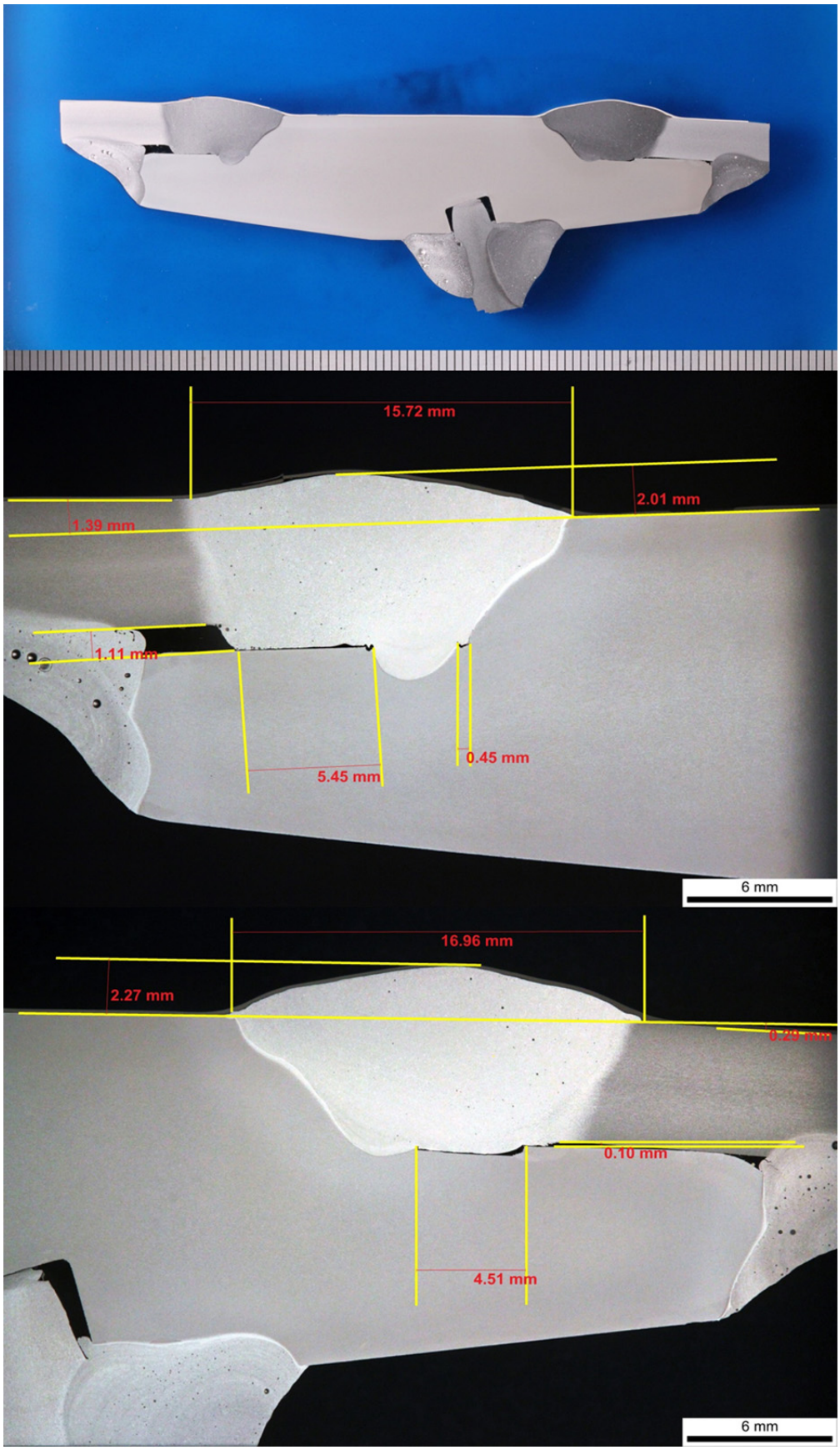

Figure K12 J3564 sample W05-06, slice 3.

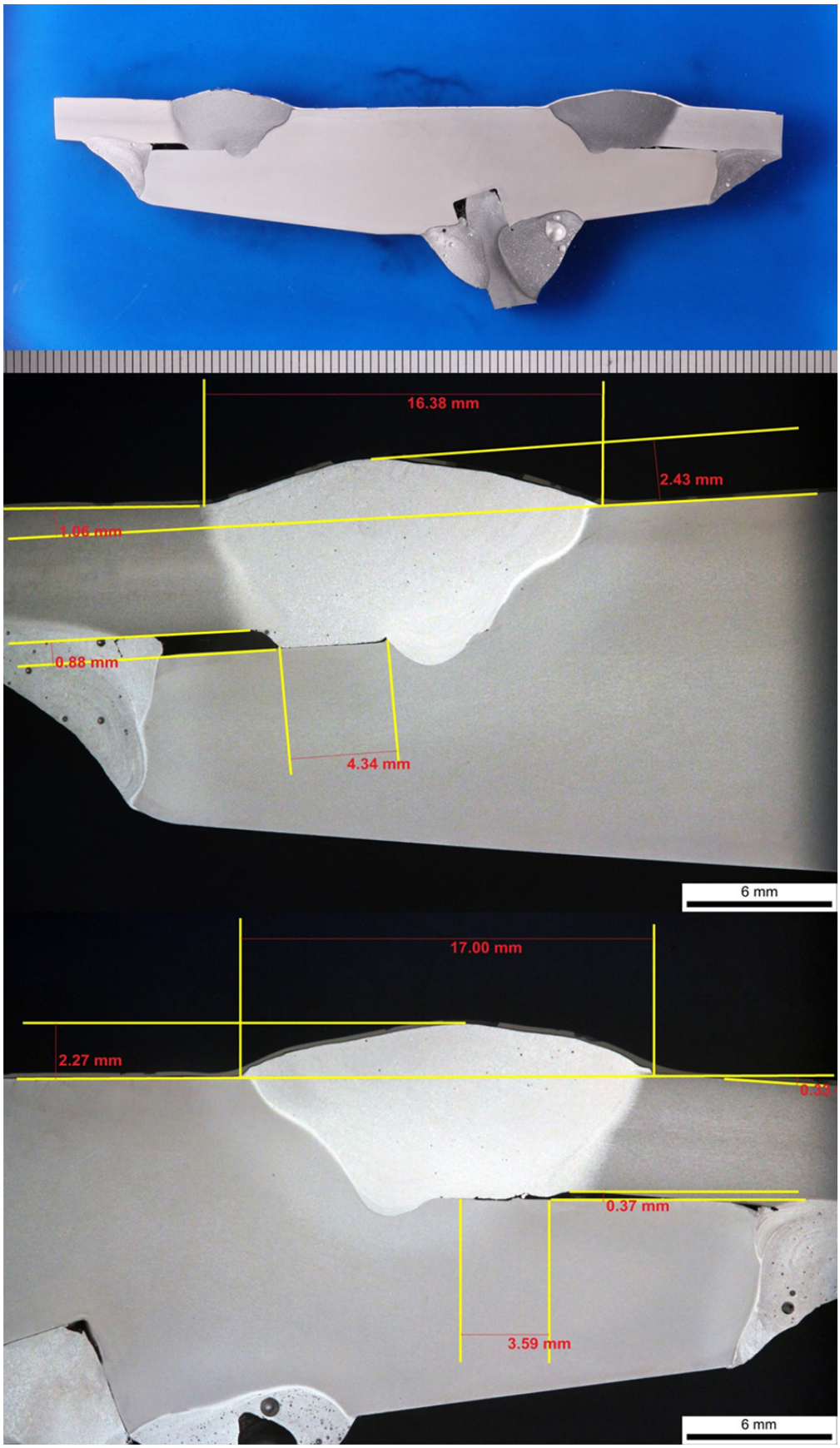

Figure K13 J3564 sample W05-06, slice 4.

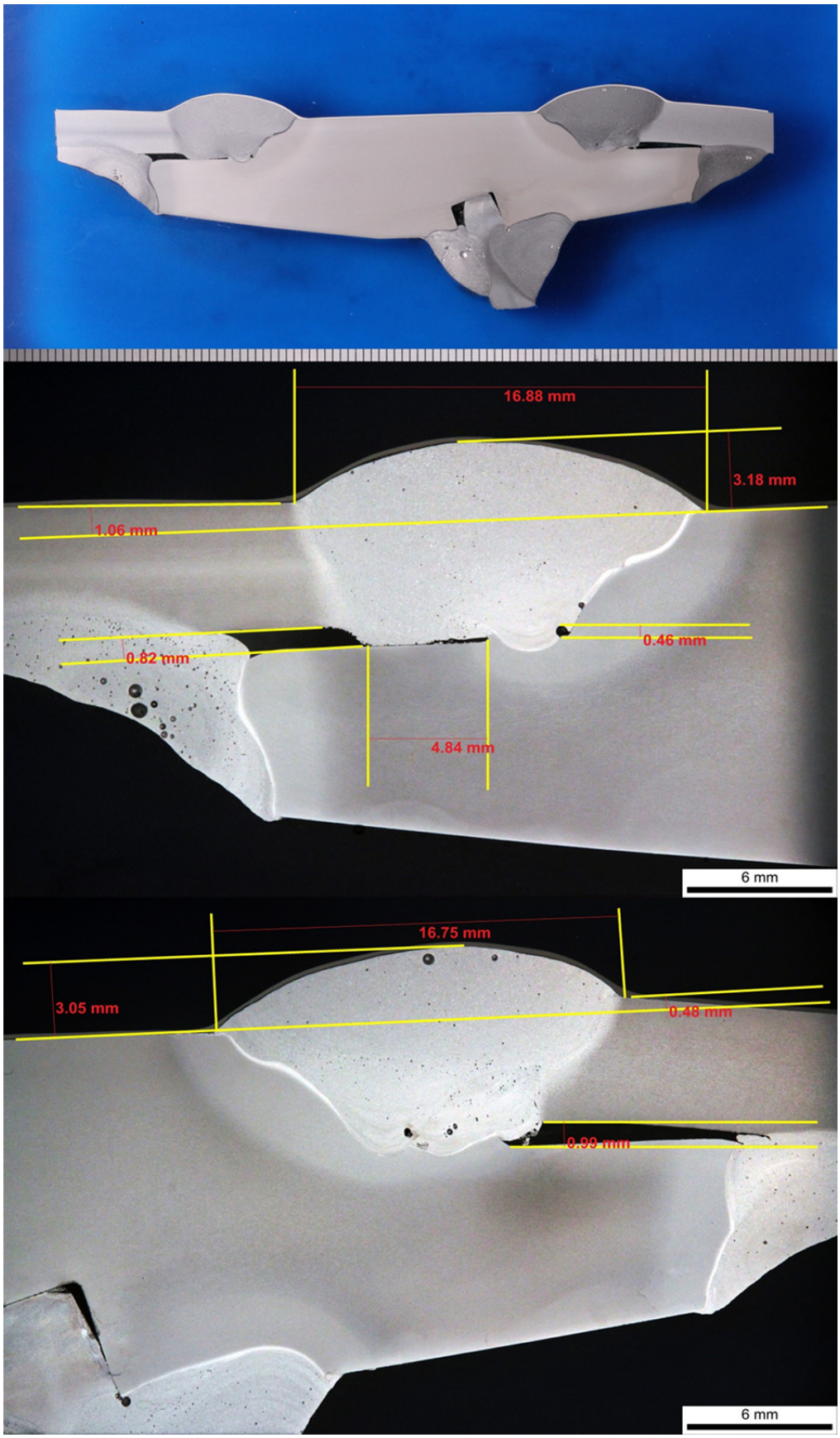

Figure K14 J3564 sample W05-06, slice 5.

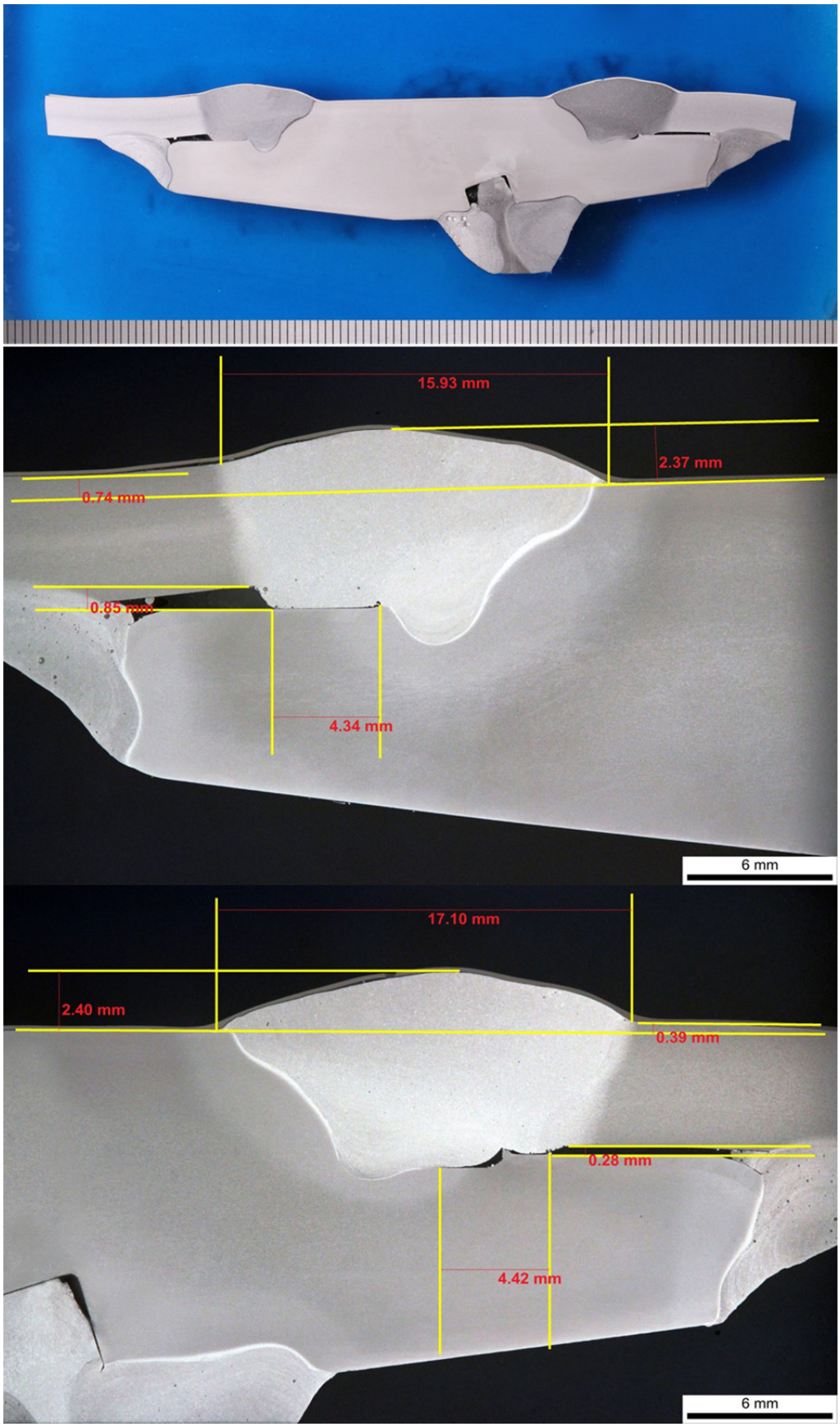

Figure K15 J3564 sample W05-06, slice 6.

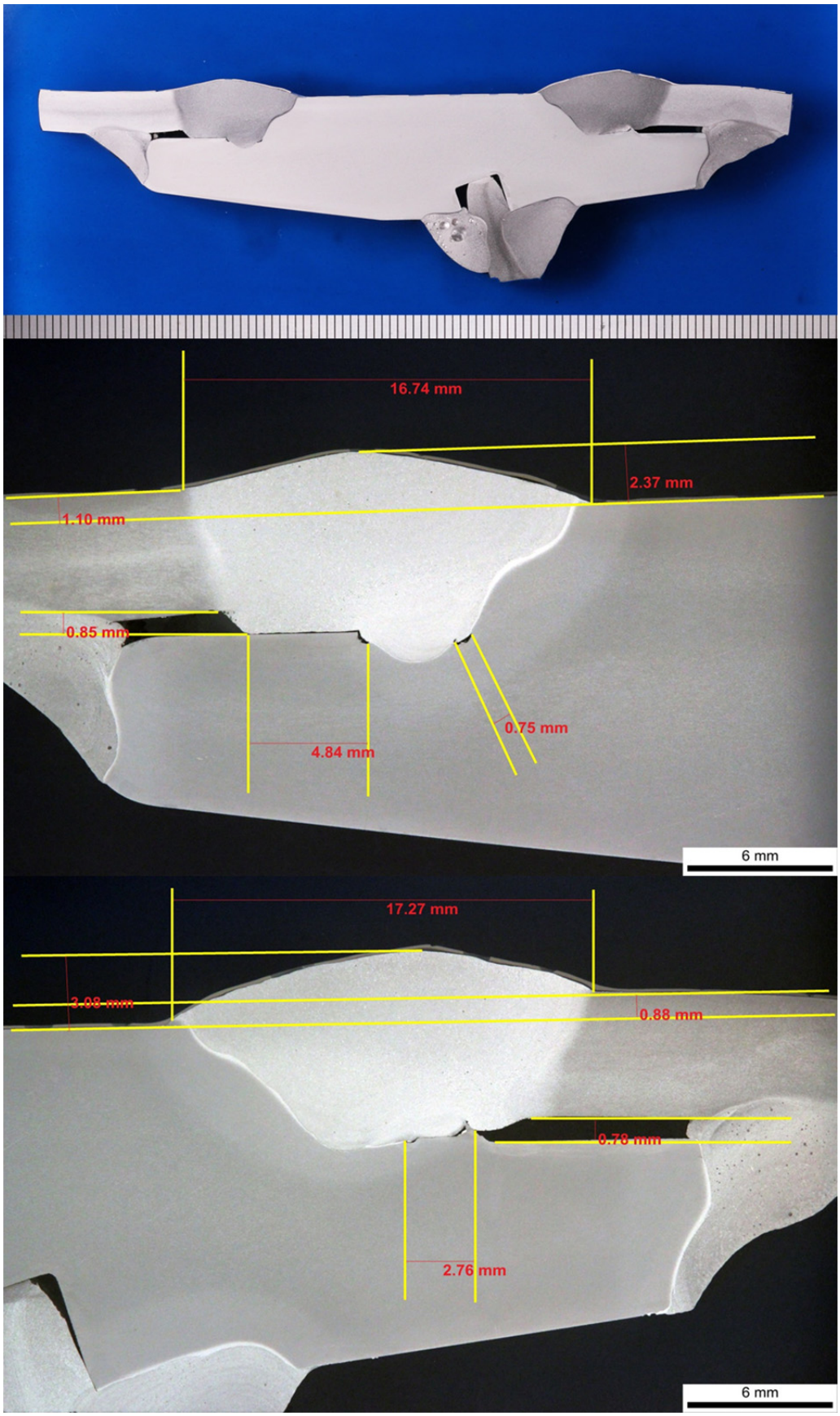

Figure K16 J3564 sample W05-06, slice 7.

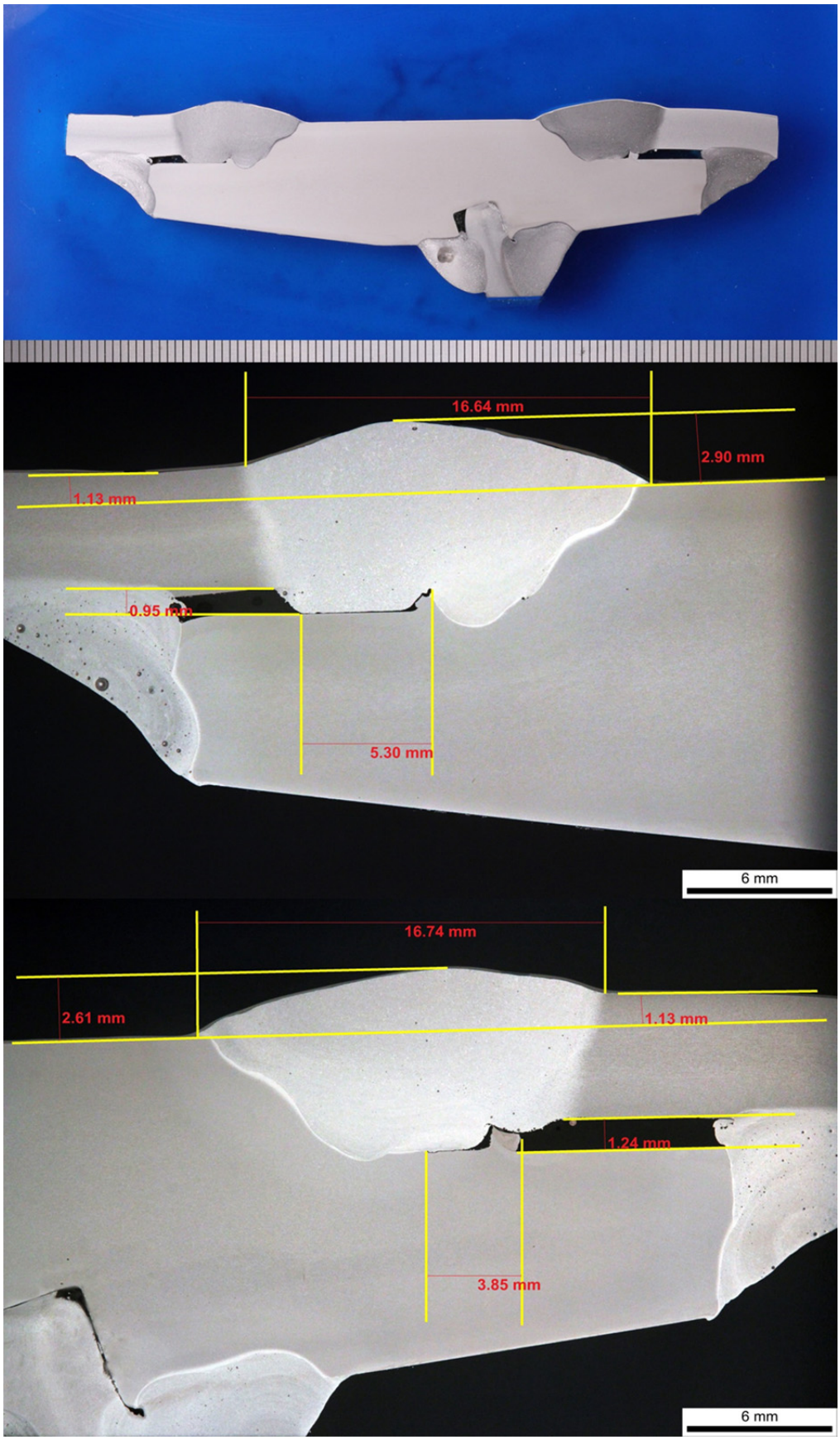

Figure K17 J3564 sample W05-06, slice 8.

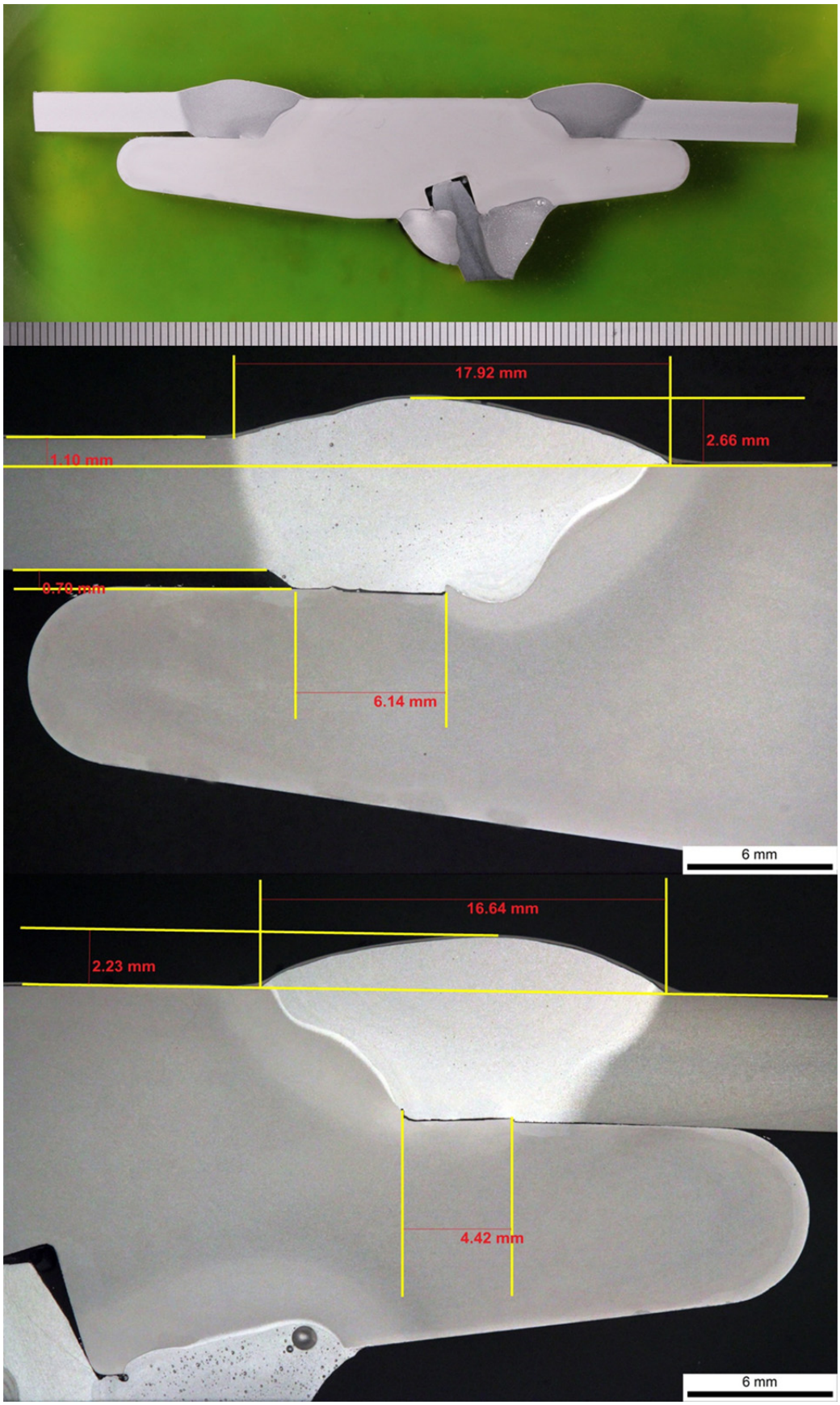

Figure K18 J3564 sample W07-08, slice 1.

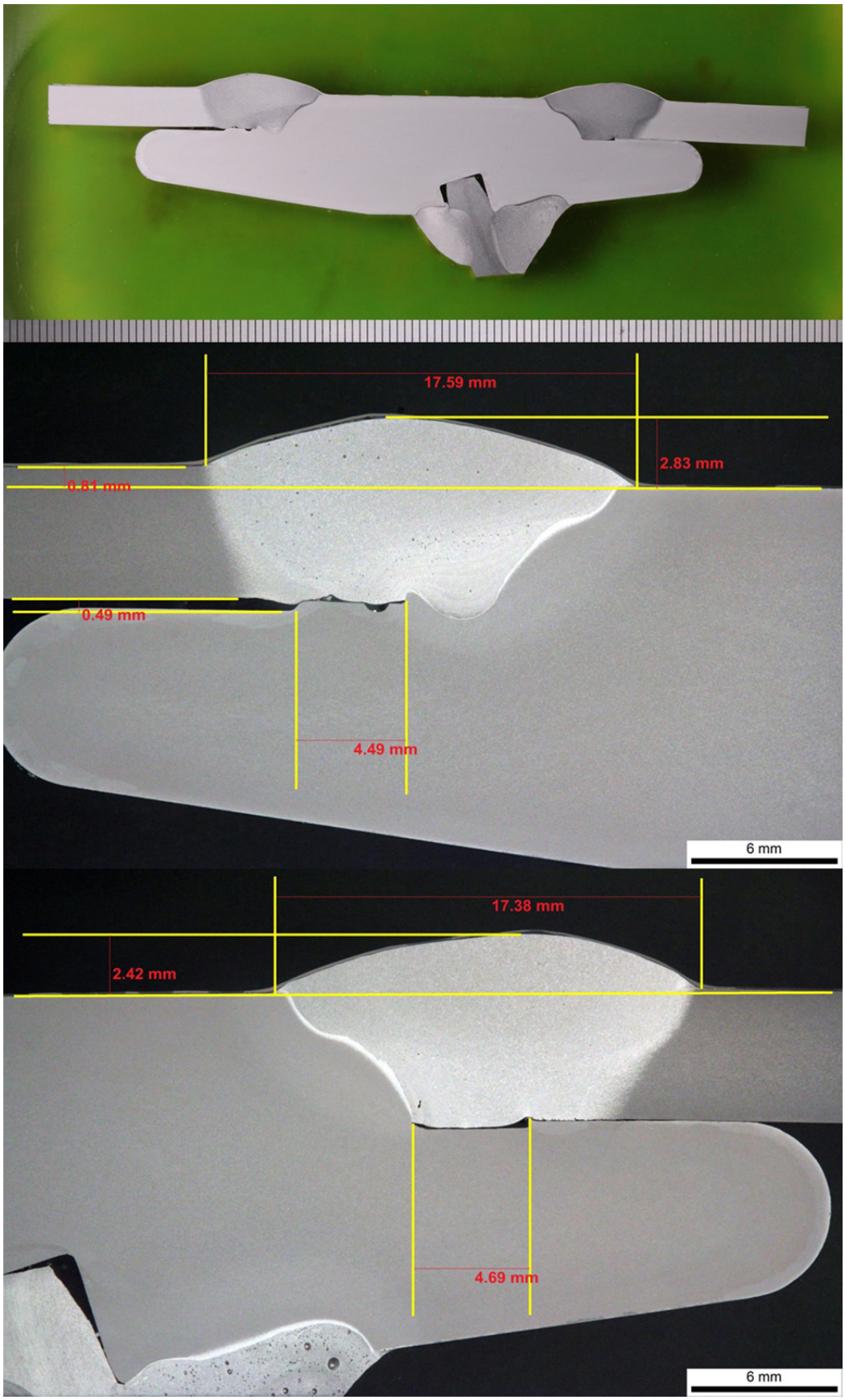

Figure K19 J3564 sample W07-08, slice 2.

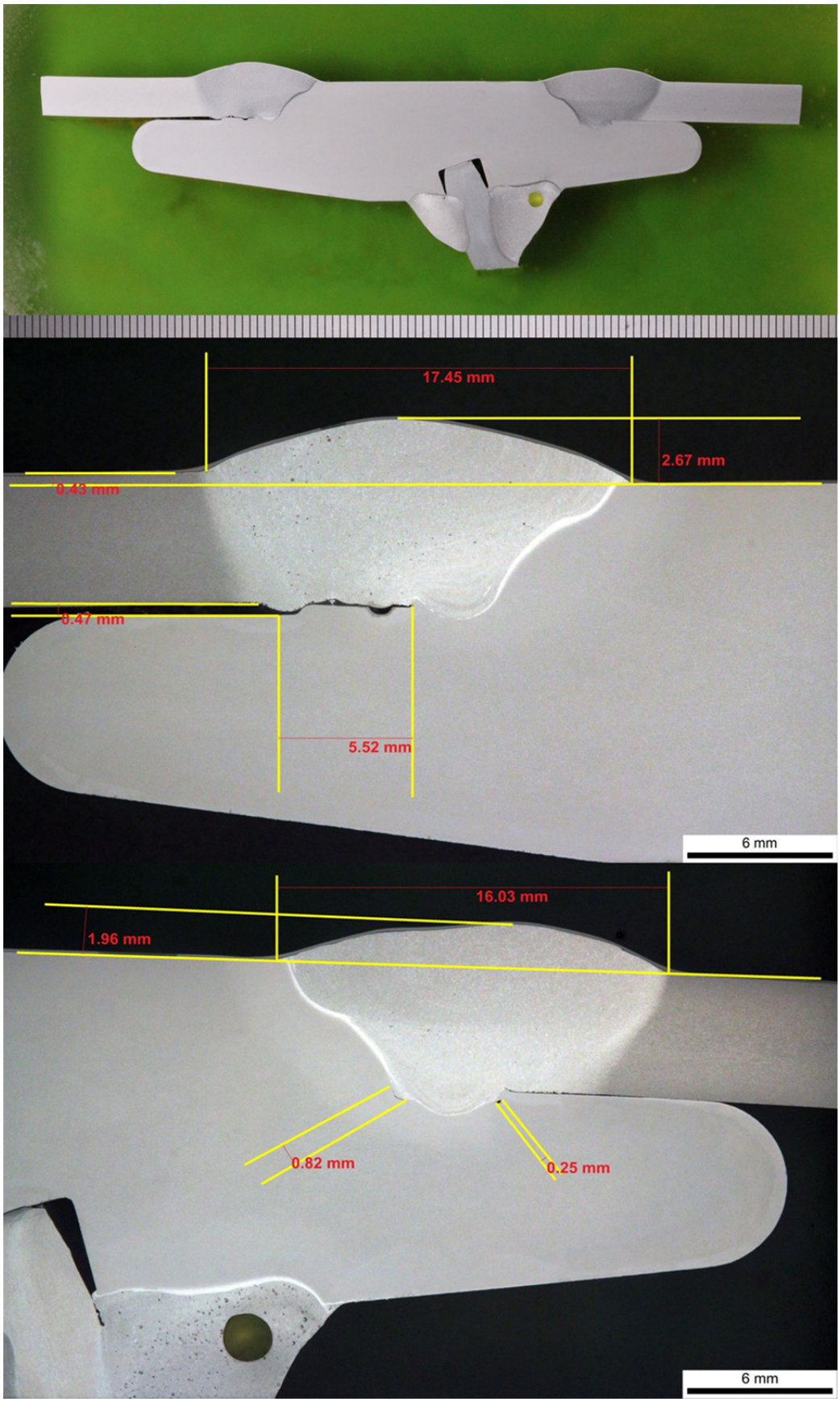

Figure K20 J3564 sample W07-08, slice 3.

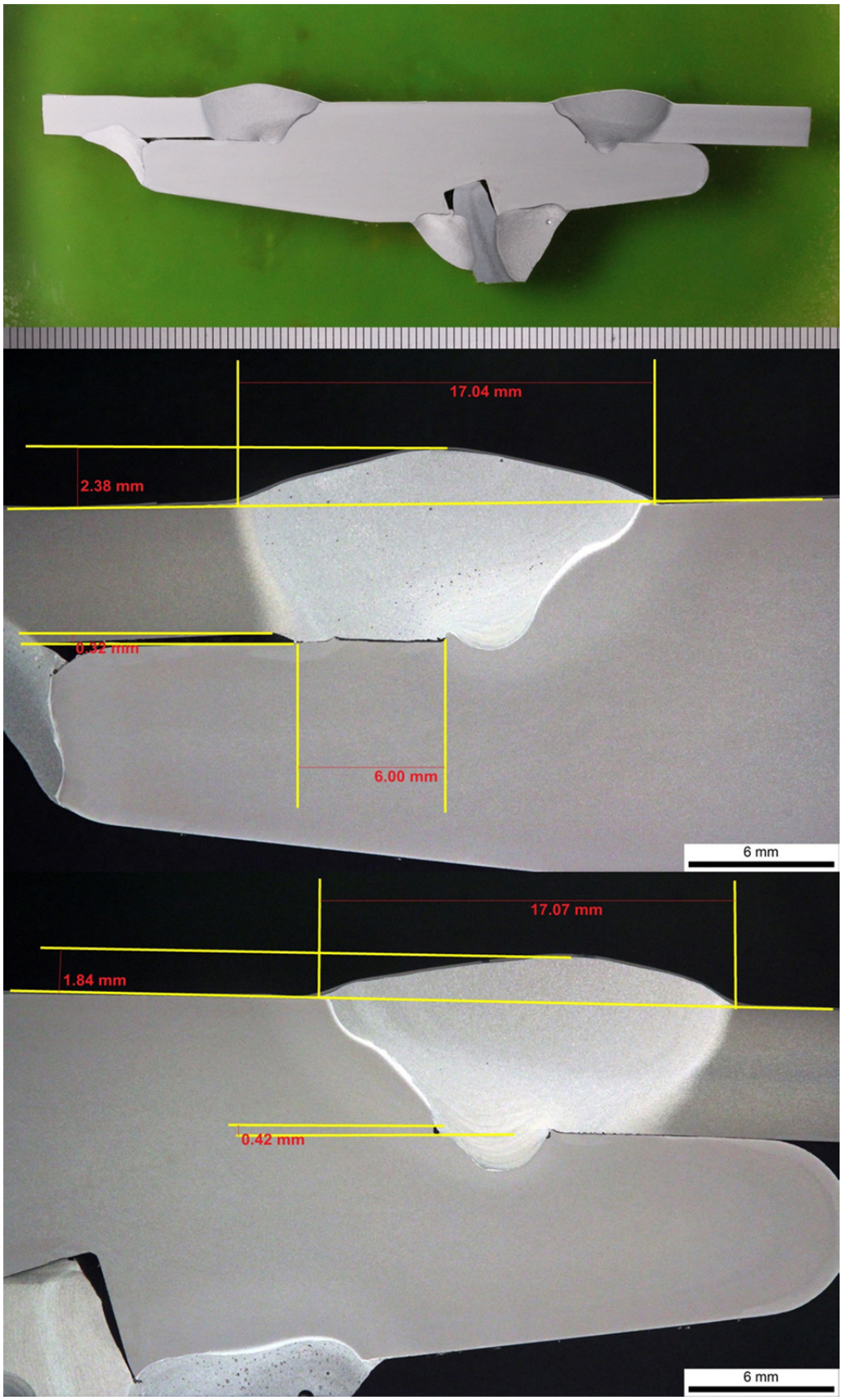

Figure K21 J3564 sample W07-08, slice 4.

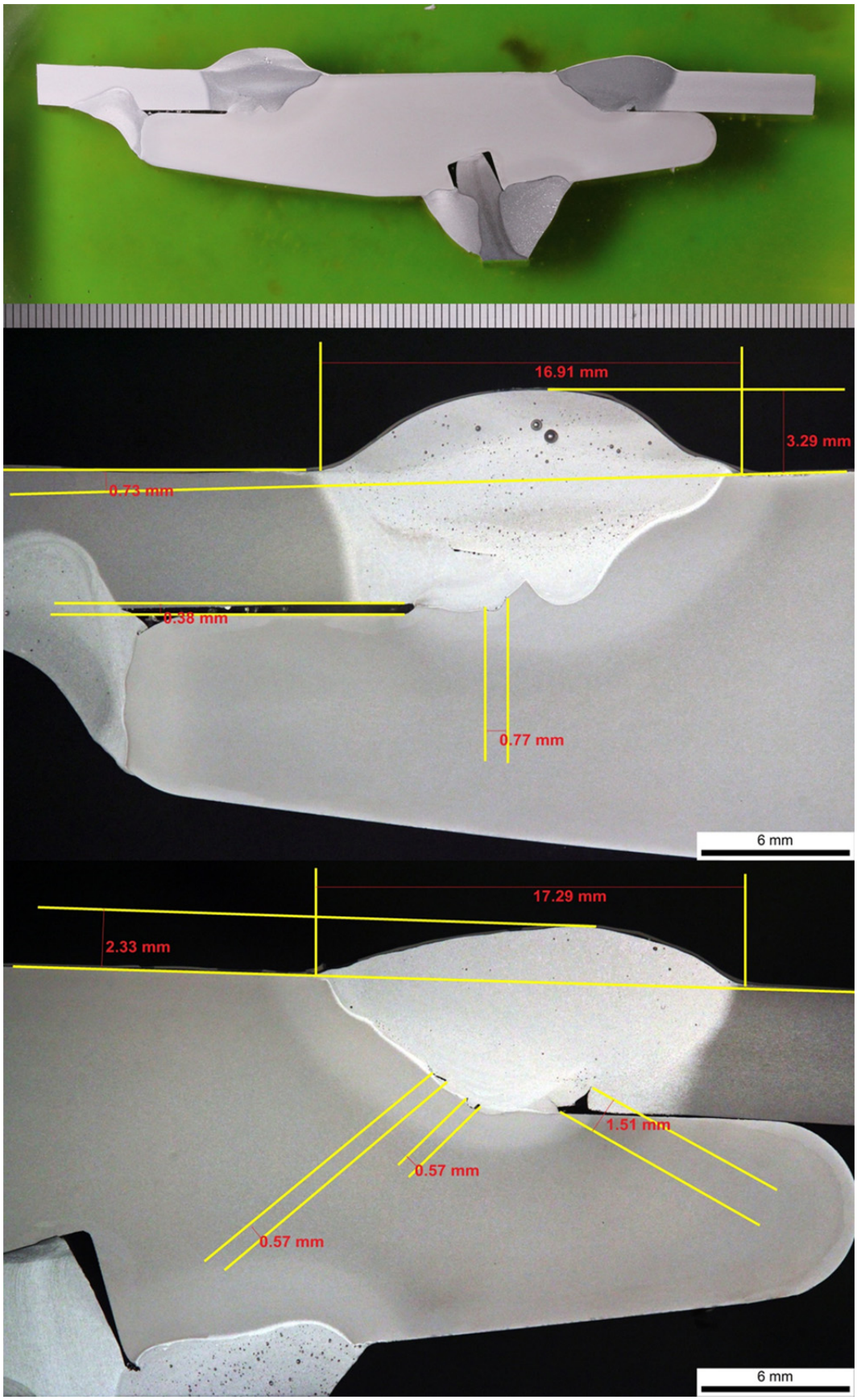

Figure K22 J3564 sample W07-08, slice 5.

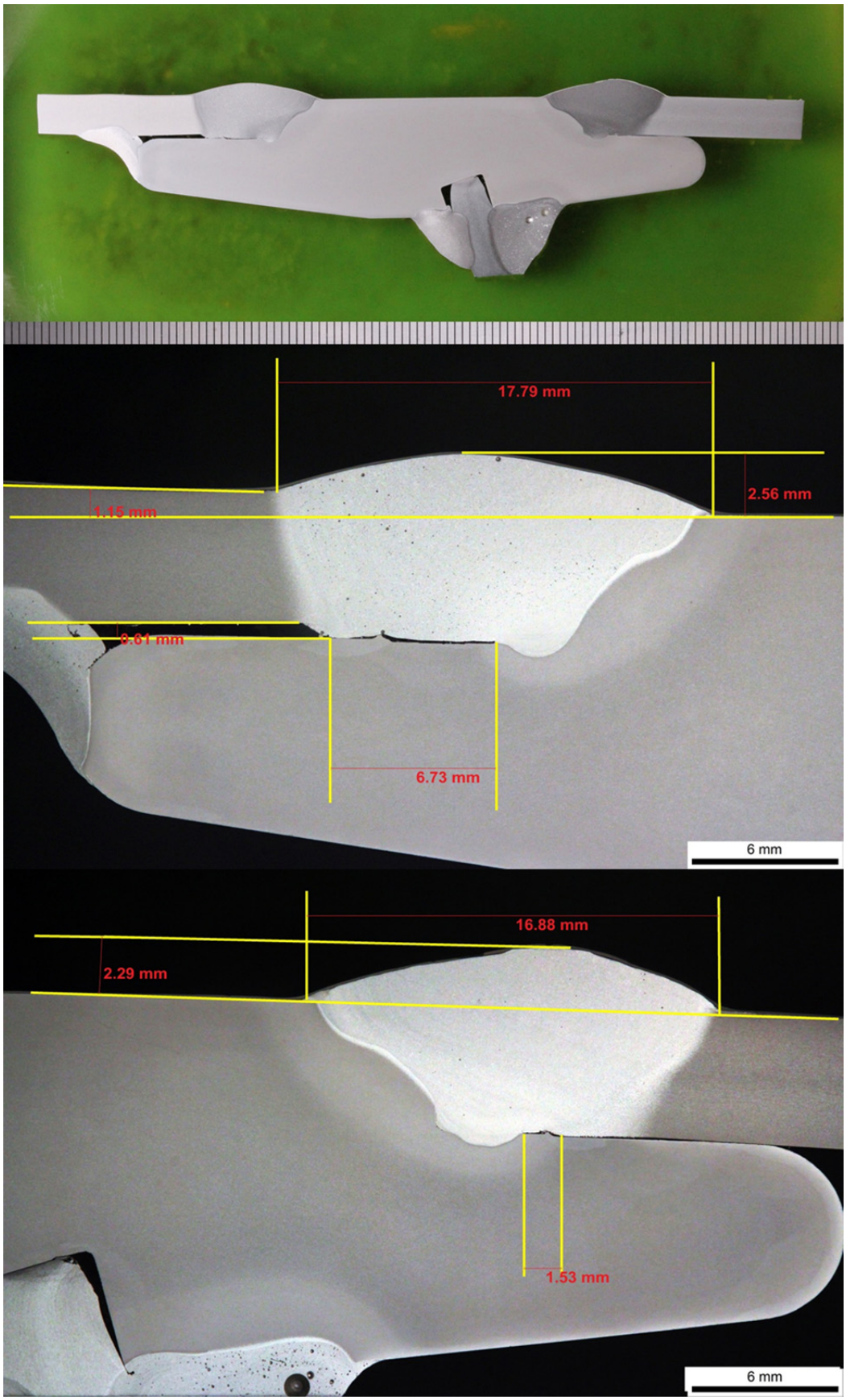

Figure K23 J3564 sample W07-08, slice 6.

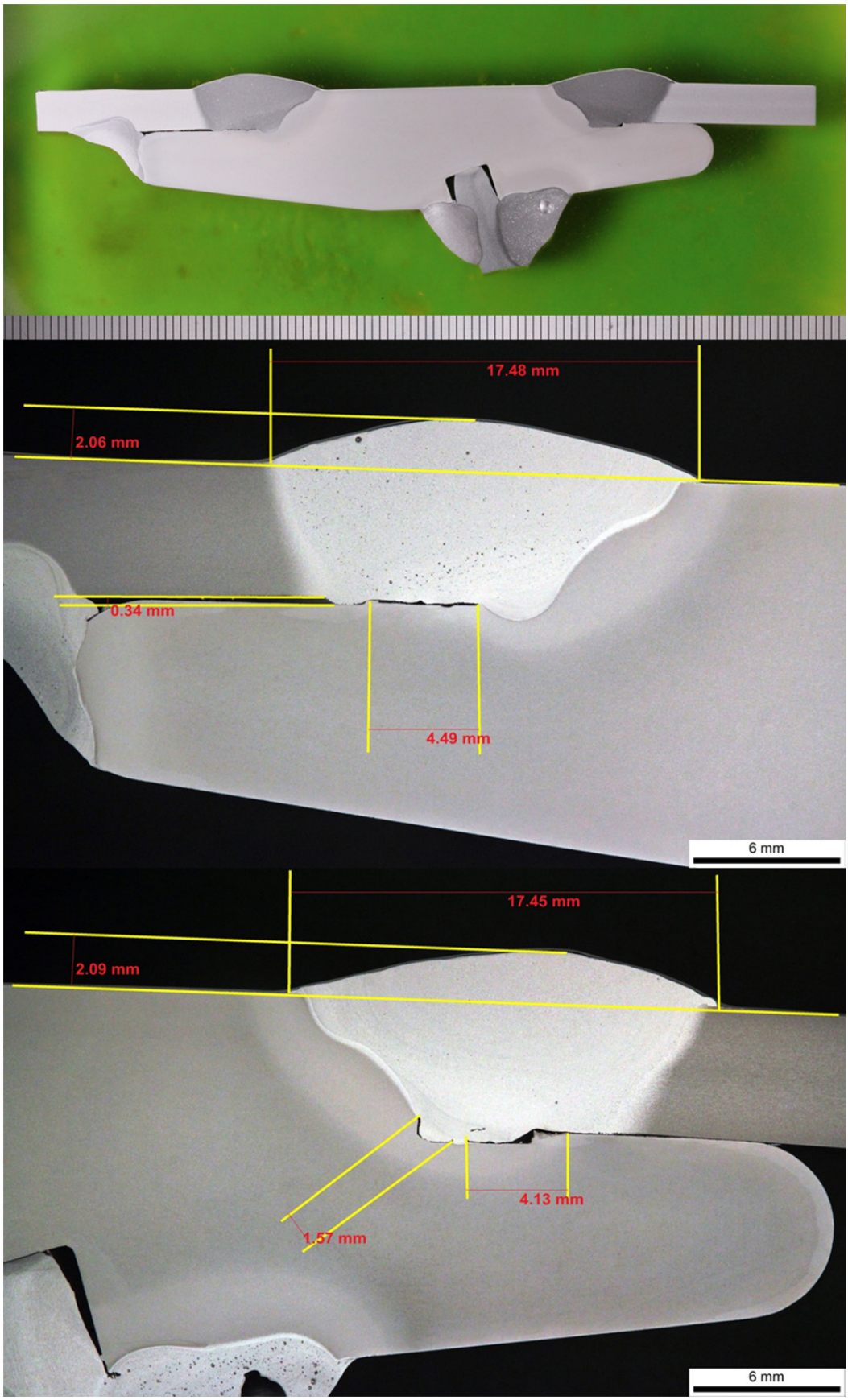

Figure K24 J3564 sample W07-08, slice 7.

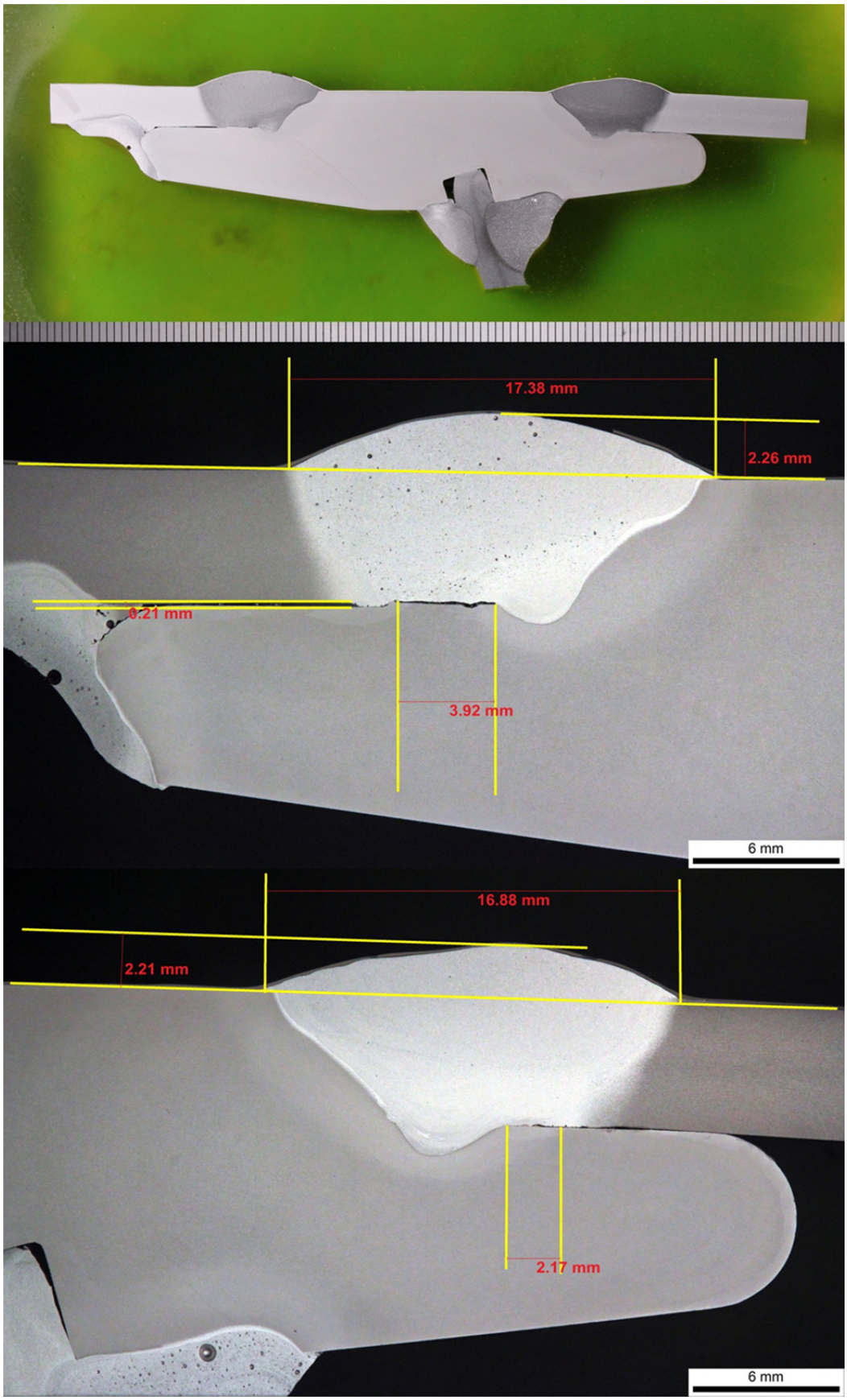

Figure K25 J3564 sample W07-08, slice 8.

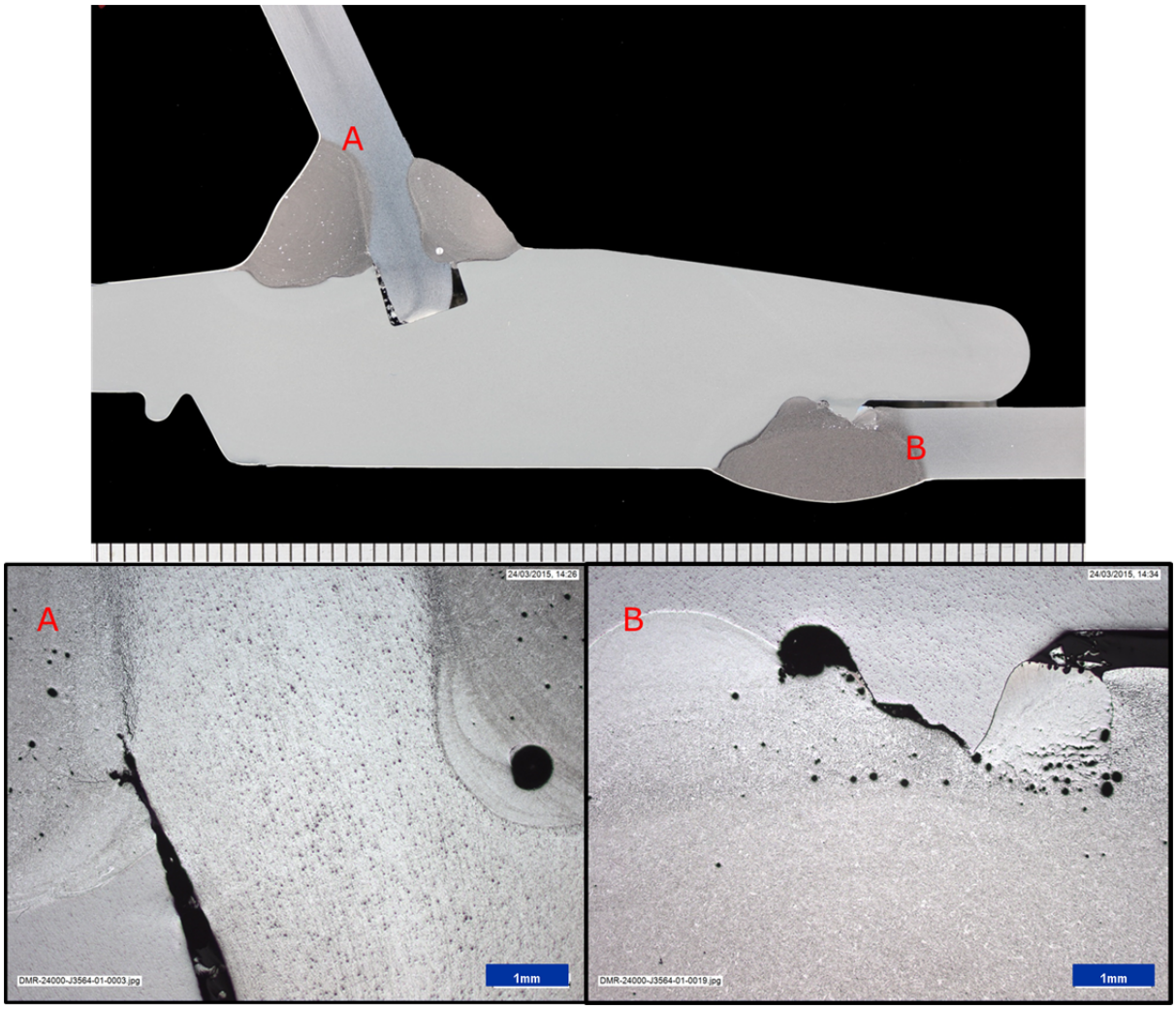

Figure K26 J3564 Sample W-01 from the rear weld.

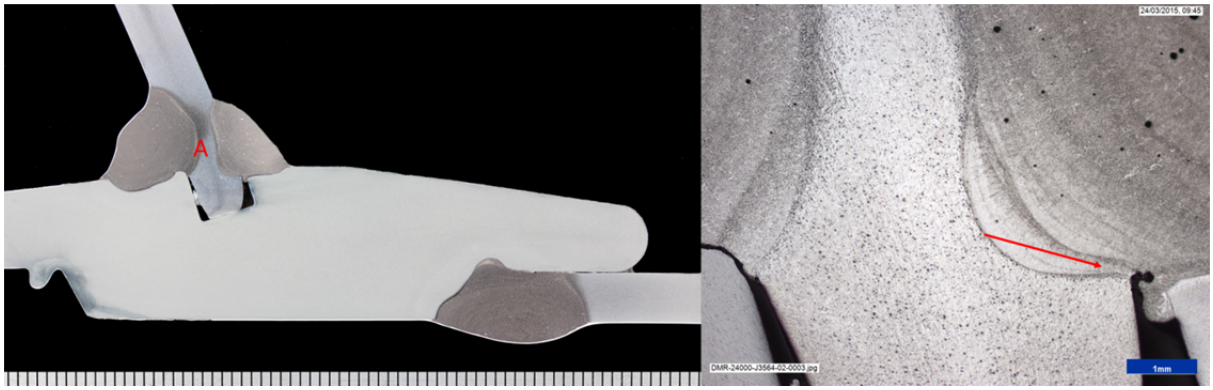

Figure K27 J3564 Sample W-02 from the rear weld.

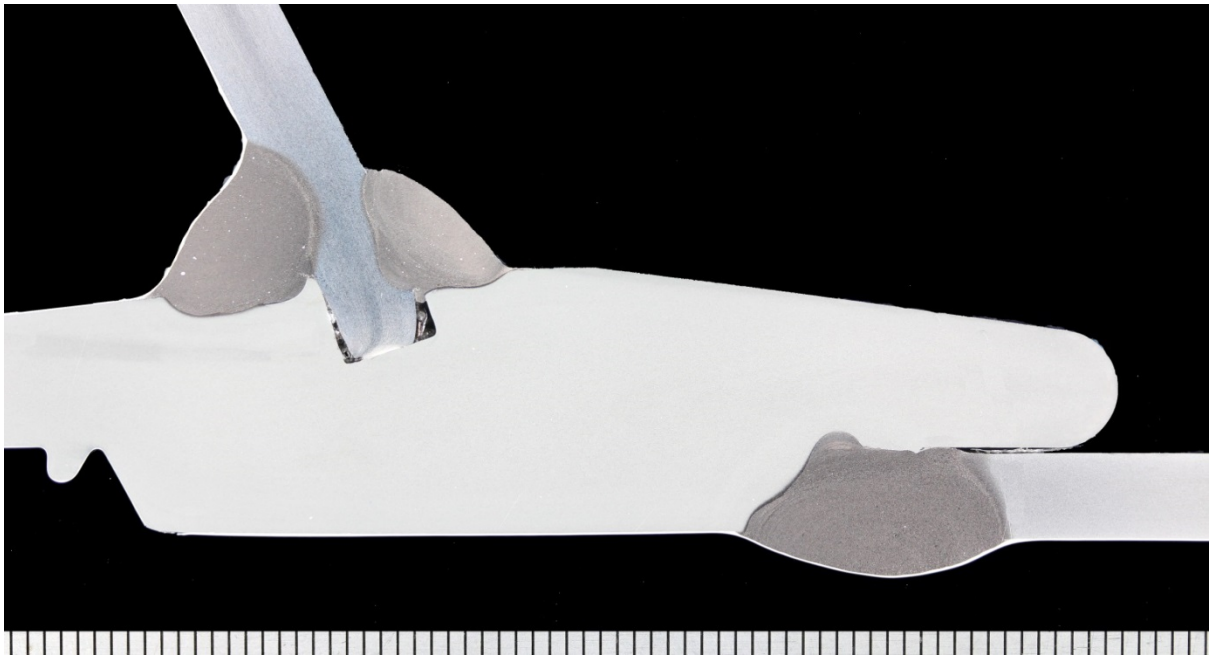

Figure K28 J3564 Sample W-03 from the rear weld.

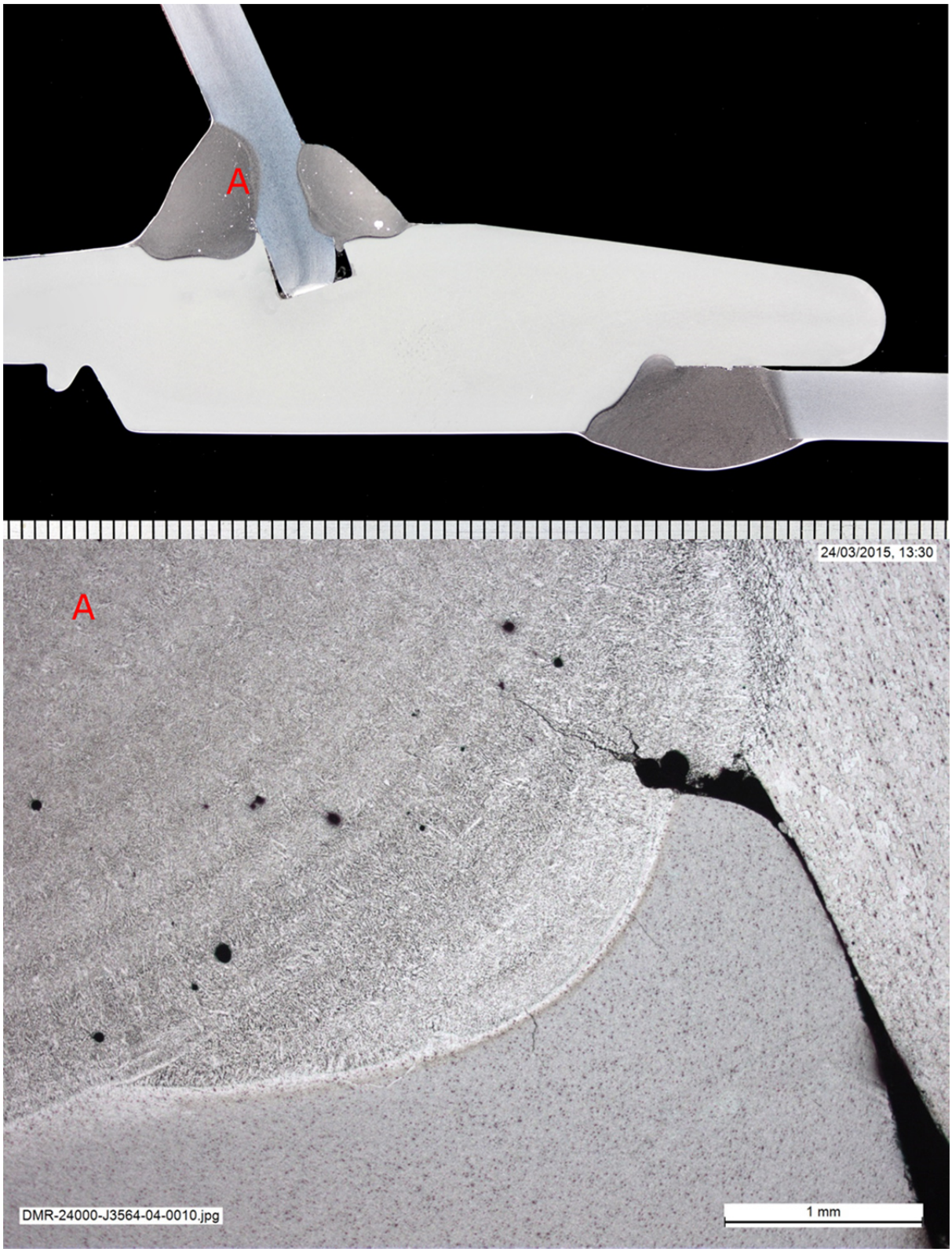

Figure K29 J3564 Sample W-04 from the rear weld. Potential evidence of fatigue.

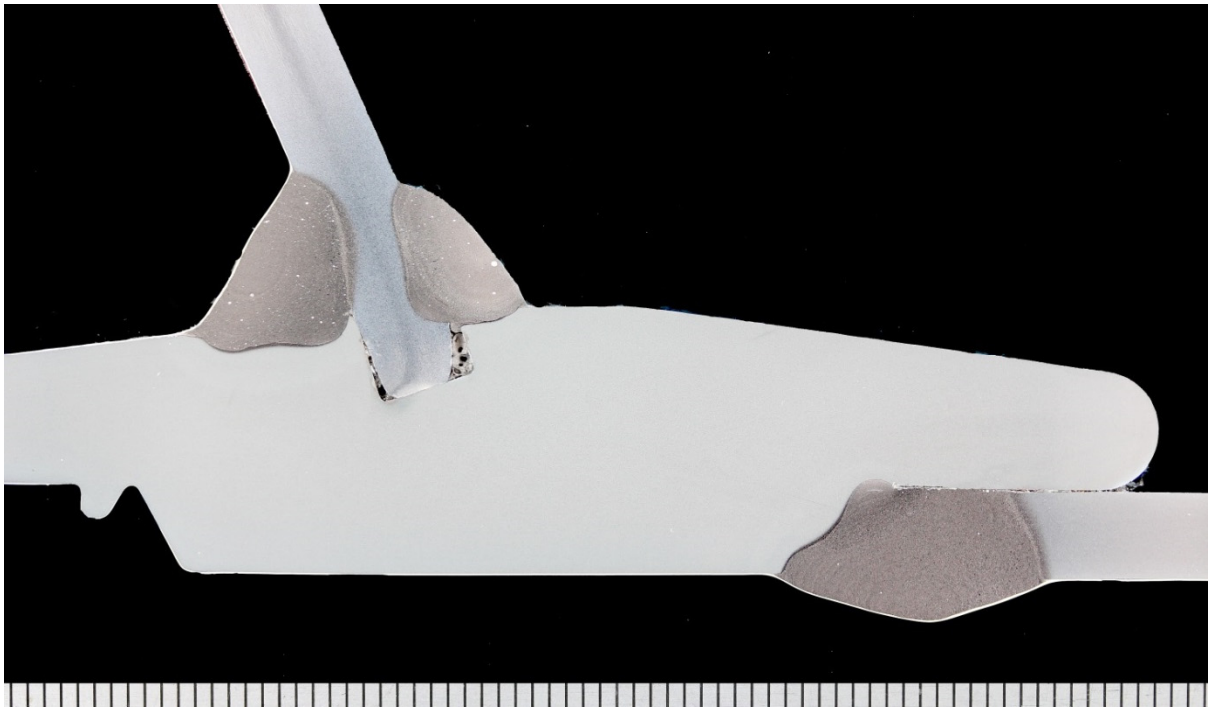

Figure K30 J3564 Sample W-05 from the rear weld.

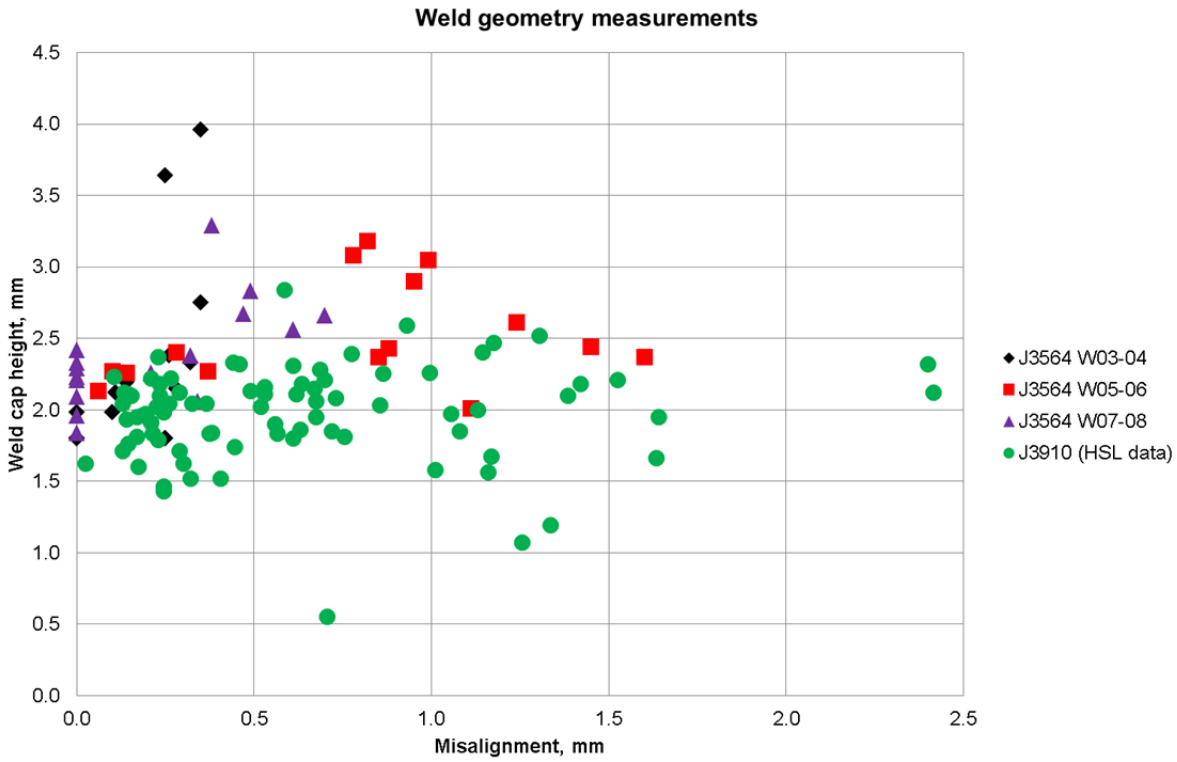

Figure K31 Measurements of weld cap height and misalignment from J3564 and J3910.

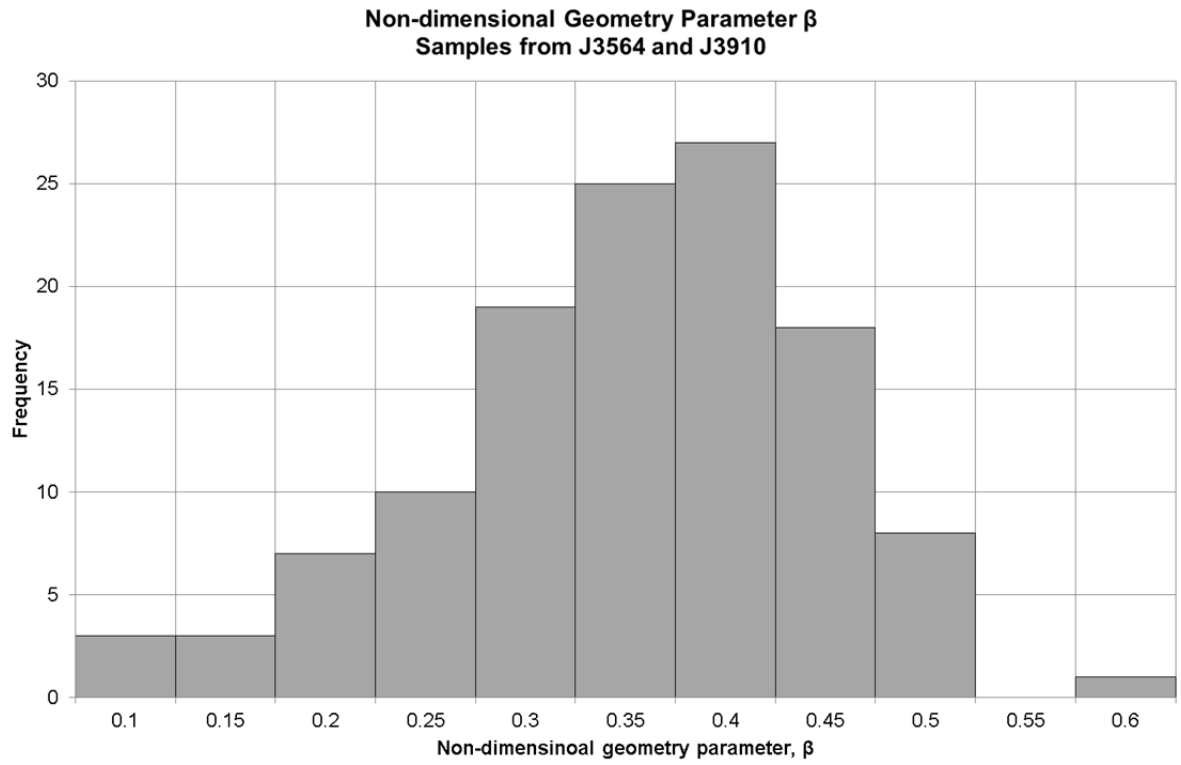

Figure K32 Histogram of non-dimensional geometry parameter β = (h-m)/5 for the J3564 and J3910 data shown in Figure I99. The data follows nearly a Gaussian distribution.

UKAS TESTING 1046

The TEST HOUSE

Certificate of Test

Client: TWI, Granta Park, Great Abington, Cambridge, CB21 6AL
Date of receipt: 7 October 2014 *Date of test:* 8 October 2014
Reference No.: T41348 *MI No.:* 1742
Order No.: To follow *Specification:* N/A

Description: Section of aluminium butt welded fuel tanker reservoir containing 2 longitudinal welds (W3 and W4),16mm thick (in area of interest) x 740mm long.
Identity: Project No. 24000/11, Project Leader: M Haslett
Test methods: *Procedure:* TP29, BSEN ISO 17636-1:2013
Inspection Authority: N/A

RADIOGRAPHIC INSPECTION REPORT

INSPECTION DETAILS						Focus film distance (mm): 800	
Single wall single image	✓	Double wall single image		Double wall double image		Object film distance (mm): 16	
						Exposure time (mA min): 20	Beam angle (°): 90
Type of equipment: Pantak 160kV CP Unit						Screens: Nil	Filters: Nil
Tube voltage (kV): 48						IQI	Type & size: BSEN 462 10 Al EN
Focal spot/source dimensions: 3mm							Source side: ✓
Film - make and type: Fuji 80							Film side:
Film density range: 1.9 to 2.4							Sensitivity: Wire No. 13

RESULTS	Acceptance criteria: None specified		
Radiograph identity	Weld/Sample identity	Accepted/ Rejected	No space to place the IQI alongside the weld so a specific IQI shot was taken at each end of the weld, before and after the radiography of the weld was completed
N/A	Trial shot	N/A	Settings assessment and adjustment
N/A	A-B IQI shot	N/A	N/A
P0716	A-B	N/A	See Appendix 1
P0717	B-C	N/A	
P0718	C-D	N/A	

- End of Test Results -

Note - The test results detailed above apply only to the sample(s) of material submitted to the laboratory.

Tests Performed by: *P R Robinson* *Witnessed by:*

Certificate Approved by: *P Robinson, Section Leader*

Signed ..... *Date* 10/10/2014

Certificate of Test

Client: TWI, Granta Park, Great Abington, Cambridge, CB21 6AL
Date of receipt: 7 October 2014 *Date of test:* 8 October 2014
Reference No.: T41348 *MI No.:* 1743
Order No.: To follow *Specification:* N/A

Description: Section of aluminium butt welded fuel tanker reservoir containing 2 longitudinal welds (W5 and W6),16mm thick (in area of interest) x 820mm long.
Identity: Project No. 24000/11, Project Leader: M Haslett
Test methods: *Procedure:* TP29, BSEN ISO 17636-1:2013
Inspection Authority: N/A

RADIOGRAPHIC INSPECTION REPORT

INSPECTION DETAILS						Focus film distance (mm): 800	
Single wall single image	✓	Double wall single image		Double wall double image		Object film distance (mm): 16	
						Exposure time (mA min): 20	Beam angle (°): 90
Type of equipment: Pantak 160kV CP Unit						Screens: Nil	Filters: Nil
Tube voltage (kV): 48						IQI	Type & size: BSEN 462 10 Al EN
Focal spot/source dimensions: 3mm							Source side: ✓
Film - make and type: Fuji 80							Film side:
Film density range: 1.9 to 2.4							Sensitivity: Wire No. 13

RESULTS Acceptance criteria: None specified

Radiograph identity	Weld/Sample identity	Accepted/ Rejected	No space to place the IQI alongside the weld so a specific IQI shot was taken at each end of the weld, before and after the radiography of the weld was completed
P0719	A-B	N/A	See Appendix 1
P0720	B-C	N/A	
P0721	C-D	N/A	

- End of Test Results -

Note - The test results detailed above apply only to the sample(s) of material submitted to the laboratory.

Tests Performed by: *P R Robinson* *Witnessed by:*

Certificate Approved by: *P Robinson, Section Leader*

Signed ..... *Date* 10/2014

UKAS TESTING 1046

The TEST HOUSE

Certificate of Test

Client: TWI, Granta Park, Great Abington, Cambridge, CB21 6AL
Date of receipt: 7 October 2014 *Date of test:* 8 October 2014
Reference No.: T41348 *MI No.:* 1744
Order No.: To follow *Specification:* N/A

Description: Section of aluminium butt welded fuel tanker reservoir containing 2 longitudinal welds (W7 and W8), 16mm thick (in area of interest) x 820mm long.
Identity: Project No. 24000/11, Project Leader: M Haslett
Test methods: *Procedure:* TP29, BSEN ISO 17636-1:2013
Inspection Authority: N/A

RADIOGRAPHIC INSPECTION REPORT

INSPECTION DETAILS						Focus film distance (mm): 800	
Single wall single image	✓	Double wall single image		Double wall double image		Object film distance (mm): 16	
						Exposure time (mA min): 20	Beam angle (°): 90
Type of equipment: Pantak 160kV CP Unit						Screens: Nil	Filters: Nil
Tube voltage (kV): 48						IQI	Type & size: BSEN 462 10 Al EN
Focal spot/source dimensions: 3mm							Source side: ✓
Film - make and type: Fuji 80							Film side:
Film density range: 1.9 to 2.4							Sensitivity: Wire No. 13

RESULTS Acceptance criteria: None specified

Radiograph identity	Weld/Sample identity	Accepted/ Rejected	No space to place the IQI alongside the weld so a specific IQI shot was taken at each end of the weld, before and after the radiography of the weld was completed
P0722	A-B	N/A	See Appendix 1
P0723	B-C	N/A	
P0724	C-D	N/A	
N/A	C-D-IQI Shot	N/A	N/A

- End of Test Results -

Note - The test results detailed above apply only to the sample(s) of material submitted to the laboratory.

Tests Performed by: *P R Robinson* *Witnessed by:*

Certificate Approved by: *P Robinson, Section Leader*

Signed ..... *Date* 10/10/2014

The TEST HOUSE

TEST REPORT

Client:	TWI	Sample identity:	
Job reference:	T42348		Appendix 1
Date:	09-Oct-14		

Radiographic Interpretation

Weld	Position (mm)	Results
3	0 - 100	Lack of sidewall fusion throughout
	100 - 200	Intermittent lack of sidewall fusion
	155 - 170	Elongated cavity
	200 - 300	Intermittent lack of sidewall fusion
	300 - 400	Intermittent lack of sidewall fusion
	400 - 500	Intermittent lack of sidewall fusion
	500 - 600	Isolated pores
	600 - 700	Intermittent lack of sidewall fusion
5	0 - 45	No significant indications
	45 - 160	Intermittent lack of sidewall fusion and isolated pores
	160 - 300	Intermittent lack of sidewall fusion
	300 - 400	Intermittent lack of sidewall fusion and pores
	400 - 500	Intermittent lack of sidewall fusion and pores
	500 - 600	Intermittent lack of sidewall fusion and pores
	600 - 700	Intermittent lack of sidewall fusion and pores
	700 - 800	Intermittent lack of sidewall fusion and pores
		Please note that W5 hs an indication along the side of the weld that is thinner than the surounding plate
7	0 - 100	Intermittent lack of sidewall fusiona nd longitudinal indications throughout
	100 - 200	Intermittent lack of sidewall fusion and longitudinal indications throughout
	200 - 300	Intermittent lack of sidewall fusion and longitudinal indications throughout
	300 - 400	Lack of sidewall fusion and lack of root fusion
	400 - 500	Intermittent lack of siewall fusion and lack of root penetration
	500 - 550	Intermittent lack of root penetration
	550 - 700	Isolate and scattered pores
	700 - 800	Isolate and scattered pores

Report prepared by: P Robinson Signed.....Date: 09/10/2014	Inspection:

Gammax Independent Inspection Services Ltd
Inspection House, Bury St. Edmunds, Suffolk IP29 4BY *Telephone:01284 850888 Fax:01284 850808*

Radiographic Inspection Report

Client:	**TWI Ltd**	*GIIS No.:*	**150311BR**	*Rev.:*	**0**
Client's P.O. No.:	**P746043**	*S.O. No.:*	**301**	*W.O. No.:*	**485**
Client's Job Ref.:	**J3564**	*Inspection Date:*		**10 March 2015**	
Sheet No.:	**1 of 1**				

Details of Item Tested

Material:	**Aluminium**	*Thickness:*	**15mm**
Diameter:	**-**	*Welding Process:*	**131:MIG**
Type of Joint:	**Butt/Fillet**	*Parent Metal Condition:*	**As rolled**
Surface Weld Condition:	**As welded**		

Radiographic Equipment

Type of Equipment/~~Source~~:	**Andrex 3002**		
Tube Voltage/~~Source Strength~~:	**80Kv**		
Focal Spot/~~Source Dimensions~~:	**3 x 1**		
Film (Make and Type):	**Fuji 50**	*Processing:*	**Automatic**
Screens:	**None**	*Filters:*	**None**
IQI (Type and Size):	**10 AL EN**	*Position:*	**Source Side**

Inspection Details

Test Procedure/Standard:	**RTP-04/BS EN 17636-1**	*Technique:*	**SWSI/Panoramic**
Focus to Film Distance:	**900mm**	*Object to Film Distance:*	**Contact**
Exposure Time (~~CiMins~~/mAmin) :	**Butt: 3 x 30** **Fillet: 3 x 50**	*Film Density:*	**≥2.3**
Sensitivity:	**W13**	*Acceptance Criteria:*	**Advisory**

Inspection Results

Item Tested	*Interpretation*	*Recommendations*
J3564		
Butt Weld	**Lack of side wall fusion, intermittent 0 to 1500mm from datum.** **Lack of root fusion 10mm long, 1425 to 1485mm from datum.**	
Internal Fillet Weld	**Lack of root fusion, full length of weld.**	
External Fillet Weld	**Lack of root fusion, full length of weld.**	

Inspection Performed By: **Thomas Donohoe PCN306055**
Verified By: **Jamie Cartwright-Thomas PCN 309169 CSWIP673131**

CSWIP 3.1
RAD PCN II
UT PCN II
MPI PCN II
DPI PCN II

Digitally signed by Jamie Cartwright-Thomas
DN: cn=Jamie Cartwright-Thomas, o=Gammax Independent Inspection Services, ou, email=jamie@gammaxuk.co.uk, c=GB
Date: 2015.03.13 13:43:28 Z

Client	*Inspection Authority*
.....	.....

The test results detailed above apply only to the item(s) of material submitted for testing. gammax@gammaxuk.co.uk