Mountain Valley PIPELINE

August 28, 2024

Mr. Robert Burrough
Director, Eastern Region
Pipeline and Hazardous Materials Safety Administration
840 Bear Tavern Road
Suite 300
West Trenton, New Jersey, 08628

Dear Mr. Burrough,

Attached please find a final report that DNV prepared regarding the elbow failure that occurred on May 1, 2024, during a hydrostatic pressure test of the Mountain Valley Pipeline (MVP). Hydrostatic pressure testing is a common tool used to substantiate the strength and integrity of pipeline systems. The requirements for conducting hydrostatic pressure testing of gas pipelines are prescribed in 49 C.F.R. Part 192, Subpart J.

Hydrostatic pressure testing generally occurs after the installation of a pipeline. The process involves isolating a completed section of the pipeline with engineered testing equipment, strategically filling it with water, implementing engineered controls to monitor pressures and temperatures, effecting a controlled pressurization of the pipeline segment, and precisely monitoring the test's pressures and temperatures throughout its typical 8-hour hold duration while continuously assessing the readings to identify leaks and prove integrity. Every hydrostatic pressure test is designed to assure minimum pressures are met while controlling the maximum pressure to predetermined tolerable limits.

MVP had 43 separate mainline test sections to accommodate achieving the minimum test pressures without exceeding engineered maximum test pressure limits. The primary limitation for these tests was due to increased pressure caused by the elevation changes and the weight of the water. MVP utilized a commercial, highly acclaimed, software program to assess the real-time testing data.

The H4 section that failed during hydrostatic pressure testing involved a manufactured "buttwelding" fitting that mechanically failed before reaching its target test pressure. Fittings are designed following engineering specifications but are not required to be factory pressure tested for reasons of impracticability.

The H4 test section failure was the project's only hydrostatic pressure test failure, and it was due to a manufacturer's defective weld as indicated in the attached independent report. As stated, one purpose of hydrostatic pressure testing is to prove the integrity of the test section. For MVP, there are more than 2500 such fittings installed and hydrotested with a single failure resulting in a negligible fitting failure rate. From a manufacturing perspective, the failed fitting had a “sister” fitting in the same test section that was proactively removed from the pipeline and used to provide material for a portion of the mechanical testing aspect of the failure analysis. There were only two fittings with matching pedigree, neither of which remains in the pipeline.

Each MVP test section, including H4, received a successful hydrostatic pressure test to at least 125 percent of the pipeline’s maximum allowable operating pressure. As a result, the pipeline is considered to be stable for purposes of any material defect under 49 C.F.R. § 192.917 (e)(3) and not subject to a risk of experiencing a similar failure in the future.

Sincerely,

Justin Trettel
Vice President

cc: FERC Docket No. CP16-10

Final Summary Report

Metallurgical Analysis of 42-Inch MVP Line H600 Hydrotest Elbow Fitting Failure (05/01/2024)

Mountain Valley Pipeline, LLC
Canonsburg, Pennsylvania

Report №: E-AD-LI / GTQU (10513119)
August 1, 2024

DNV

Project Name:	Metallurgical Analysis of 42-Inch MVP Line H600 Hydrotest Elbow Fitting Failure (05/01/2024)	
Customer:	Mountain Valley Pipeline, LLC	
Contact Person:	Jim Swatzel	
Date of Issue:	August 1, 2024	
Project No.:	10513119	
Organization Unit:	Incident Investigation	
Report No.:	E-AD-LI / GTQU	

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Objective:

Please see Report below.

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0	2024-07-23	First Issue			
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2	2024-08-21	Final			

Mountain Valley Pipeline, LLC (*MVP*), which was formally owned by Equitrans Midstream (ETRN) and is now owned by EQT Corporation, retained DNV GL USA, Inc. (*DNV*) to perform a metallurgical analysis on a pipe section from the Line H600 Pipeline, a 42-inch diameter natural gas pipeline that ruptured at a 36° elbow fitting during a pre-commissioning hydrostatic pressure test (hydrotest). The failure occurred on May 1, 2024 in Roanoke (Roanoke County), Virginia on MVP Spread H, Test Section H4, at Milepost (MP) 246, GPS Coordinates 37.128333, -80.129444.

The elbow fitting is 42-inch diameter by 0.740-inch wall thickness, MSS SP-75-2014 Grade WPH70 carbon steel that contains a longitudinal seam and was manufactured by Custom Alloys. The elbow fitting was installed on June 30, 2018.

The maximum allowable operating pressure (MAOP) of the pipeline is 1,480 psig, which corresponds to 60.0% of the specified minimum yield strength (SMYS). The hydrostatic pressure at the time and location of the failure was 2,105 psig (85.3% of SMYS, 1.42 x MAOP), 240 psig short of the target pressure of 2,345 psig (1.6 test pressure [TP] / MAOP ratio) at the elbow fitting elevation.

This pressure test (H4) was one of 43 individual pipeline hydrotests on the pipeline. Of the 43, including this one (H4), 41 of the 43 were Class 1 & 2 tests and each of the Class 1 & 2 tests were prescribed to exert a minimum of 1,850 psig at the highest elevation. Ninety-one elbow fittings were manufactured with the same mill heat number and were successfully hydrotested with the lowest and highest stress levels of 75.8 and 105.2% of SMYS, respectively. Additionally, each pipeline test was assessed for yielding using a pressure vs. volume (PV) plot and commercially available industry software. The software is programmed to assess the PV plot and no test exhibited any indication of global yielding during pressurization.

A 12.6-feet long pipe section (the portion that was removed from the pipeline) that contained the failed elbow fitting and an upstream (U/S) and downstream (D/S) PUP, 1.5-foot-long coupon that contained the seam weld from a sister elbow fitting, and 1 foot-long base metal coupon from the sister elbow fitting were delivered to DNV for analysis. The objectives of the analysis were to determine the metallurgical cause of the failure and identify any contributing factors.

The results of the metallurgical analysis indicate that the elbow fitting failed at the longitudinal seam weld as a result of ductile overload. A majority of the failure was at or near the fusion boundary of the seam weld metal and base metal, indicating a lower tensile strength at or near the fusion boundary compared to the base metal and weld metal. Supporting evidence for this conclusion includes the evidence of ductile overload failure of the elbow fitting (necking and the presence of ductile features on the fracture surface [dimples]), and the evidence of lower hardness midwall near the seam weld of the failed[1] and sister elbow.

Contributing factors to the lower tensile strength at or near the fusion boundary was softening of the base metal mid-thickness, adjacent to the intersection of the OD and ID weld passes, and

[1] On the side of the weld opposite the failure; cold working of the steel adjacent to the failure increased the hardness.

possibly a yield strength lower than the requirement as the base metal yield strength of the sister elbow fitting did not meet the yield strength requirement.

The following steps were performed for the analysis. The pipe section was visually inspected and photographed. Wall thicknesses, diameters, and circumferences were measured on the ends of the pipe section in areas with no coating. The fracture surfaces were photographed along the entire length of the failure opening. Coupons were removed from the fracture surfaces, containing the seam weld, for metallography and fractography.

Two metallographic transverse cross-sections were removed from across the failed seam weld (Mount M1 and M2), and Mount M3 was removed from across the seam weld from the sister elbow fitting. The cross-sections were mounted, polished, and etched. Light photomicrographs were taken to document the morphology of the failure and seam weld morphology. Hardness testing (Vickers, 10 kg load) was performed on Mounts M2 and M3 to document the hardnesses. Two fracture surface samples were removed, cleaned in ENPREP® 214, and examined at low magnification with a stereo light microscope and at high magnification in a scanning electron microscope (SEM) to document the fracture morphologies.

Duplicate tensile tests were performed on transverse base metal and seam weld specimens from the sister fitting. Triplicate Charpy V-notch (CVN) impact tests were performed on transverse specimens removed from the base metal and seam weld (weld centerline [WCL] notch) of the sister elbow fitting. Charpy V-notch impact (full curve, 10 specimens per curve) testing was performed on transverse specimens removed from the seam weld (heat affected zone [HAZ] notch) of the sister elbow fitting. Chemical analyses were performed on steel samples removed from the failed and sister elbow fitting to determine the compositions.

The results of the metallurgical analysis indicate that the elbow fitting failed at the longitudinal seam weld as a result of ductile overload. Observations leading to the conclusion that the cause of failure was ductile overload include 1) the fracture surface consisting mainly of dimples, significant wall reduction (necking of approximately 18%) at the failure, and no evidence of a pre-existing flaw. A majority of the failure occurred at or near the fusion boundary of the seam weld metal and base metal, indicating a lower tensile strength at or near the fusion boundary compared to the base metal and weld metal. A contributing factor to the lower tensile strength was softening of the base metal mid-thickness (at/near the HAZ), adjacent to the intersection of OD and ID weld passes, and possibly a yield strength lower than the requirement as the base metal yield strength of the sister elbow fitting did not meet the yield strength requirement.

Below is a summary of conclusions:

- The thickness of the elbow, in the plate material, near the seam weld was approximately 0.95 inches for both the failed and sister elbow fitting, much greater than the design thickness of 0.740 inches. The wall thickness at the failure location, even after the necking of approximately 18%, was 0.790 inches, also greater than the design thickness of 0.740 inches.

- The tensile properties of the sister elbow fitting (base metal) do not meet tensile requirements for MSS SP75 Grade WPHY70 steel at the time of construction as the yield strength is lower than the required value of 70 ksi; the values are also lower than the MTR value of 70.9 ksi.
- The ultimate tensile strength of the sister elbow fitting (cross seam weld) meets tensile requirements for MSS SP75 Grade WPHY70 steel at the time of construction. Both specimens failed in the HAZ near or at the weld fusion line, similar to the failure location of the failed elbow fitting.
- The CVN impact testing of the sister elbow fitting at -20°F meets impact energy requirements for the base metal; there are no requirements for the seam weld. The shear % values at this test temperature were all less than the MTR values for the notch in the base metal, HAZ, and WCL.
- For the CVN testing of the sister elbow fitting, the upper shelf impact energy value of the HAZ is typical when compared to 2018 vintage line pipe steel, and the 85% fracture appearance transition temperature (FATT) value is higher (poorer) than typical when compared to 2018 vintage line pipe steel.
- The chemical compositions of the fittings meet composition requirements for MSS SP75 Grade WPHY70 steel at the time of construction, are very similar and thus consistent that the sister elbow fitting is from the same heat, and also similar to the MTR results.
- The microstructures of the elbow fittings are consistent with a quench and temper (Q&T) microstructure and consistent with that reported in the MTR.

Table 1. Results of circumference and diameter measurements performed on the upstream (U/S) and downstream (D/S) ends of the pipe section containing the failed elbow in areas with no coating. The diameter values from circumference measurements meet API 5L tolerance requirements for 42-inch diameter pipe. The differences between the 41.5 inches and 42.5 inches measured at the two locations at the pipe ends show evidence of ovality; this ovality may be a result of the failure.

Pipe Section End	Circumference (feet)	Outside Diameter (inches)			
		From Circumference Measurement	3 to 9 o'clock	6 to 12 o'clock	API 5L Requirement[1]
U/S	11.01	42.1	41.5	42.4	41.84 – 42.16
D/S	11.01	42.1	41.5	42.4	

1 API 5L 45th Edition, December 2012.

Table 2. Results of wall thickness measurements performed on the U/S and D/S ends of the pipe section in areas with no coating or measurable corrosion. The wall thicknesses for the U/S and D/S joints meet API 5L tolerance requirements for a nominal wall thickness (NWT) of 0.740 inches at the time of construction.

O'clock Orientations	Wall Thickness (inches)		
	U/S End	D/S End	API Requirement[1]
12:00	0.750	0.748	0.680 – 0.800
3:00	0.754	0.738	
6:00	0.734	0.738	
9:00	0.744	0.755	
Average	**0.746**	**0.747**	

1 API 5L 45th Edition, December 2012.

Table 3. Results of tensile tests performed on transverse base metal specimens from the sister elbow fitting compared with requirements for MSS SP-75 Grade WPHY70 steel. The tensile properties of the sister elbow fitting do not meet tensile requirements for MSS SP75 Grade WPHY70 steel at the time of construction as the yield strength is lower than the required value of 70 ksi; the yield strength values are also lower than the MTR value of 70.9 ksi.

	Specimen 1	**Specimen 2**	**Average**	**MTR**	**MSS SP-75 WPHY70 Steel** [1]
Yield Strength, ksi	63.5	66.8	65.2	70.9	70.0
Tensile Strength, ksi	87.5	90.1	88.8	88.6	82.0
Elongation in 2 inches, %	35.8	33.7	34.8	29.4	18.0
Reduction of Area, %	69.2	66.5	67.9	–	–

1 – MSS SP-75-2014.

Table 4. Results of tensile tests performed on transverse seam weld specimens from the sister elbow fitting compared with requirements for MSS SP75 Grade WPHY70 steel. The ultimate tensile strength of the sister elbow fitting meets tensile requirements for MSS SP75 Grade WPHY70 steel at the time of construction. Both specimens failed in the HAZ near or at the weld fusion line, similar to the failure location of the failed elbow fitting.

	Specimen 1	**Specimen 2**	**Average**	**MTR**	**MSS SP-75 WPHY70 Steel** [1]
Tensile Strength, ksi	88.0	88.3	88.2	85.1	82.0

1 – MSS SP-75-2014

Table 5. Results of Charpy V-notch impact tests performed on transverse base metal specimens removed from the sister elbow fitting, tested at -20°F, and compared to the MTR values. According to MSS SP-75-2014, the average of three specimens shall be ≥ 20 ft-lb with no one specimen less than 15 ft-lb; the results meet this criteria. The average impact energy values are similar and the shear % values of the sister fitting are less than that stated on the MTR.

Sample ID	**Specimen size, in**		**Sub Size Impact Energy, ft-lbs**	**Full Size Impact Energy, ft-lbs**	**Lateral Expansion, mils**	**Shear, %**
	Width	**Thickness**				
1	0.394	0.394	89.0	89.0	64	45
2	0.394	0.394	73.0	73.0	56	45
3	0.394	0.394	49.0	49.0	36	35
Average			70.3	70.3	52.0	42
MTR-1			-	85.0	42	75
MTR-2			-	65.0	46	75
MTR-3			-	68.0	39	75
Average				72.6	42	75

Table 6. Results of Charpy V-notch impact tests performed on transverse seam weld (weld centerline [WCL] notch) specimens removed from the sister elbow fitting, tested at -20°F, and compared to the MTR values. The shear % values from the testing (20%) are less than that reported in the MTR (50%).

Sample ID	**Specimen size, in**		**Sub Size Impact Energy, ft-lbs**	**Full Size Impact Energy, ft-lbs**	**Lateral Expansion, mils**	**Shear, %**
	Width	**Thickness**				
1	0.394	0.394	19.0	19.0	24	20
2	0.394	0.394	19.0	19.0	21	20
3	0.394	0.394	17.0	17.0	22	20
Average			18.3	18.3	22	20
MTR-1	-	-	-	-	-	50
MTR-2	-	-	-	-	-	50
MTR-3	-	-	-	-	-	50
Average						50

Table 7. Results of Charpy V-notch impact tests performed on transverse seam weld (heat affected zone [HAZ] notch) specimens removed from the sister elbow fitting. The shear % values from the MTR for three specimens tested at -20°F were 65%, 75%, and 75%, and are greater than the single value of 20% at this test temperature, below.

Sample ID	Temperature, °F	Specimen size, in		Sub Size Impact Energy, ft-lbs	Full Size Impact Energy, ft-lbs	Lateral Expansion, mils	Shear, %
		Width	Thickness				
1	-160	0.394	0.394	11	11	10	0
2	-120	0.394	0.394	8	8	6	0
3	-90	0.394	0.394	22	22	20	5
4	-50	0.394	0.394	75	75	62	20
5	-20	0.394	0.394	70	70	54	20
6	30	0.394	0.394	106	106	82	40
7	70	0.394	0.394	131	131	90	70
8	100	0.394	0.394	148	148	90	100
9	125	0.394	0.394	149	149	98	100
10	150	0.394	0.394	152	152	88	100

Table 8. Results of analyses of the Charpy V-notch impact energy and percent shear plots for transverse seam weld (HAZ notch) specimens removed from the sister elbow fitting. When comparing to line pipe steel for a 2018 vintage, the upper shelf impact energy value is typical and the 85% fracture appearance transition temperature (FATT) value is higher (poorer) than typical.

	Seam Weld (HAZ notch)
Upper Shelf Impact Energy (Full Size), Ft-lbs	137
85% FATT, °F	91.3
85% FATT, °F (Full Scale Pipe) [1]	98.6

1 Full Scale Pipe FATT = 85% FATT + $((66*(t_w^{0.55}/t_c^{0.7})-100)$ where t_w = pipe wall thickness and t_c = width of the CVN specimen.

Table 9. Results of chemical analyses of samples removed from the failed elbow and sister elbow fitting compared with composition requirements for MSS SP75 Grade WPHY70 steel. The chemical compositions of the fittings meet composition requirements for MSS SP75 Grade WPHY70 steel at the time of construction, are very similar and thus consistent that the sister elbow fitting is from the same heat. The results also are similar to the MTR results.

Element		Composition (Wt. %)			
		Failed Fitting	Sister Fitting	MSS SP75 Req.[1] (max)	MTR, product analysis
C	(Carbon)	0.139	0.137	0.30	0.14
Mn	(Manganese)	1.446	1.434	1.60	1.47
P	(Phosphorus)	0.011	0.010	0.035	0.013
S	(Sulfur)	0.005	0.004	0.035	0.007
Si	(Silicon)	0.312	0.31	0.50	0.30
Cu	(Copper)	0.032	0.031	0.50	0.03
Sn	(Tin)	0.002	0.002	-	0.01
Ni	(Nickel)	0.023	0.023	0.50	0.04
Cr	(Chromium)	0.028	0.027	0.25	0.04
Mo	(Molybdenum)	0.003	0.003	0.25	0.003
Al	(Aluminum)	0.041	0.041	-	0.04
V	(Vanadium)	0.041	0.041	0.13	0.04
Nb	(Niobium)	0.019	0.019	0.10	0.02
Zr	(Zirconium)	0.001	0.001	-	-
Ti	(Titanium)	0.02	0.019	0.05	0.02
B	(Boron)	0.0005	0.0005	0.001	0.0008
Ca	(Calcium)	0.0012	0.0013	-	-
Co	(Cobalt)	0.003	0.003	-	-
Fe	(Iron)	Balance	Balance	Balance	Balance
Cu+Ni+Cr+Mo		0.086	0.084	1.00	0.113
CE		0.38[1]	0.37[1]	-	0.40

1 MSS SP-75-2014.

Figure 1. Photograph of the pipe section as received at DNV, after unloading. The pipe section was wrapped with plastic and tarps, with the ends sealed. The fracture surfaces were protected with foam tubing insulation. Typical of pipeline construction, various labels were written on the external pipe surface, such as "Jt: J17022807H HT: SU92709, upstream, HFB0002, HCSA1, HJCA3, HMRA8, HTPA2, 36°, Jt: 1834 Ht: RYJ1-1, HFB0001, Jt: J17022807L Ht: SU92709, downstream, TDC, Jeeped 7-17-18, 2 of 3 JT sec, .740 36°".

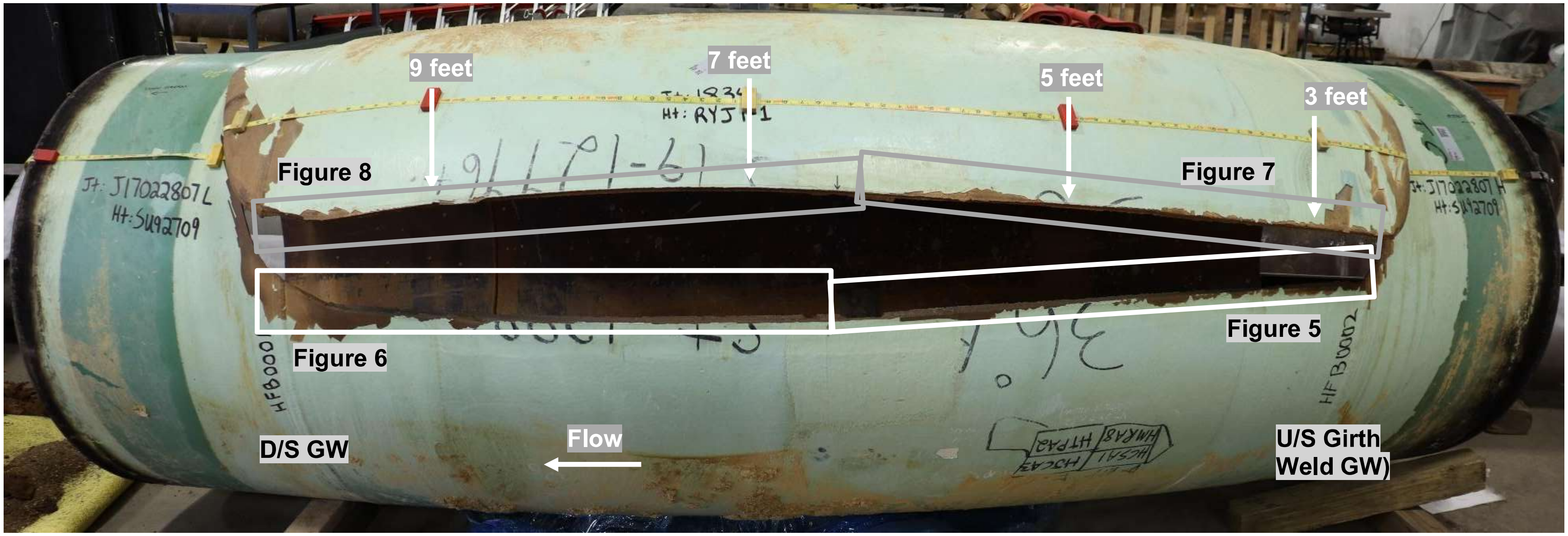


Figure 2. Photograph of the pipe section at DNV, following removal of the protective coverings. The tape measure indicates the distance, in feet, from the U/S end of the pipe section. The portion that was removed from the pipeline (*pipe section*) consists of an elbow fitting and two PUP sections. The pipe section ruptured along the seam weld of the elbow fitting and terminated in the PUP sections. The rupture opening was located between 1.55 and 11.22 feet (116 inches long) from the upstream (U/S) end of the pipe section, with a maximum opening of 10.9 inches at a distance of 7.42 feet from the U/S end of the pipe section or 4.97 feet from the U/S girth weld (GW). Measured near the fracture surface, close to the extrados, the pipe section was approximately 12.6 feet long, the U/S PUP was 2.45 feet long, and the elbow fitting was 7.65 feet long. The seam weld that failed on the elbow fitting was at the 9:06 orientation. The seam welds on the U/S and downstream (D/S) PUPs were at the 6:00 orientations and appeared to be submerged arc welds (SAWs). There was no evidence of external or internal corrosion. The external coating was adhered except for some portions adjacent to the fracture surfaces that disbonded due to the rupture. Portions of the pipe in the white and grey boxes were removed for further fractographic and metallographic analyses.

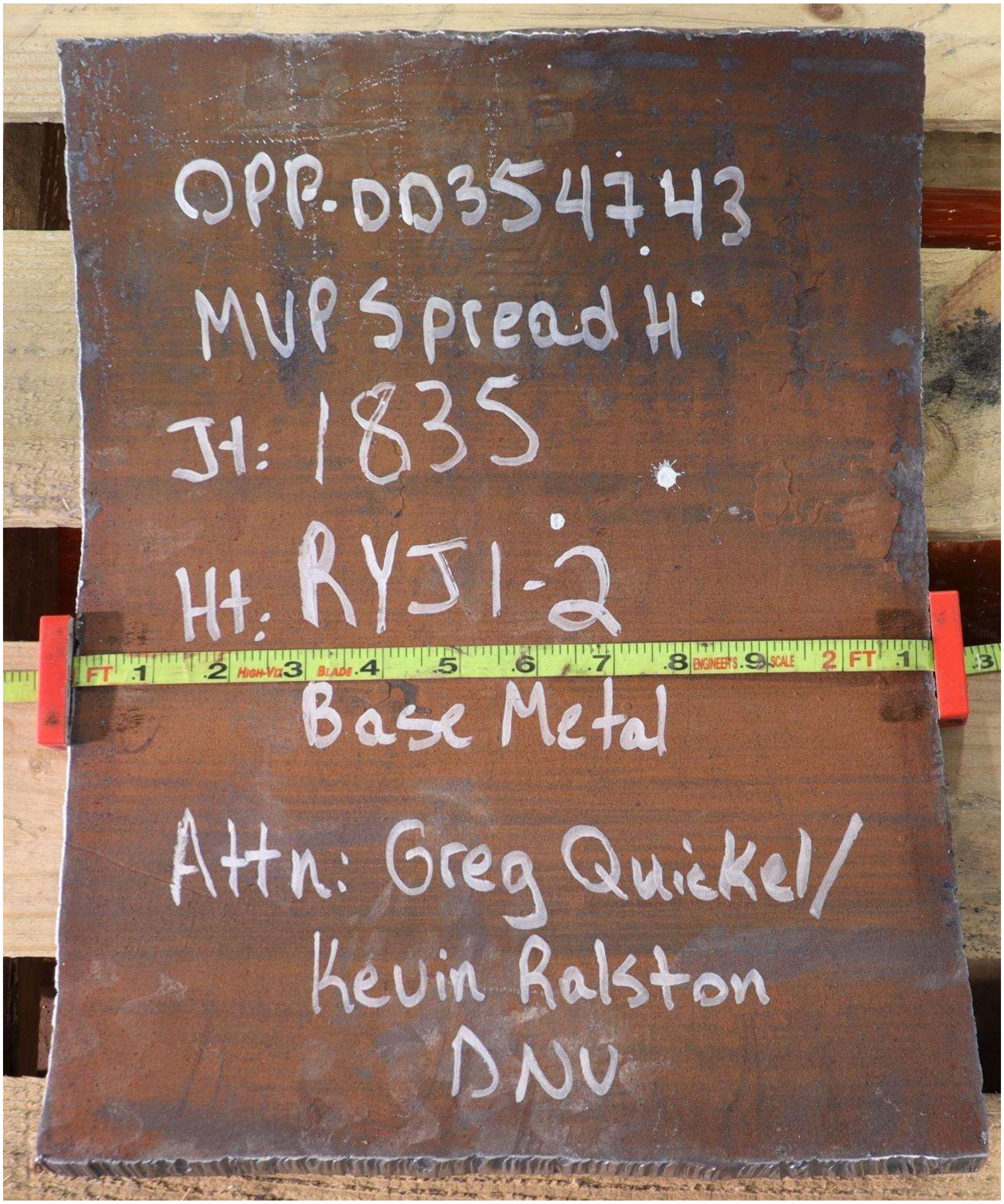


Figure 3. Photograph of the base metal coupon from the sister elbow fitting that was used for base metal tensile testing and Charpy V-notch (CVN) impact testing. The tape measure indicates dimensions in feet.

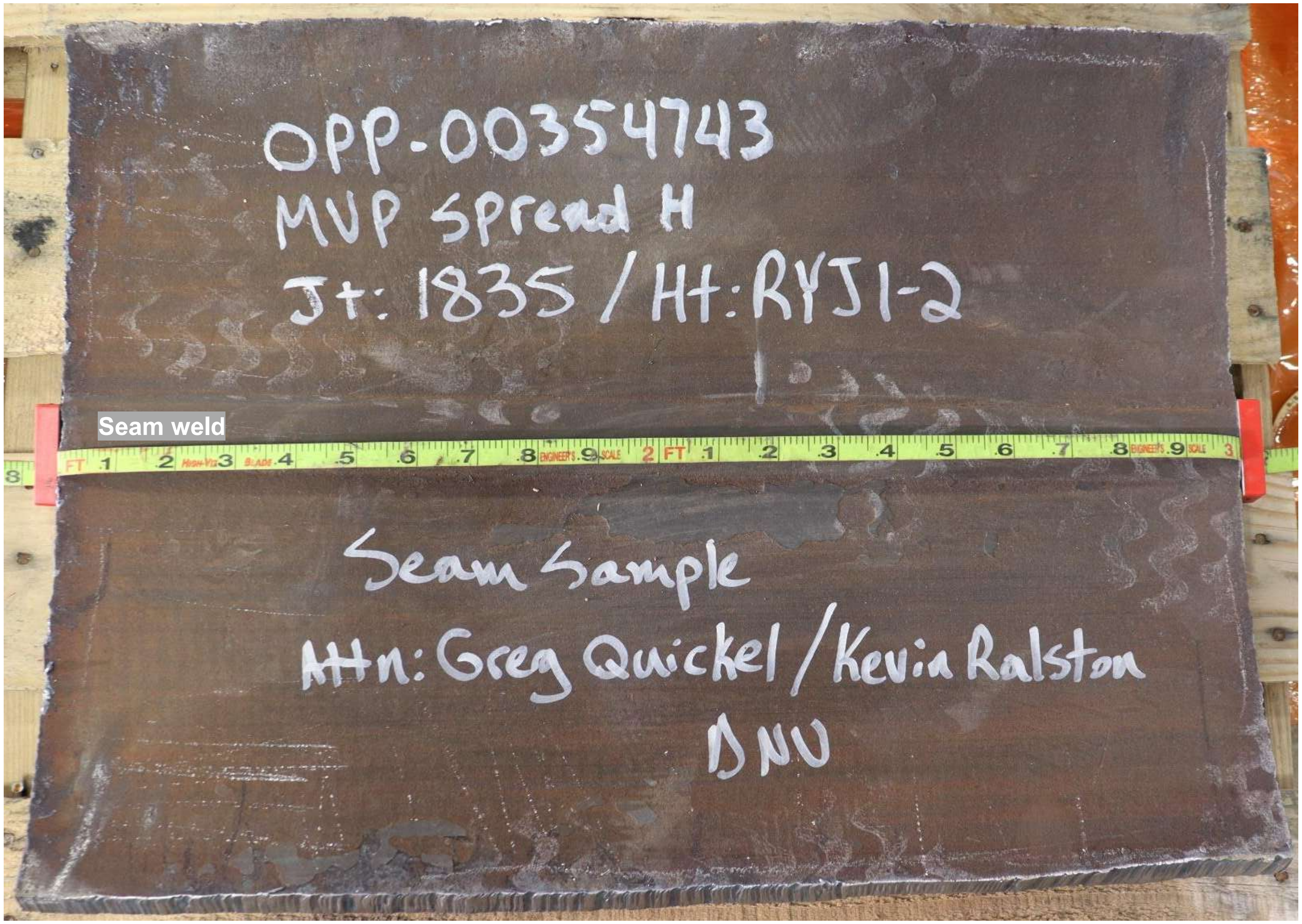


Figure 4. Photograph of the seam weld coupon from the sister elbow fitting that was used for seam weld tensile testing, Charpy V-notch (CVN) impact testing, base metal steel chemistry testing, and metallography of the seam weld. The tape measure indicates dimensions in feet.

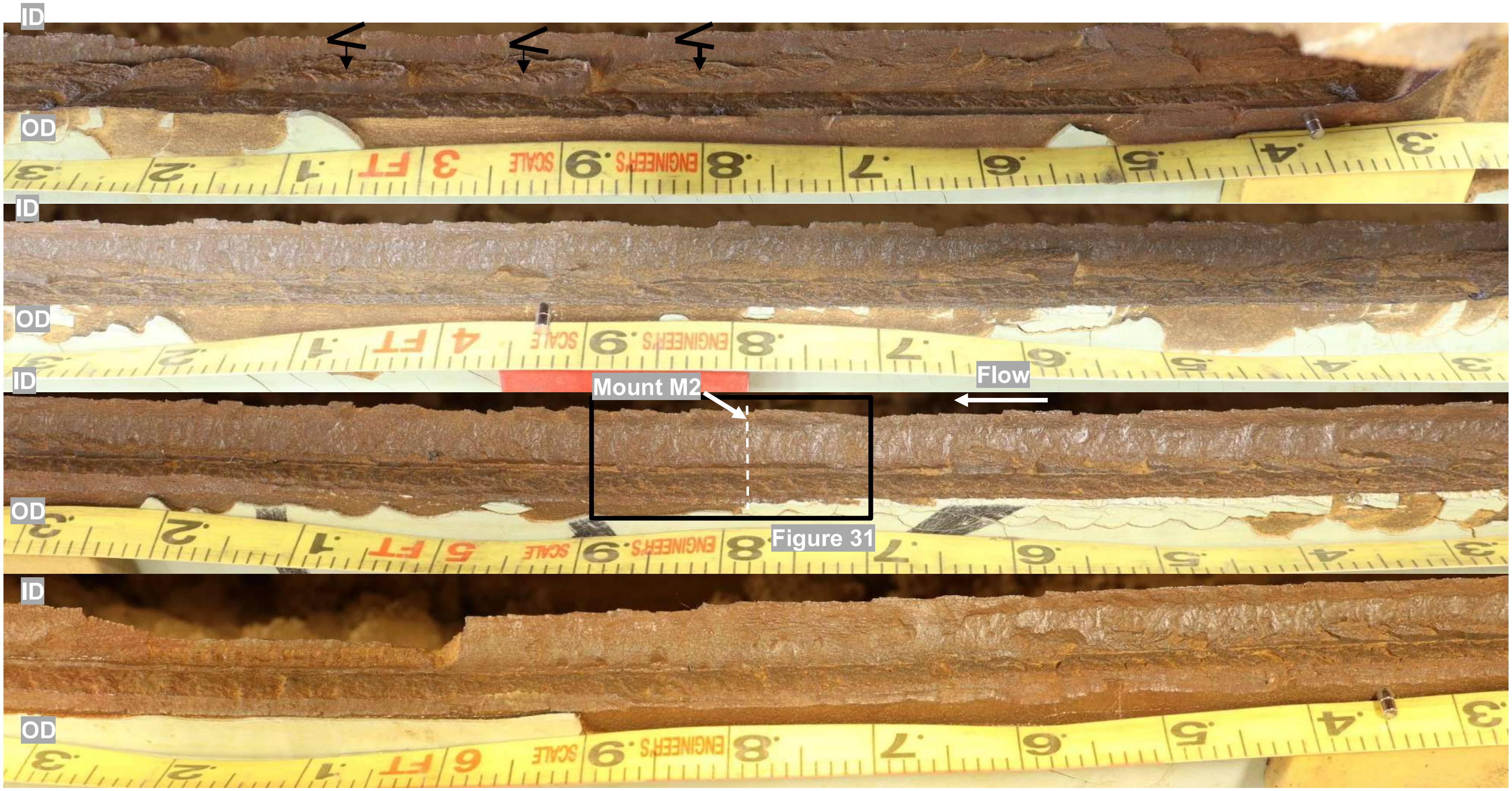


Figure 5. Photographs (4) of the fracture surface counter clockwise (CCW) of the rupture opening from 2.3 to 6.3 feet from the U/S end of the pipe section; area indicated in Figure 2. The tape measure indicates the distance from the U/S end of the pipe section. Chevrons are located on the top photograph indicating that the origin was D/S of that location (3.1 feet D/S from the U/S end of the pipe section). No obvious pre-existing flaws were observed on the fracture surface.

Figure 6. Photographs of the fracture surface CCW of the rupture opening from 6.3 to 10.1 feet from the U/S end of the pipe section; area indicated in Figure 2. The tape measure indicates the distance from the U/S end of the pipe section. Chevrons are located in the bottom two photographs indicating that the origin was U/S of 8.9 feet from the U/S end of the pipe section, indicating the origin is between 3.1 and 8.9 feet from the U/S end of the pipe section, near the middle of the elbow fitting. No obvious pre-existing flaws were observed on the fracture surface. Overall, the fracture surfaces had a similar profile for the entire length where midwall was further away from the camera compared to the OD and ID surfaces. Additionally, the fracture surfaces are slightly rough to macroscopically smooth, except for a few places near the ends of the fracture surfaces.

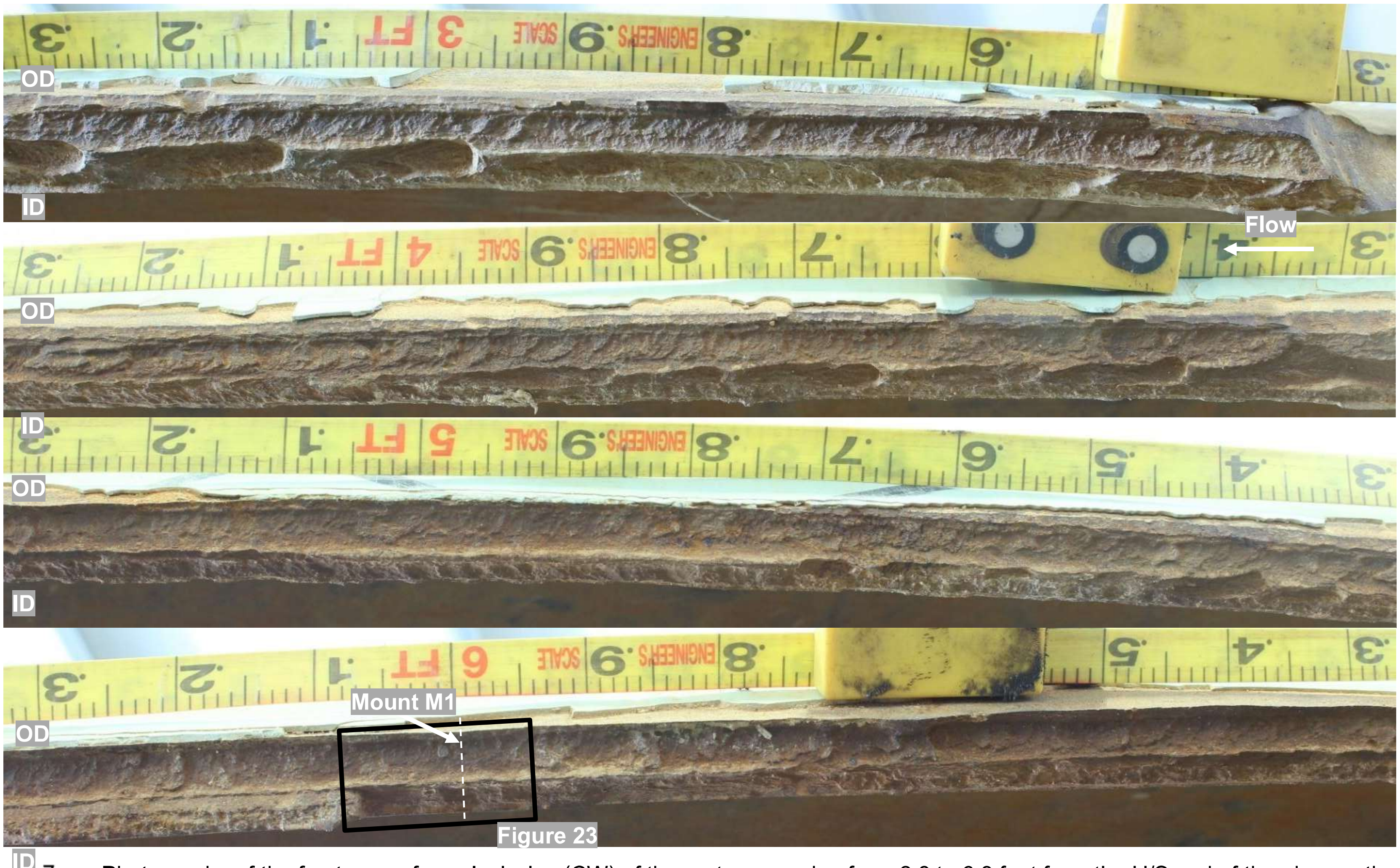


Figure 7. Photographs of the fracture surface clockwise (CW) of the rupture opening from 2.3 to 6.3 feet from the U/S end of the pipe section. The tape measure indicates the distance from the U/S end of the pipe section. The fracture morphology is similar to the CCW fracture surface expect more topography is visible due to the lighting.

Figure 8. Photographs of the fracture surface CW of the rupture opening from 6.3 to 10.2 feet from the U/S end of the pipe section. The tape measure indicates the distance from the U/S end of the pipe section. The fracture morphology is similar to the CW fracture surface expect more topography is visible due to the lighting.

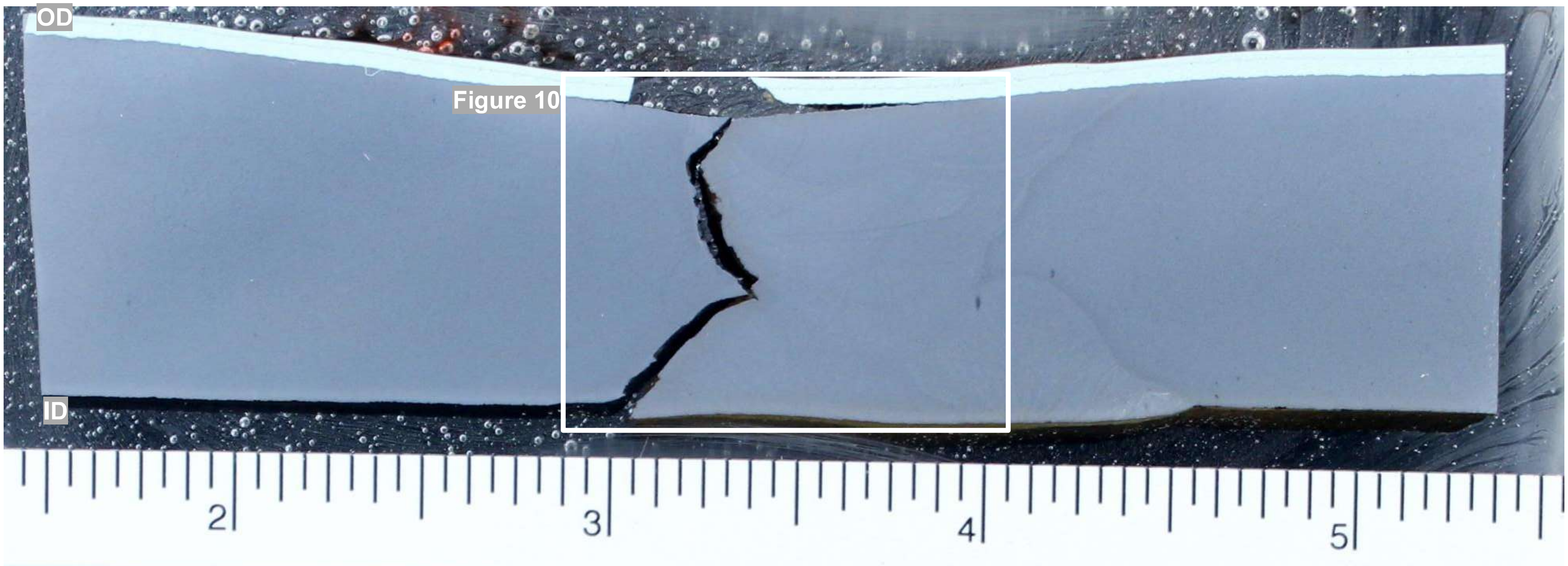


Figure 9. Photograph of the transverse metallographic section (Mount M1) that was removed across the rupture opening, approximately 5.99 feet from the U/S end of the pipe section, near the middle of the elbow fitting. The scale is in inches. See Figure 7 for the mount location. The middle of the fitting was 6.27 feet from the U/S end of the pipe section, near this location. The fracture path appears to be located at or near the fusion line between the weld metal and base metal. The wall thickness at the far left of the cross-section, at the rupture opening, and far right of the cross-section are approximately 0.965 inches, 0.790 inches, and 0.904 inches, respectively. The significant wall reduction/necking is evident in the cross-section and maximum at the rupture opening, consistent with a ductile overload failure. The weld metal on the ID surface is approximately 1.5 inches wide (in the circumferential direction). This cross-section (and adjacent SEM sample) was removed at this location since it appeared to be the thinnest region of the fracture surfaces, due to the necking.

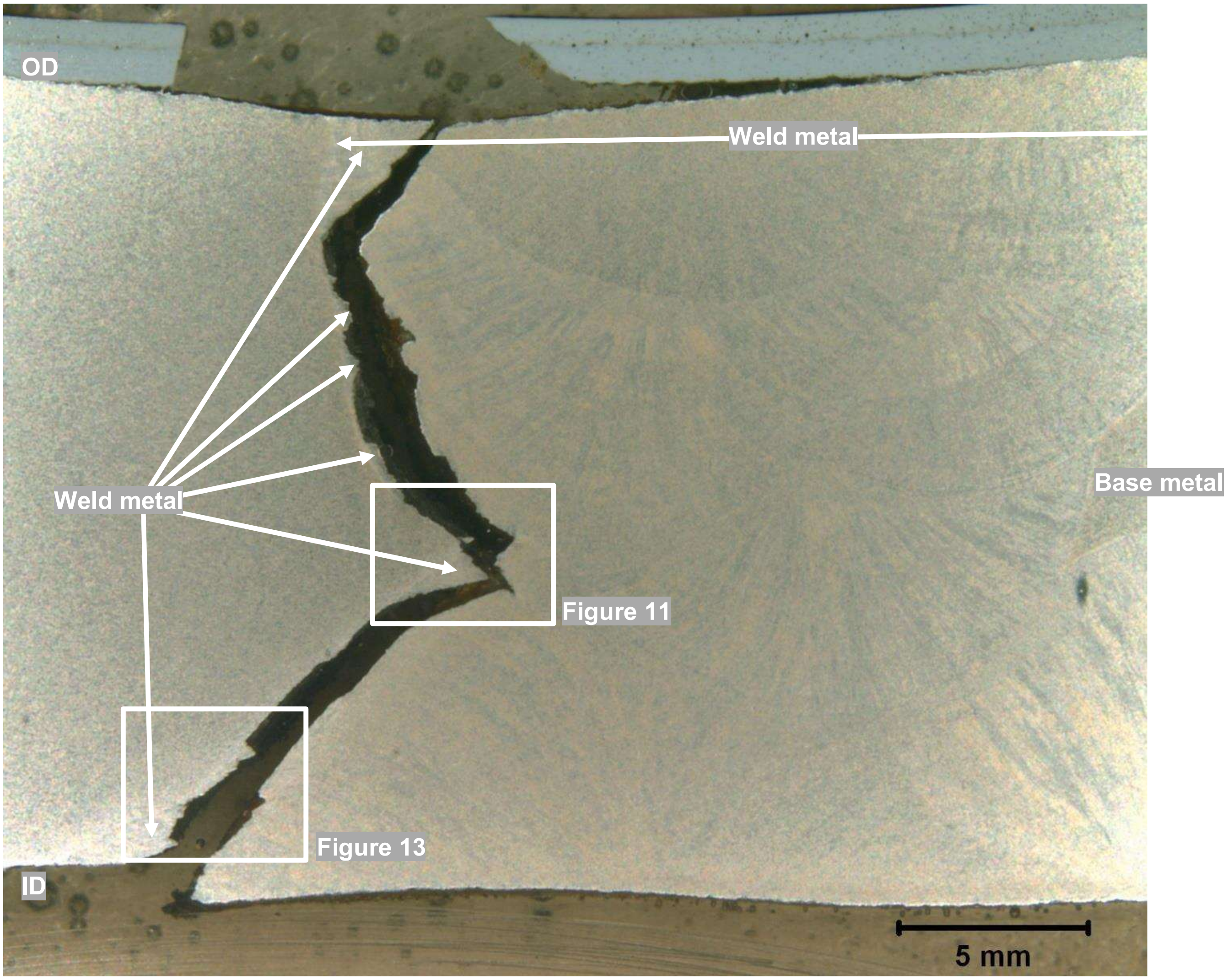


Figure 10. Light photomicrograph of transverse Mount M1 showing the fractures surfaces in cross-section (2% Nital Etchant); area indicated in Figure 9. There appears to be 5 (or 6) weld passes made from the OD surface and 2 from the ID surface with the ID passes being deposited first. The figure shows that the crack path is through the weld metal at the OD surface, ID surface, and midwall, and located at or near the fusion boundary elsewhere. Most of the material is base metal left of the fracture path and weld metal right of the fracture path.

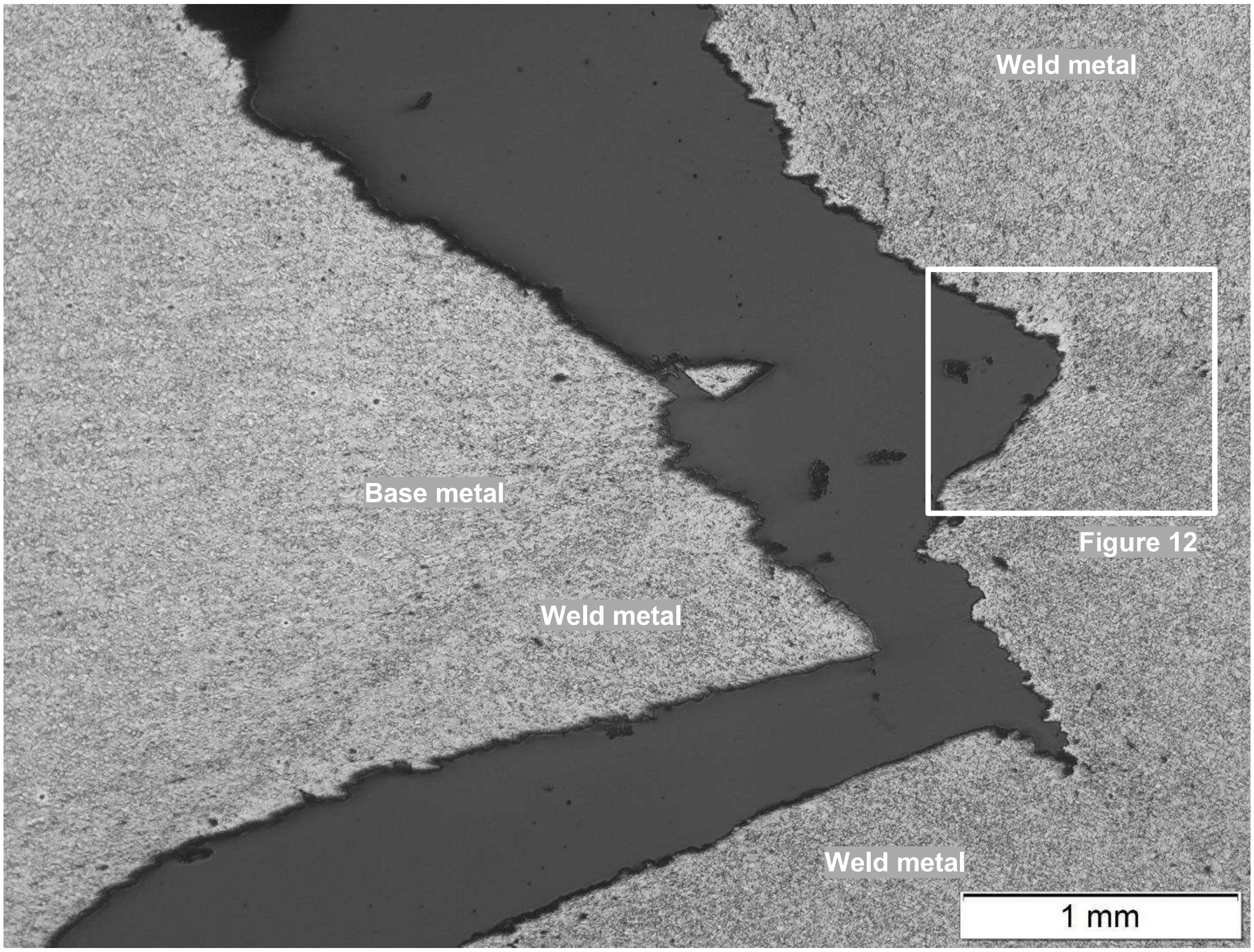


Figure 11. Light photomicrograph of Mount M1 midwall (2% Nital Etchant); area indicated in Figure 10. The figure shows where a portion of the path is through the weld metal and the remainder is at or near the fusion boundary.

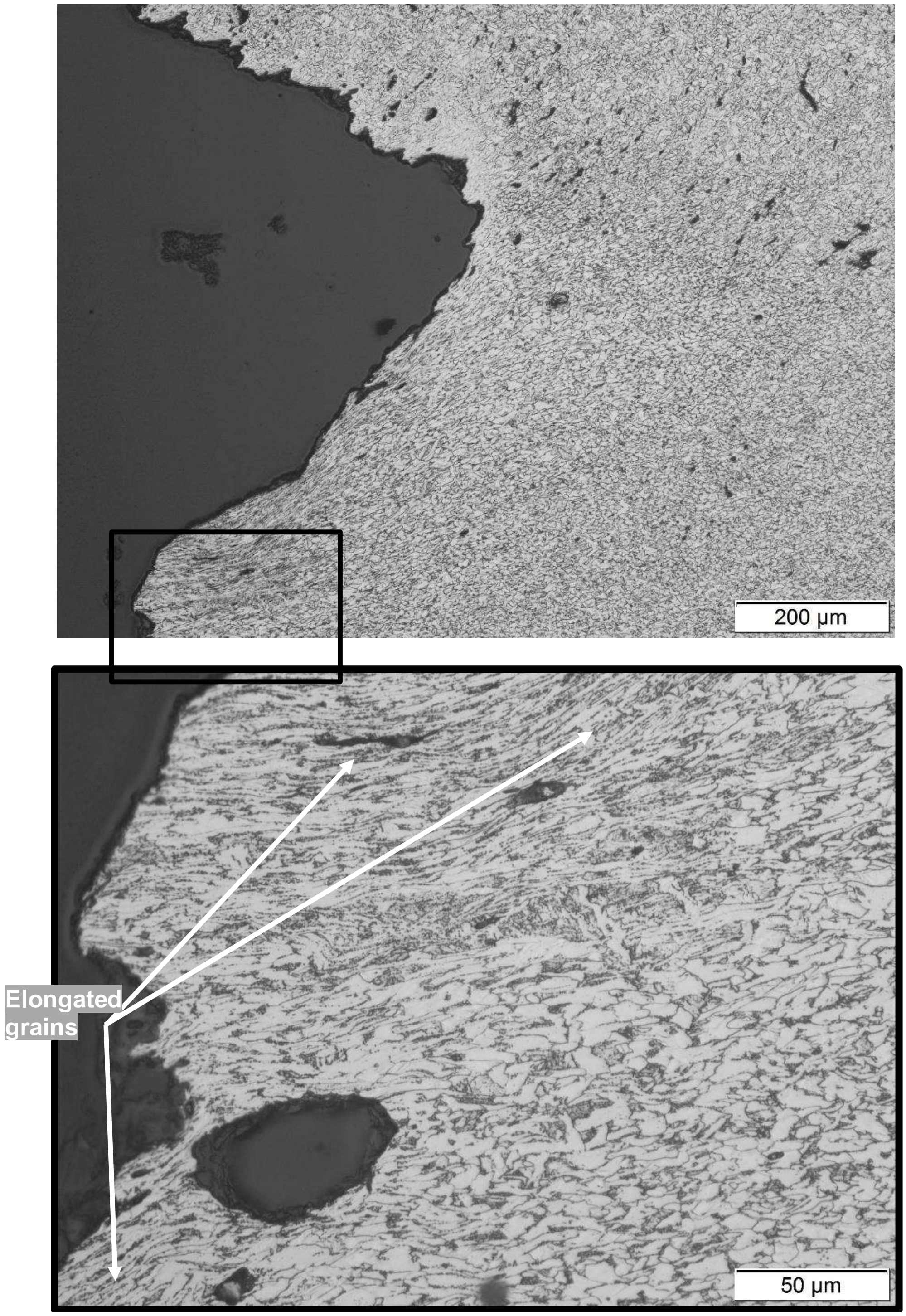


Figure 12. Low and high magnification light photomicrographs of Mount M1 midwall (2% Nital Etchant); area indicated in Figure 11. The figures shows elongated grains adjacent to the fracture surface, which is consistent with ductile overload.

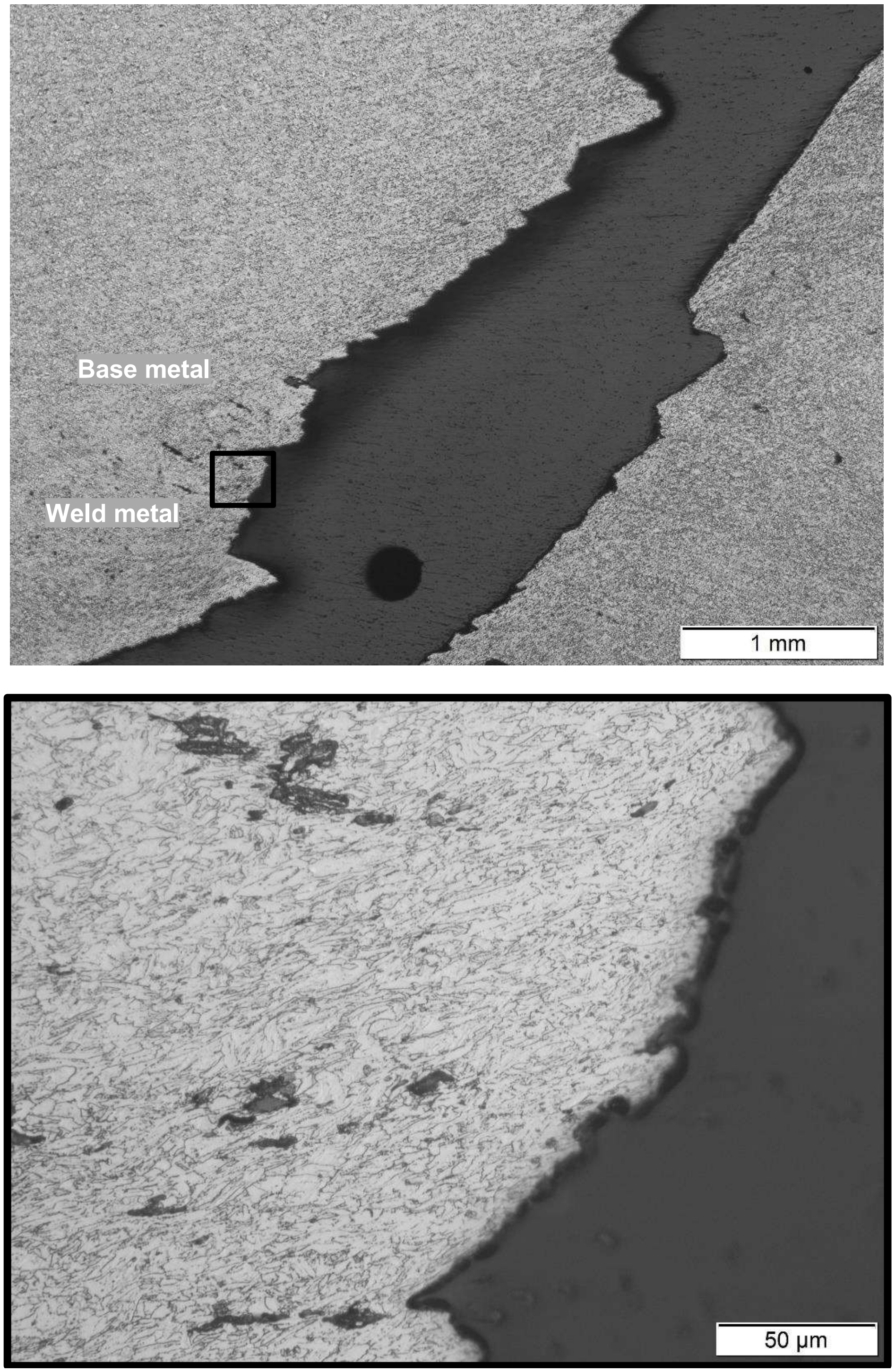


Figure 13. Low and high magnification light photomicrograph of Mount M1 near the ID surface (2% Nital Etchant); area indicated in Figure 10. The bottom photomicrograph shows elongated grains in the weld metal.

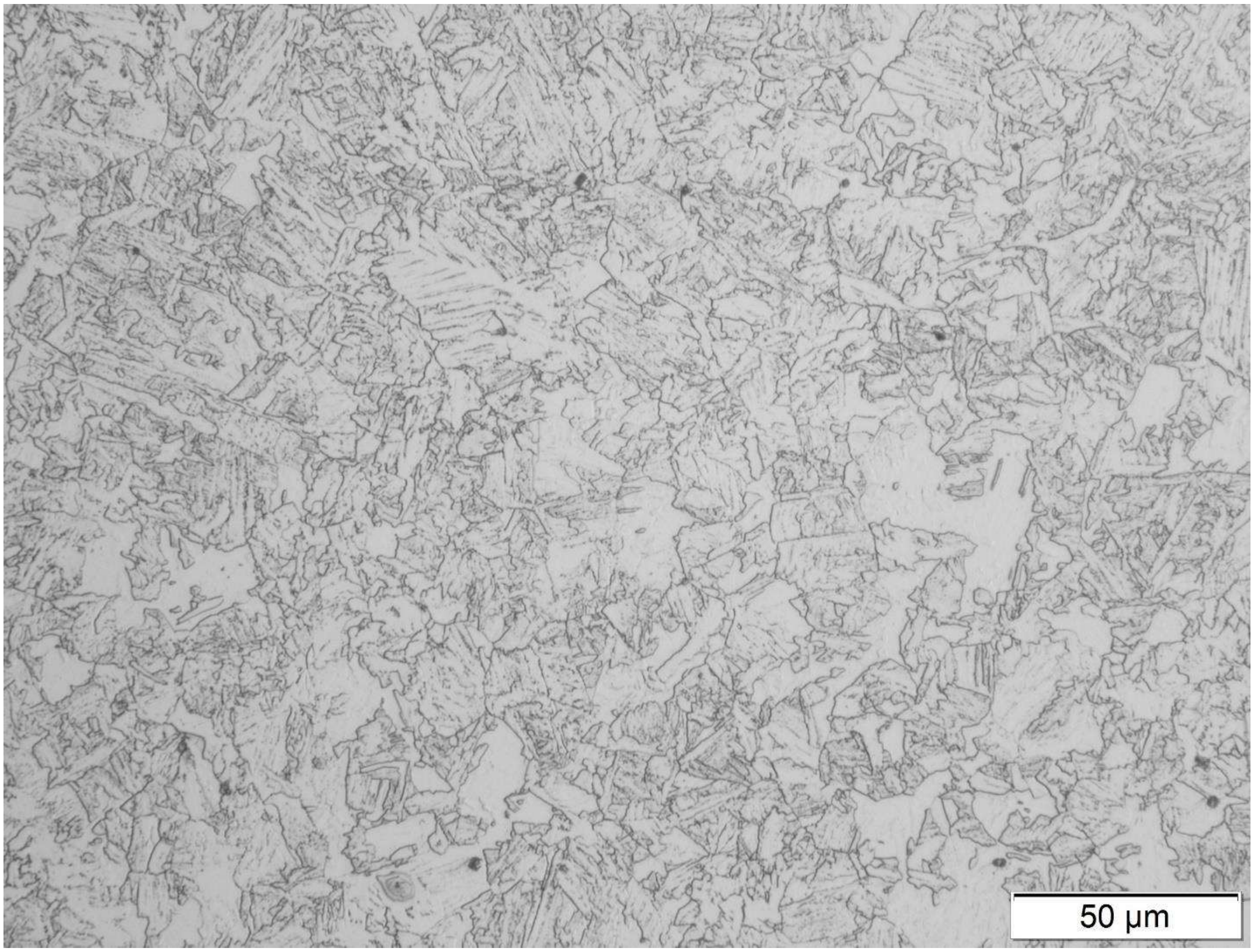


Figure 14. Light photomicrographs of Mount M1 showing the typical base metal microstructure of the fitting (2% Nital Etchant). The microstructure is consistent with a quench & temper (Q&T) microstructure and consistent with that reported in the MTR.

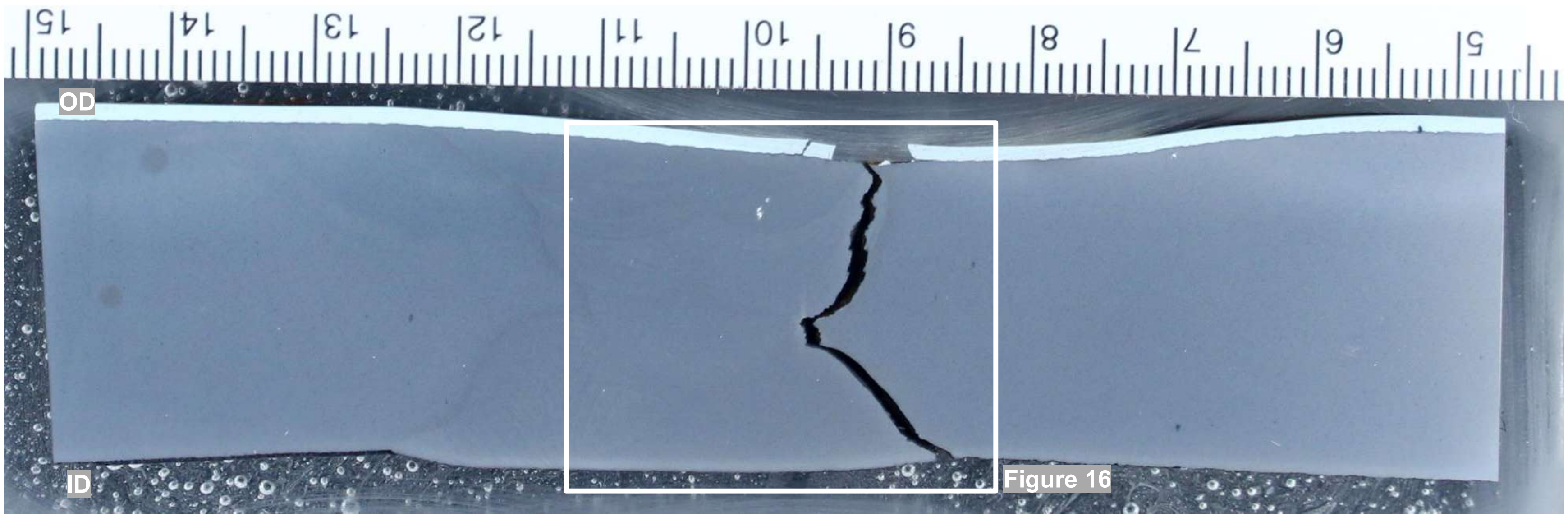


Figure 15. Photograph of the transverse metallographic section (Mount M2) that was removed across the rupture opening, approximately 4.78 feet from the U/S end of the pipe section. The scale is in millimeters. See Figure 5 for the mount location. The fracture path appears to be located at or near the fusion line between the weld metal and base metal. The wall thickness at the far left of the cross-section, at the rupture opening, and far right of the cross-section are approximately 0.926 inches, 0.823 inches, and 0.943 inches, respectively. The significant wall reduction/necking is evident in the cross-section and the necking is maximum at the rupture opening, consistent with a ductile overload failure. The weld metal on the ID surface is approximately 1.5 inches wide (in the circumferential direction). The morphology of the weld and the fracture path are similar at this location compared to in Mount M1. The cross-section (and adjacent SEM sample) was removed from this location along the fracture surface in order to examine the midwall vertical portion.

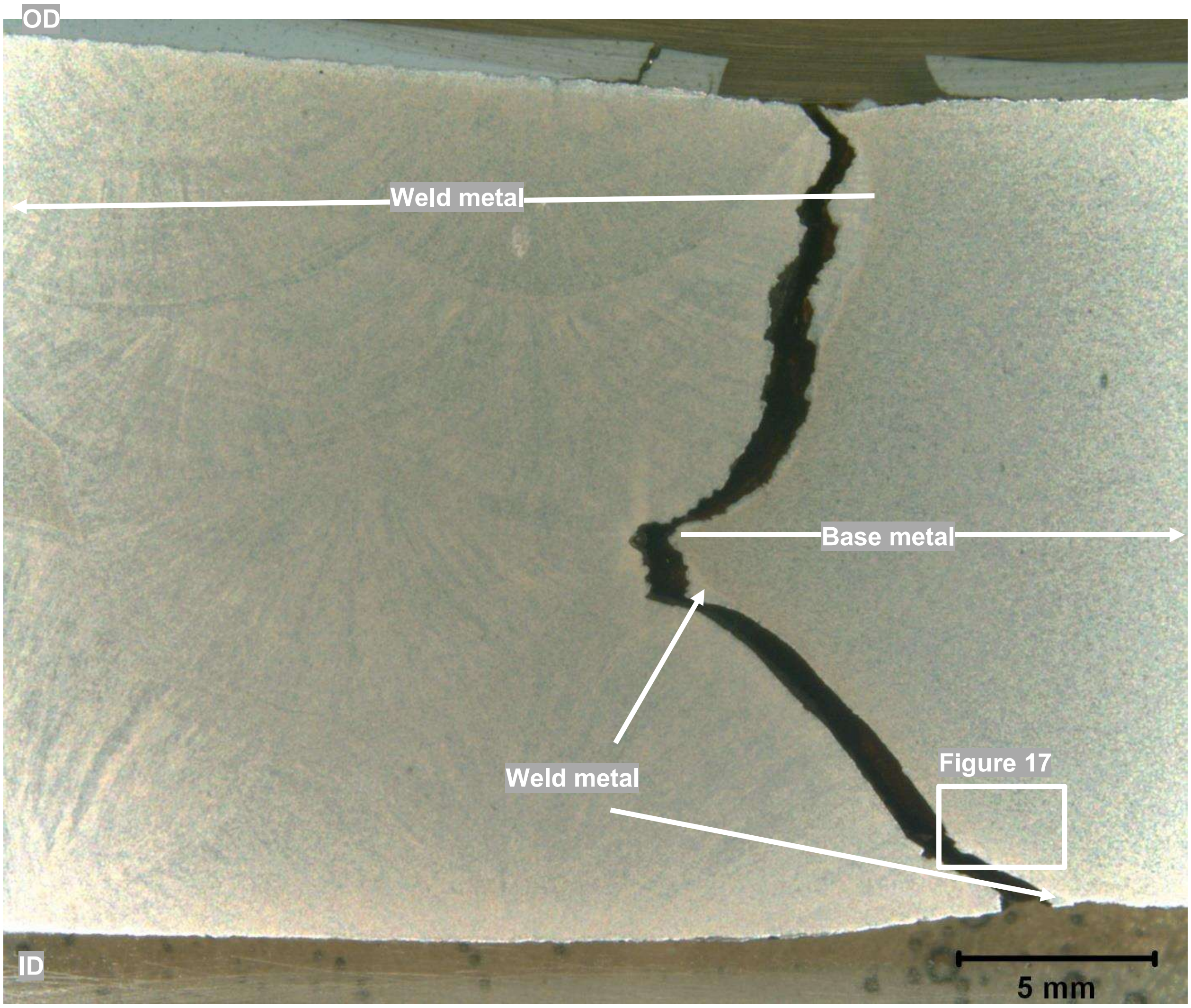
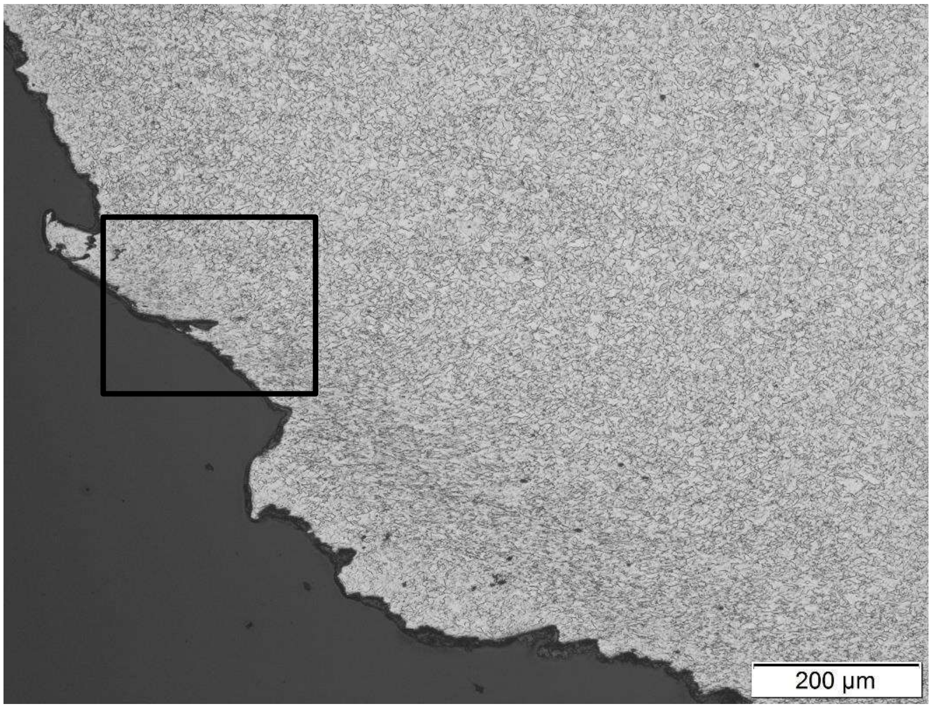


Figure 16. Light photomicrograph of transverse Mount M2 showing the fractures surfaces in cross-section (2% Nital Etchant); area indicated in Figure 15. There appears to be 5 weld passes made from the OD surface and 2 from the ID surface with the ID passes being deposited first. The figure shows that the crack path is through the weld metal at the OD surface, ID surface, and midwall, and located at or near the fusion boundary elsewhere. Most of the material is weld metal left of the fracture path and base metal right of the fracture path.



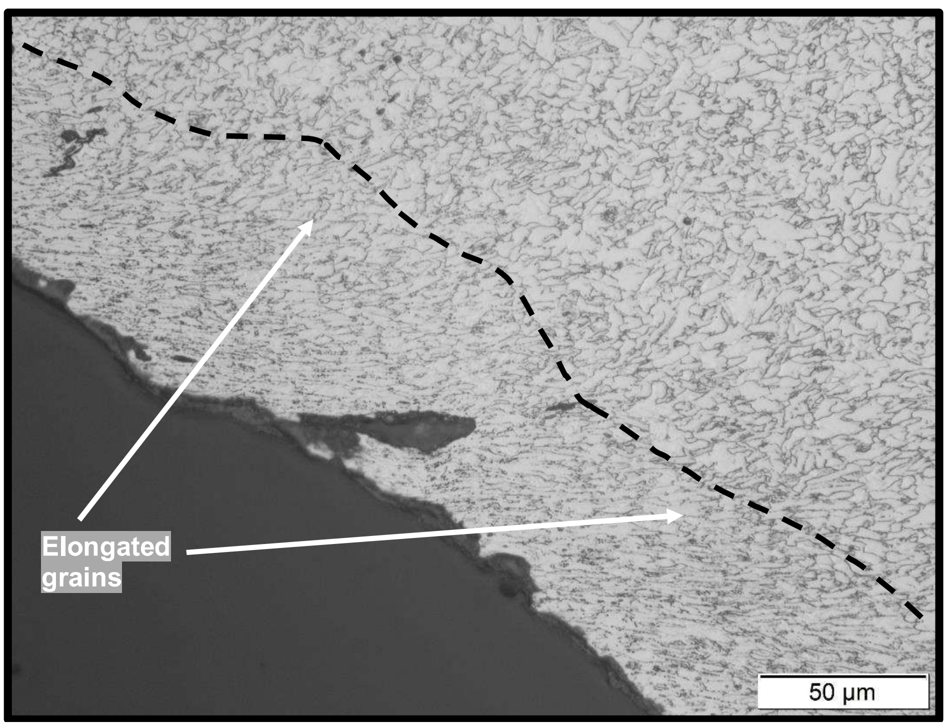


Figure 17. Low and high magnification light photomicrographs of Mount M2 near the ID surface (2% Nital Etchant); area indicated in Figure 16. The figure shows elongated grains at the fracture surface and unaffected grains away. The elongated grains are consistent with ductile overload.

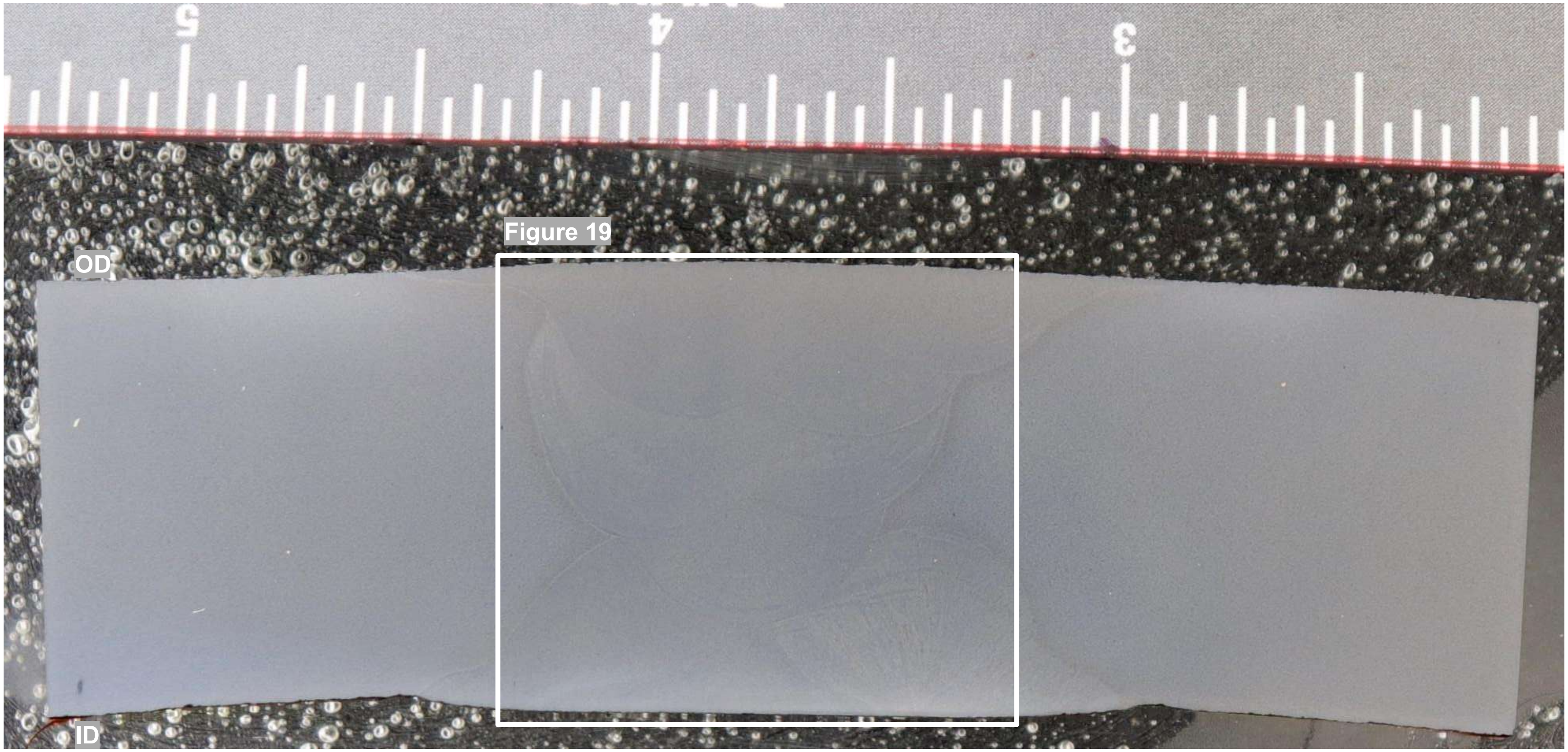


Figure 18. Photograph of the transverse metallographic section (Mount M3) that was removed across the seam weld of the sister elbow fitting. The scale is in inches. The morphology of the weld is similar to that in Mounts M1 and M2. The wall thickness at the far left of the cross-section, at the middle of the weld, and far right of the cross-section are approximately 0.925 inches, 0.959 inches, and 0.921 inches, respectively. Compared to Mounts M1 and M2, the fitting at this location does not show any evidence of wall reduction. The weld metal on the ID surface is approximately 1.5 inches wide (in the circumferential direction), similar to the failed elbow fitting.

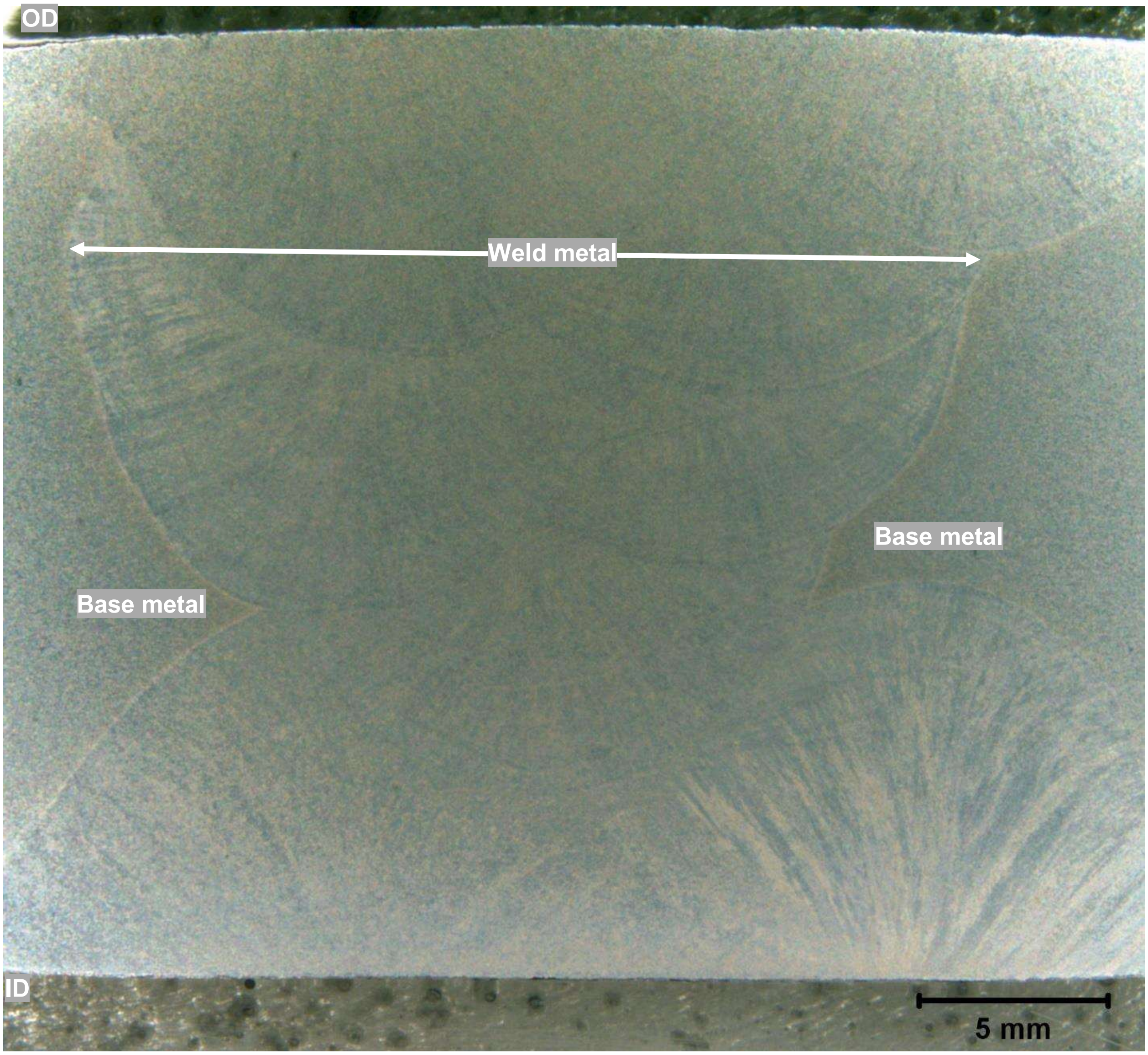


Figure 19. Light photomicrograph of Mount M3 showing the morphology of the weld (2% Nital Etchant); area indicated in Figure 18. There appears to be 6 weld passes made from the OD surface and 2 from the ID surface with the ID passes being deposited first. No pre-existing flaws are visible.

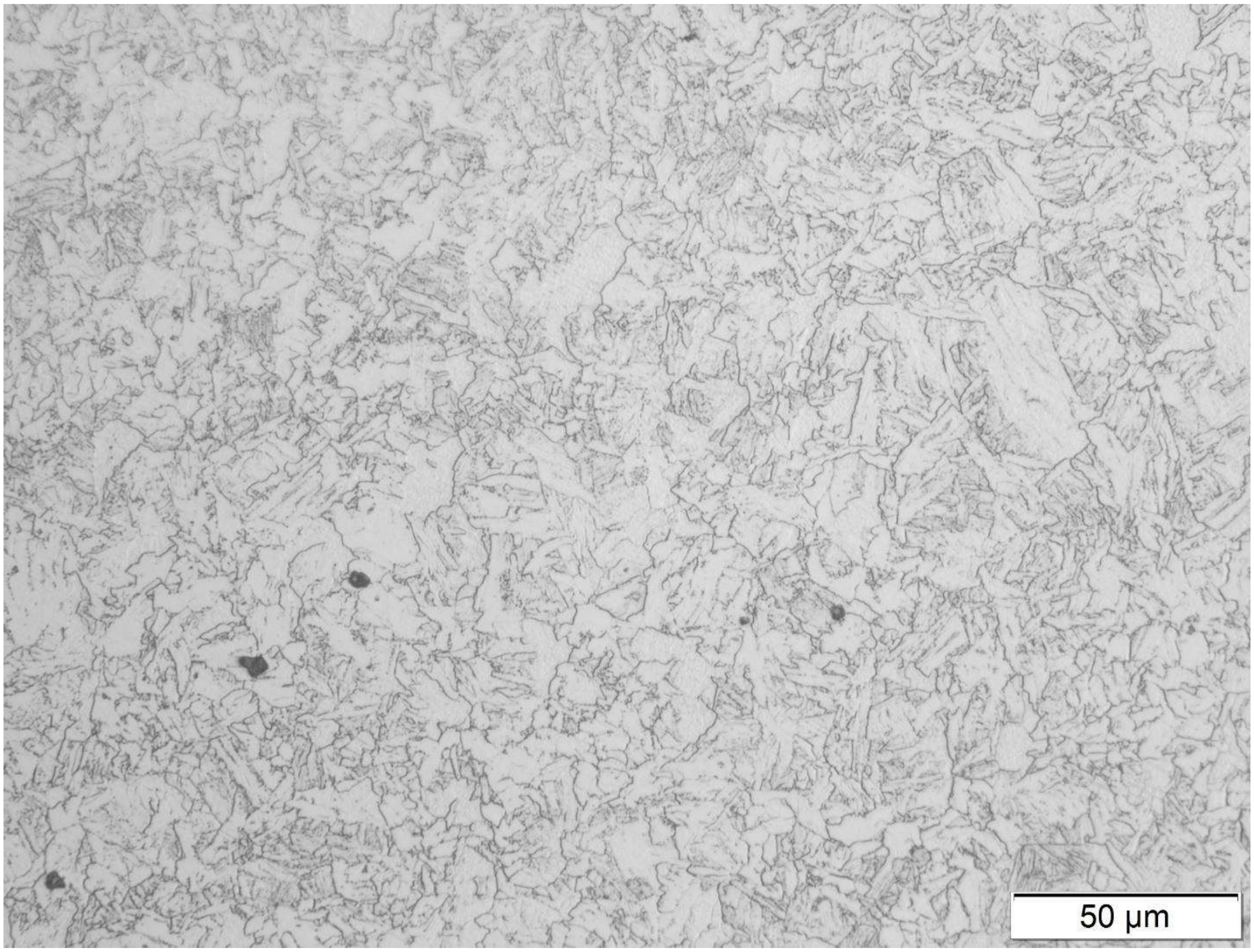


Figure 20. Light photomicrographs of Mount M3 showing the typical base metal microstructure of the sister elbow fitting (2% Nital Etchant). The microstructure is similar to that in the failed elbow fitting, consistent with a Q&T microstructure, and consistent with that reported in the MTR.

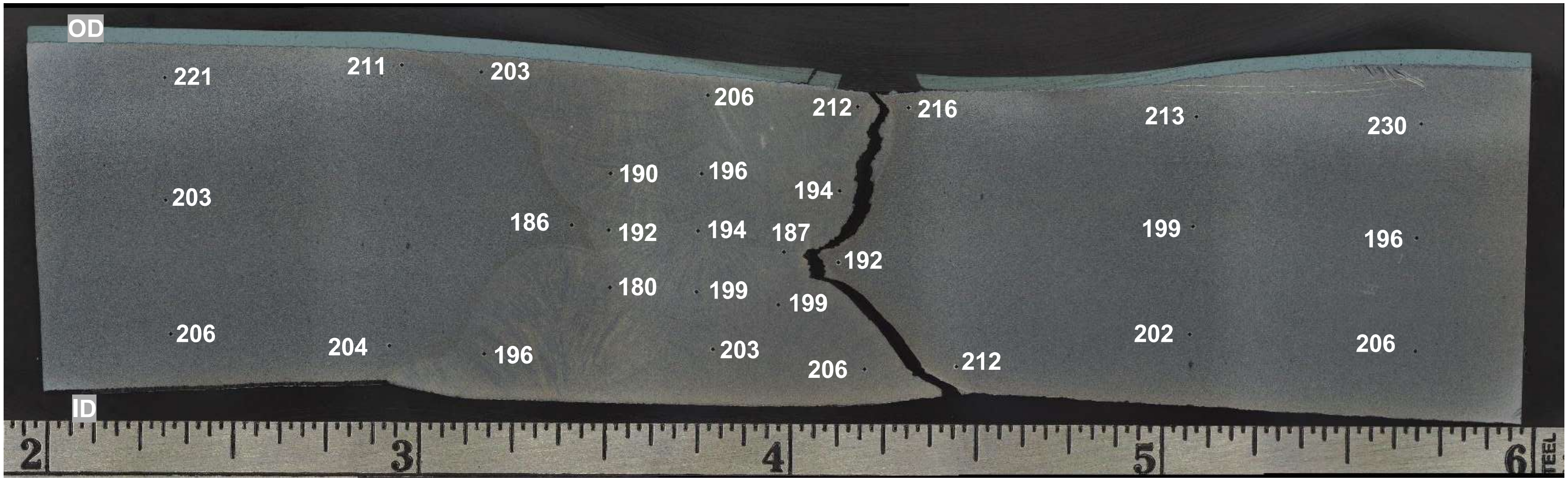


Figure 21. Light photomicrograph of Mount M2 from the failed elbow fitting following hardness testing (Vickers 10 kg load) showing the indents and corresponding hardness values (2% Nital Etchant). The hardness values are between 180 HV and 230 HV, with an average value of 202HV. The mid-thickness of the sample is slightly softer than the outer edges. The softest portion of the base metal is mid thickness near the weld metal (186 HV), near the intersection of OD and ID weld passes. The second lowest base metal value of 192 HV is adjacent to the fracture surface, mid-thickness, adjacent to the second softest weld metal value of 187 HV. The value of 192 HV may be higher than what was present prior to the hydrotest as grain elongation from the overload would locally increase the hardness. Overall, there appears to be a slight softening of the base metal mid-thickness adjacent to the weld metal, where the weld metal is also somewhat softer compared to the outer edges of the weld metal. This mid-thickness softening at and near the weld is what would be expected since those regions of the weld have been tempered by subsequent weld passes.

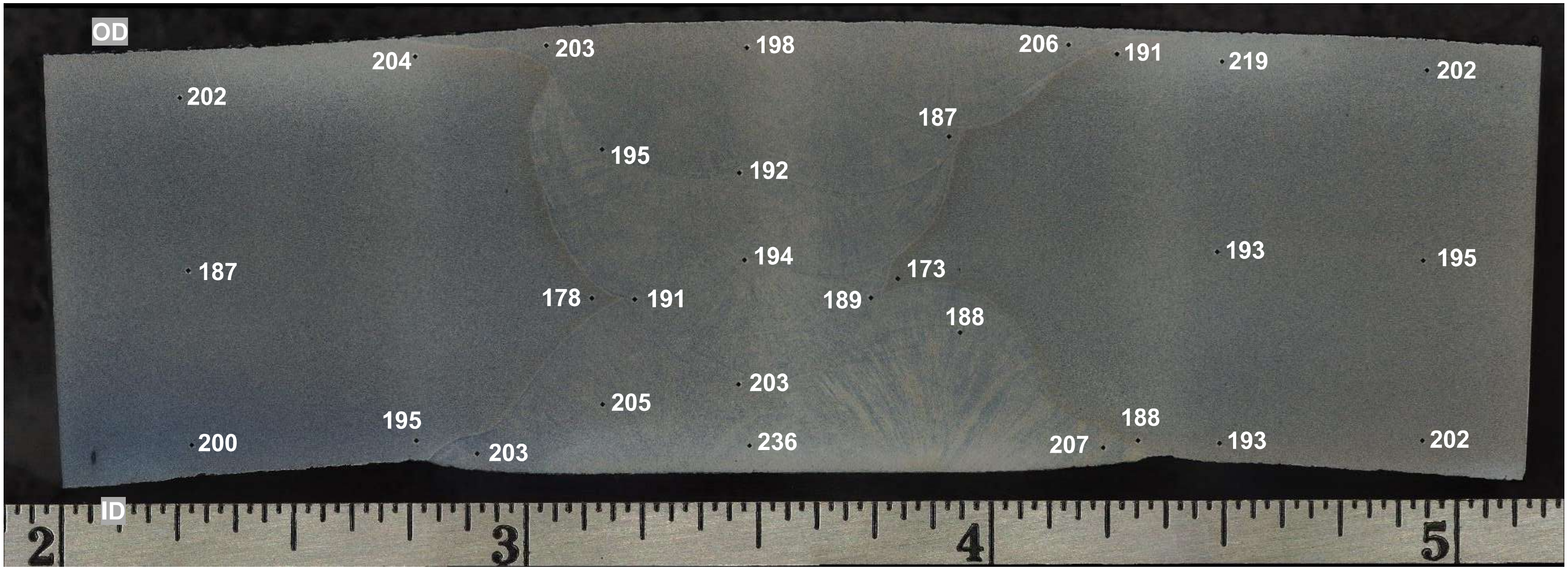


Figure 22. Light photomicrograph of Mount M3 from the sister elbow fitting following hardness testing (Vickers 10 kg load) showing the indents and corresponding hardness values (2% Nital Etchant). The hardness values are between 173 HV and 236 HV, with an average value of 197HV. A similar trend is present at this cross-section when comparing to Mount M2. The mid-thickness of the sample is slightly softer than the outer edges. The softest portion of the base metal is mid thickness near the weld metal (173 and 178 HV), near the intersection of OD and ID weld passes, compared to the next highest base metal value of 187 HV. Overall, there appears to be a softening of the base metal mid-thickness adjacent to the weld metal, where the weld metal is also somewhat softer compared to the outer edges of the weld metal.

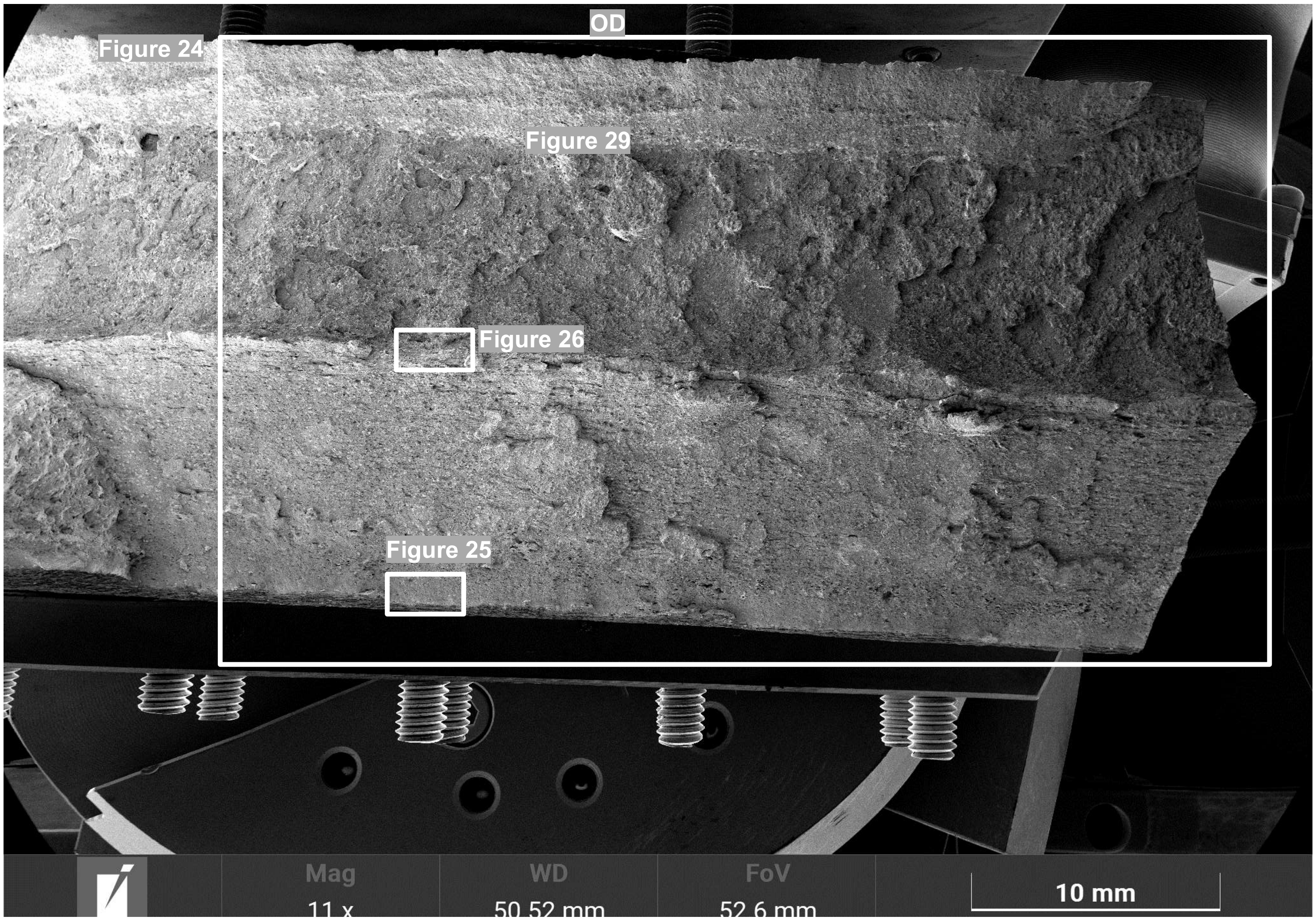


Figure 23. SEM image of Sample S1 showing the fracture surface, following cleaning in ENPREP®214; area indicated in Figure 7. The figure shows where higher magnification SEM images were taken. As mentioned above, the sample was removed at this location since it appeared to be the thinnest region of the fracture surface.

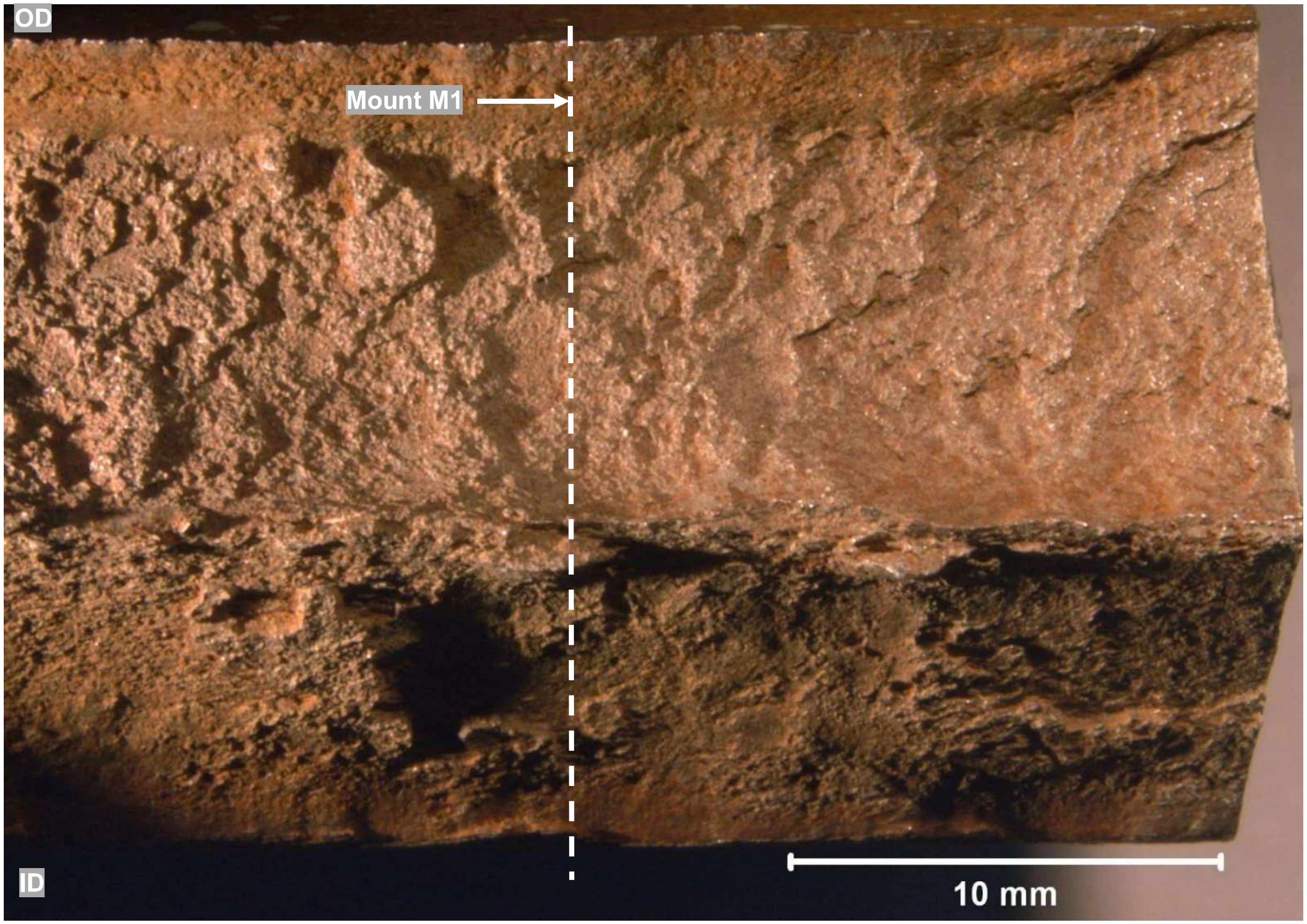


Figure 24. Light photomicrograph of Sample S1 showing the fracture surface; area indicated in Figure 23. The figure shows where Mount M1 was removed. The fracture surface is somewhat smooth from the ID surface to midwall, transitions to a rougher portion from midwall to just below the OD surface, and then the remaining portion adjacent to the OD surface is similar to the portion adjacent to the ID surface.

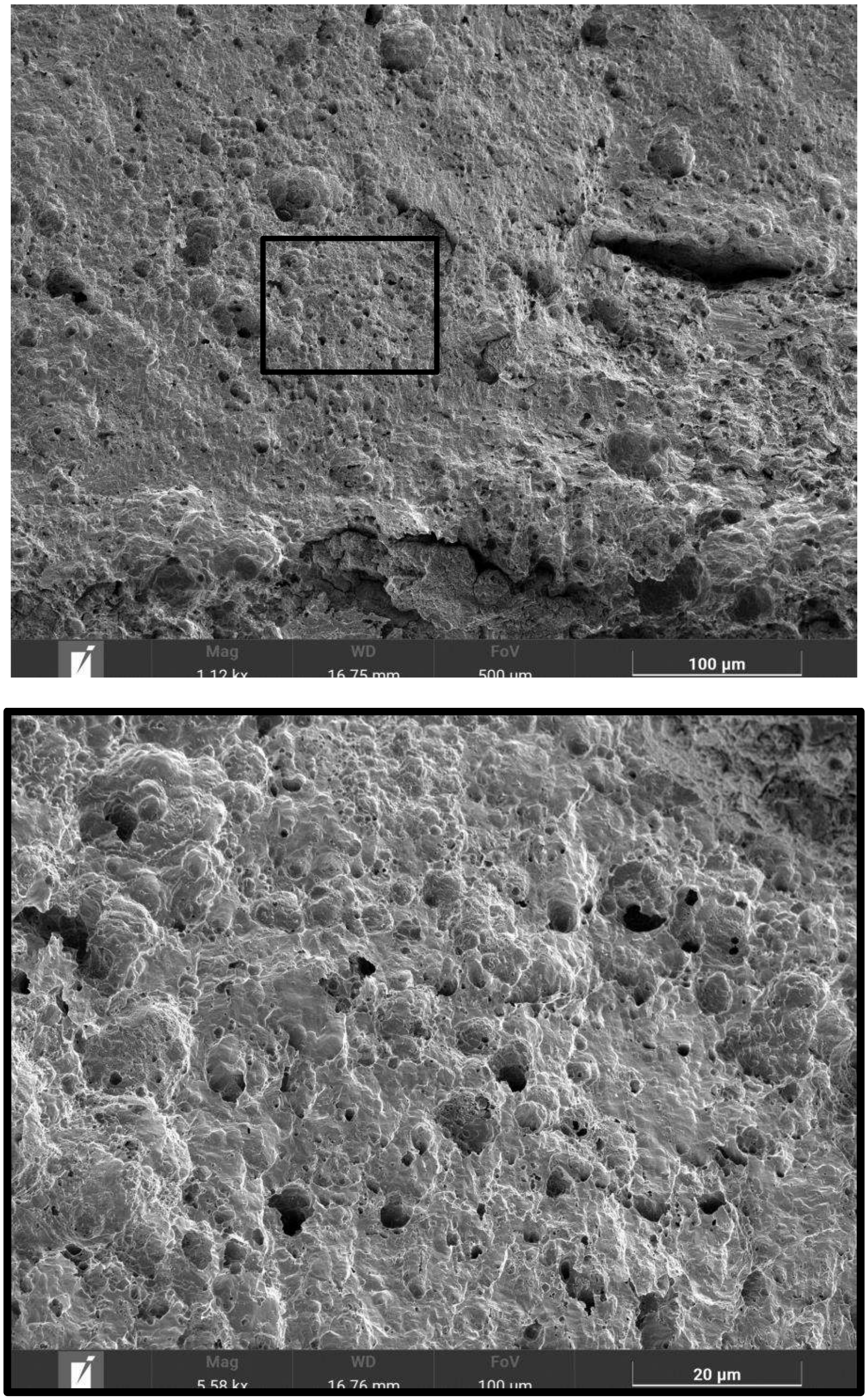


Figure 25. Low and high magnification SEM images of Sample S1 near the ID surface showing the fracture surface in Region 1; area indicated in Figure 23. The fracture surface consists of dimples, consistent with ductile fracture overload. This morphology is consistent with the metallographic cross-section.

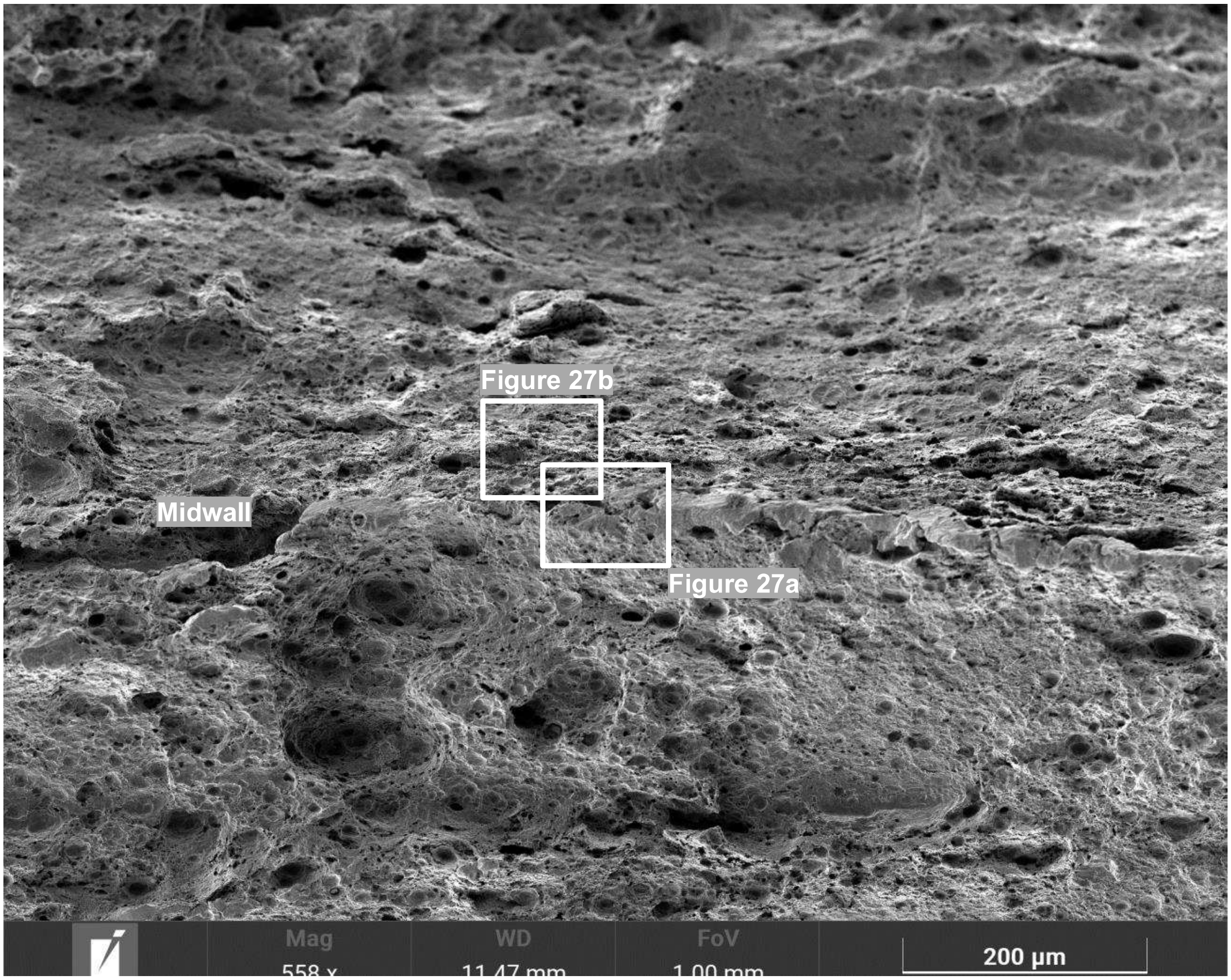


Figure 26. SEM image of Sample S1 midwall showing the fracture surface near midwall; area indicated in Figure 23. The fracture surface at this location also contains dimples, consistent with ductile overload.

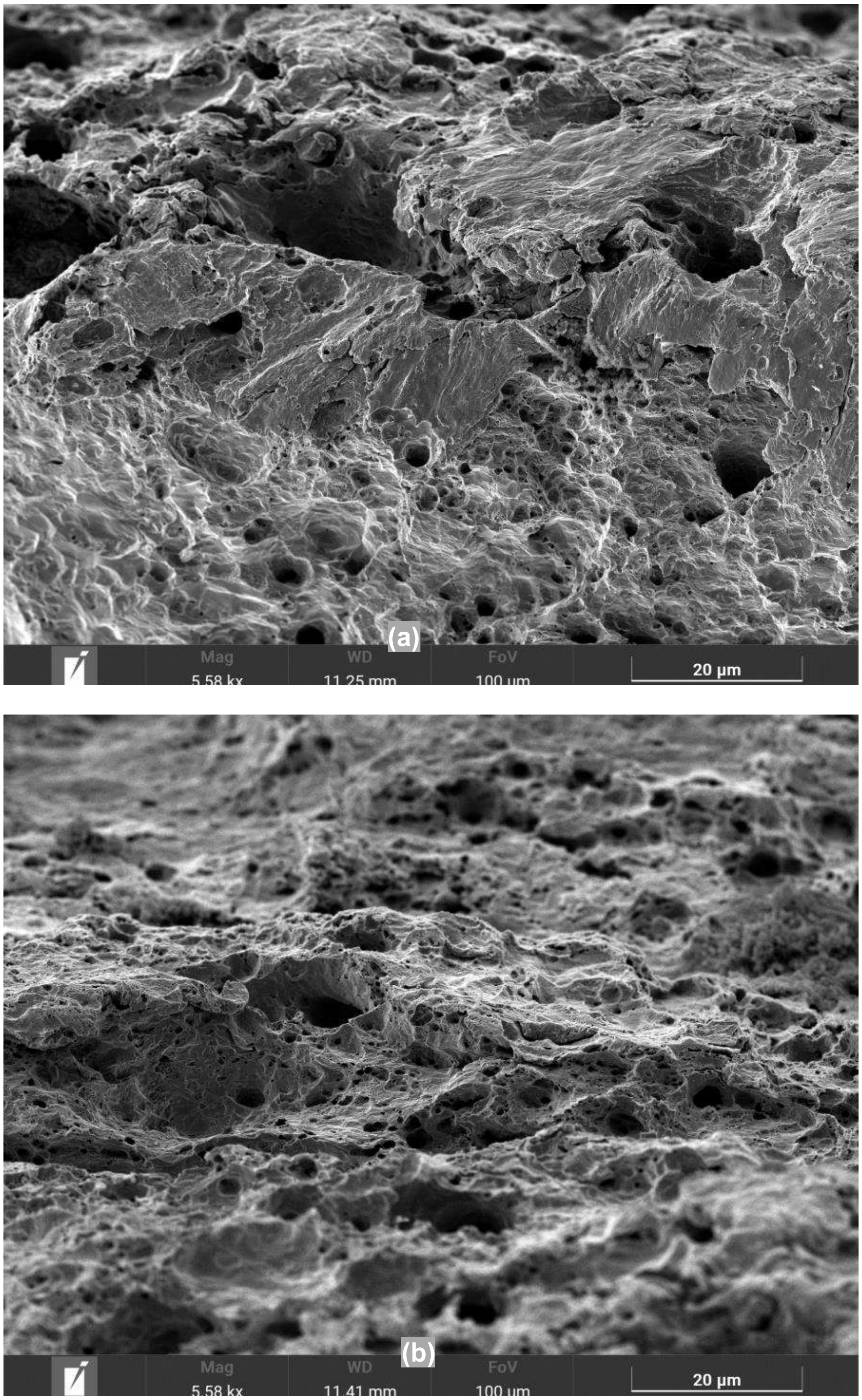


Figure 27. SEM images of Sample S1 at/below midwall (a) and above (b) showing the fracture surface; area indicated in Figure 26. The fracture surface appears smooth and smeared midwall as shown in (a) above and dimples are located above and below it.

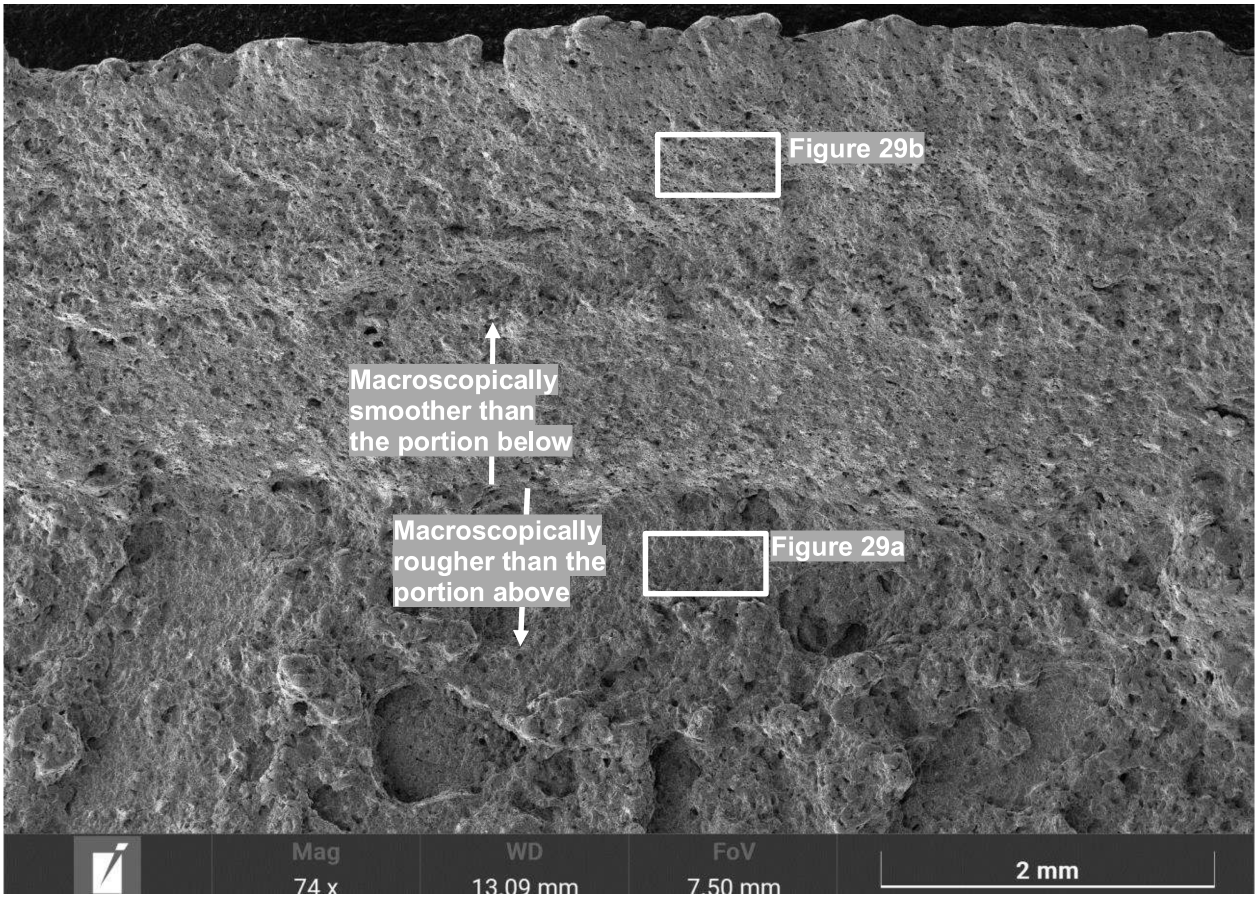


Figure 28. SEM image of Sample S1 showing the fracture surfaces near the OD surface; area indicated in Figure 23. The figure shows the difference in the topography of the fracture surface and where higher magnification SEM images were taken.

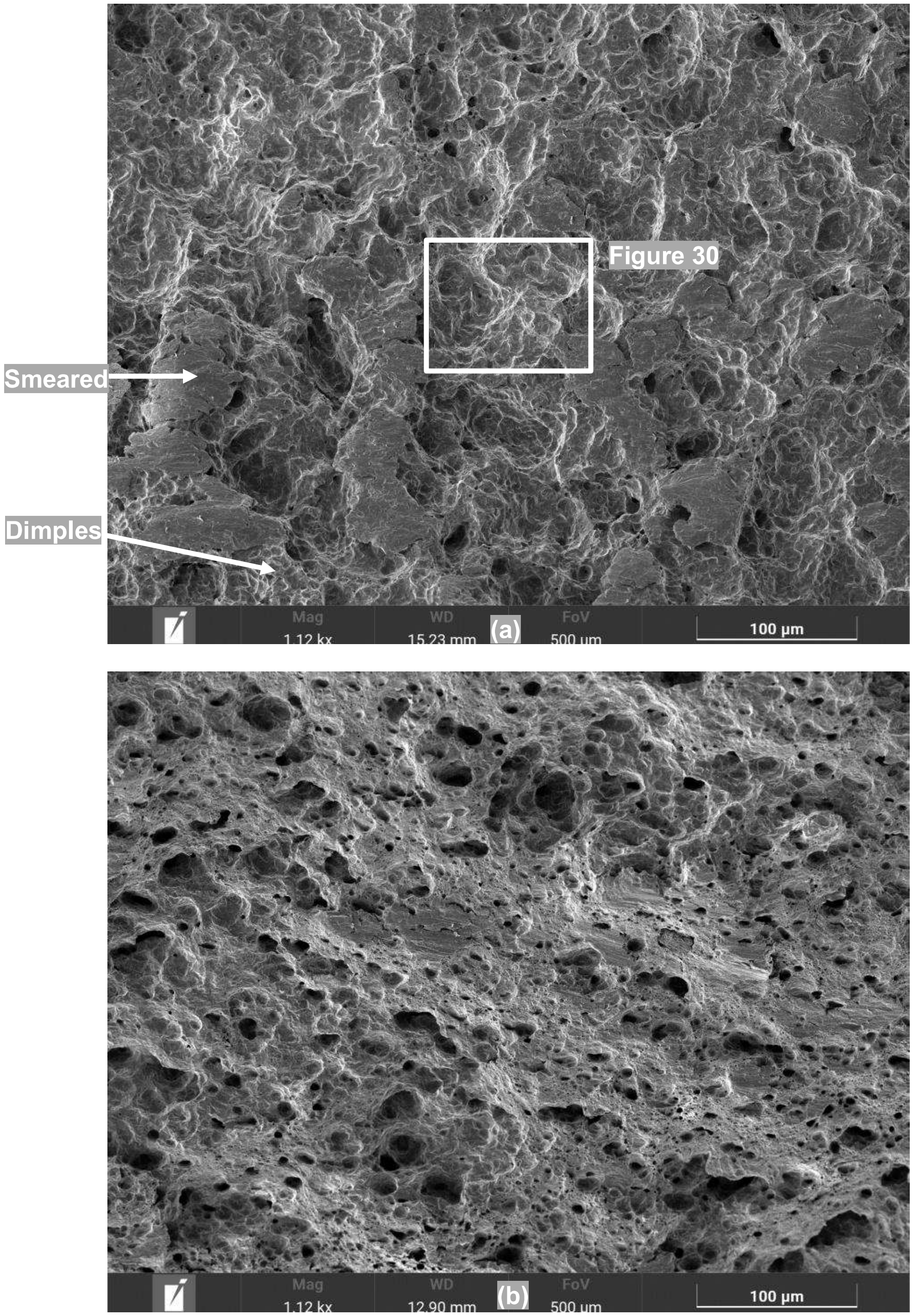


Figure 29. High magnification SEM images of Sample S1 showing the fracture surfaces at the areas described in Figure 28; areas indicated in Figure 28. The fracture surface contains in (a) above contains some dimples and smeared metal, less evidence of ductility compared to the other portions of the fracture surface. The fracture surface in (b) contains dimples. The dimples are consistent with ductile fracture.

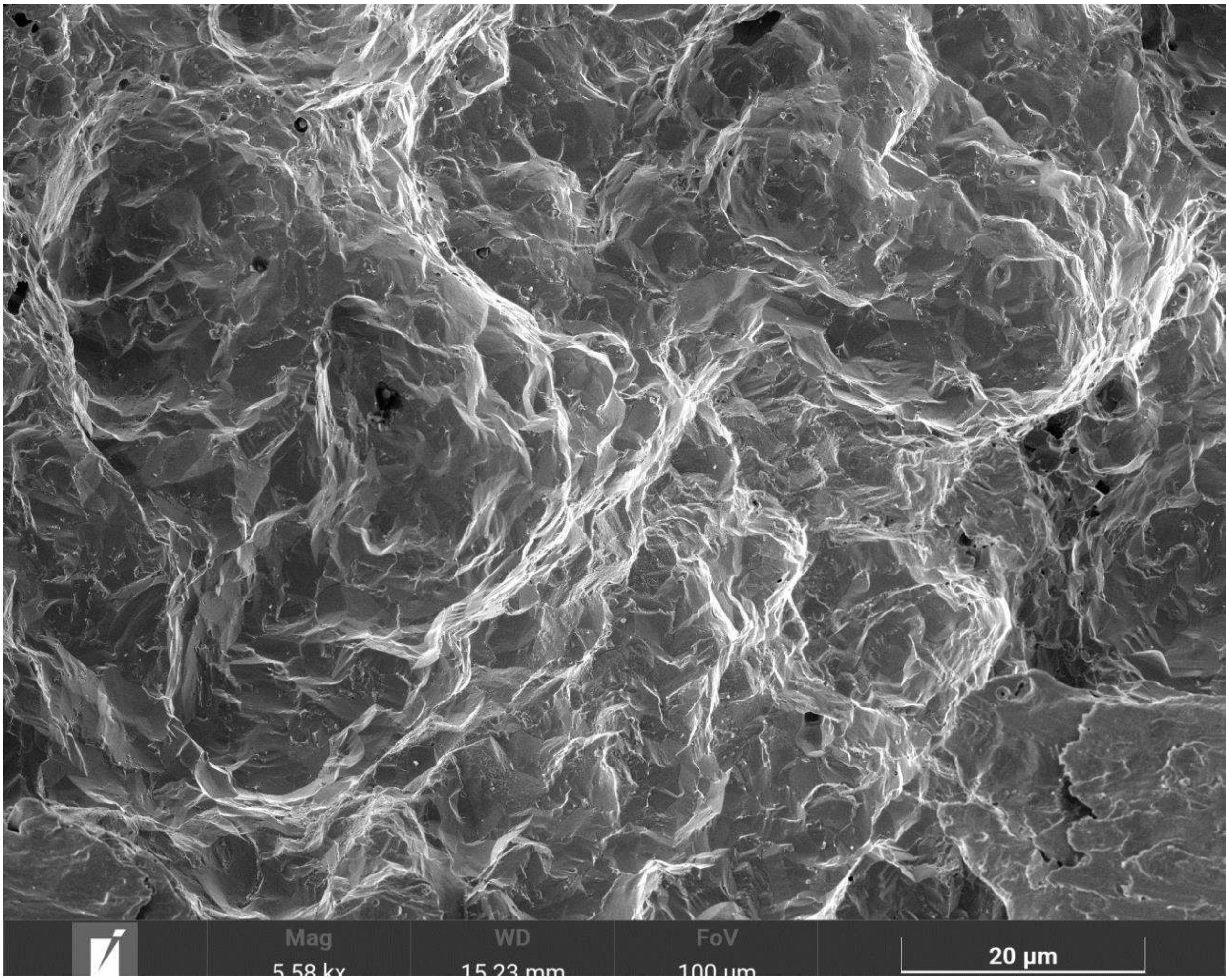


Figure 30. High magnification SEM images of Sample S1 showing the fracture surfaces where there was less evidence of ductility; area indicated in Figure 29. The fracture surface has a “glassy” appearance and appears to be quasi cleavage, and thus is likely more brittle compared to the other areas of the fracture surface that just contain dimples.

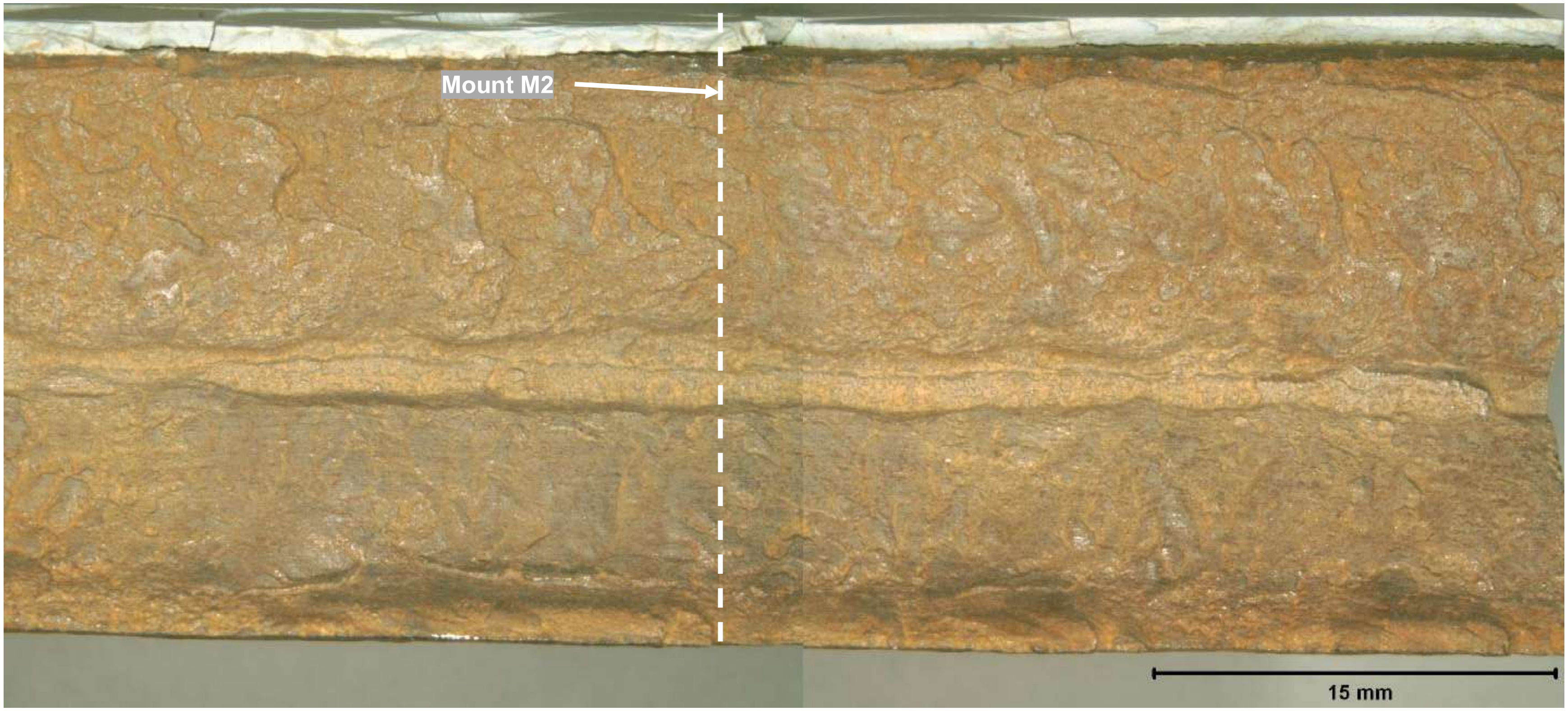


Figure 31. Light photomicrograph of Sample S2 showing the fracture surface; area indicated in Figure 5. The figure shows where Mount M2 was removed. Examination in the SEM showed similar features as Sample S1, with areas of smearing and areas of dimples. There was no evidence of pre-existing flaws. The slight difference in this fracture surface from Sample S1 is that midwall is flatter in the thickness direction, which is obvious when looking at the fracture surface in cross-section in Mount M2 in Figure 16. As mentioned above, this sample was removed from this location along the fracture surface in order to examine the midwall vertical portion.

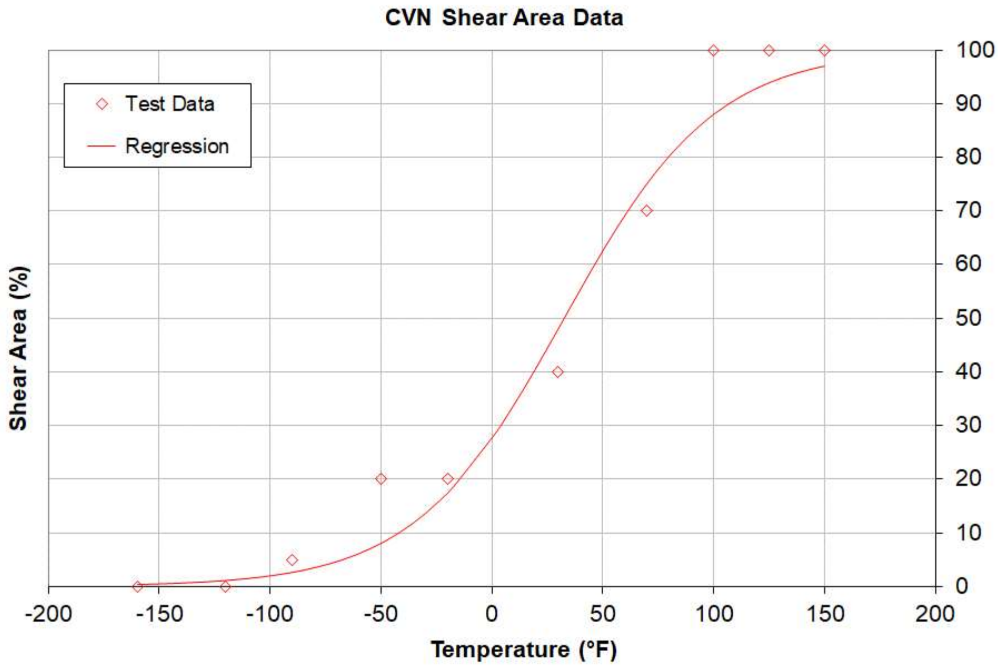


Figure 32. Percent shear from Charpy V-notch tests as a function of temperature for transverse seam weld (HAZ notch) specimens removed from the sister elbow fitting.

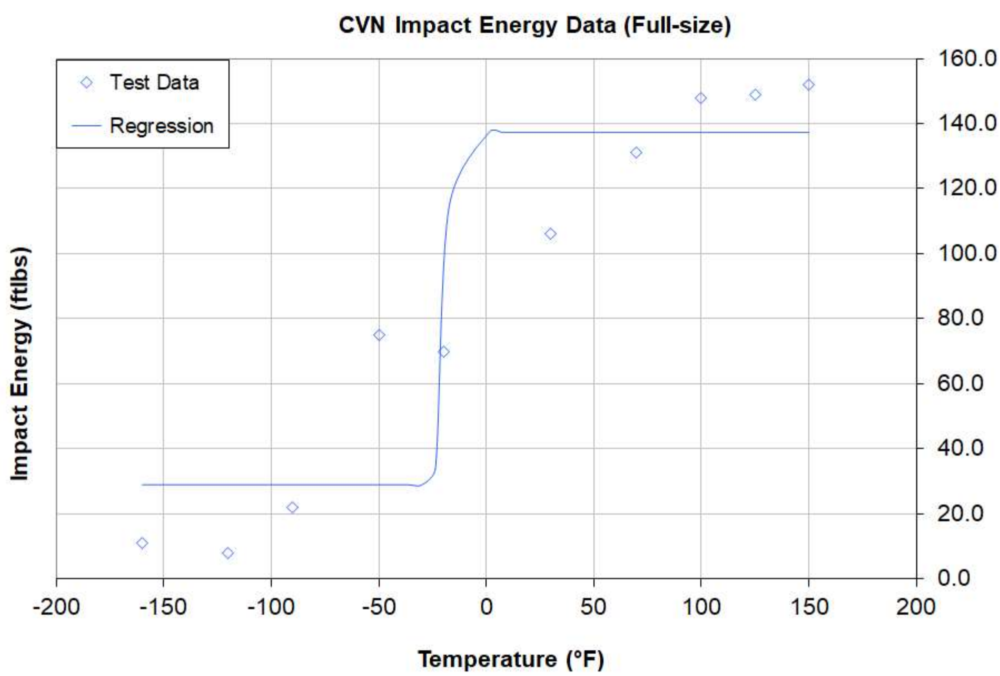


Figure 33. Charpy V-notch impact energy as a function of temperature for transverse seam weld (HAZ notch) specimens removed from the sister elbow fitting.

About DNV

DNV is a global quality assurance and risk management company. Driven by our purpose of safeguarding life, property, and the environment, we enable our customers to advance the safety and sustainability of their business. We provide classification, technical assurance, software, and independent expert advisory services to the maritime, oil and gas, power, and renewables industries. We also provide certification, supply chain, and data management services to customers across a wide range of industries. Operating in more than 100 countries, our experts are dedicated to helping customers make the world safer, smarter, and greener.