Wire Rope Analysis

ESi Project No: 96960

Report Prepared For

Kate Campbell, Contracting Officer
NTSB Office of the Chief Financial Officer, Acquisition Division (CFO-30)

Michael Budinski, Chief
NTSB Office of Research & Engineering, Materials Laboratory Division (RE-30)

Requisition/Reference No. PUR230081 Contract No. 9531BM23P0029

Submitted by:

Date

Ronald J. Parrington, P.E., FASM
Senior Managing Consultant

Technical Review by:

Date

Robert J. Cooley, P.E.
Senior Staff Consultant

Phone: (763) 557-9090| Fax: (763) 557-0710| Toll Free: 866-596-3994

www.engsys.com

Summary and Conclusions

1. The wire rope exhibits a significant level of external corrosion. The severity rating for external corrosion is high or approximately 60%, where 100% requires that the wire rope be discarded.
2. External wear of the wire rope is severe. However, a quantitative severity rating based on uniform decrease in the wire rope diameter could not be assigned, because the reference diameter of the wire rope is not available.
3. If a % severity rating for external wear could be calculated, it is possible that the combined corrosion and wear damage to the wire rope would require discard.
4. The eye piece of the wire rope (Specimen 1, Evidence Tag #74) has an area of local increase in rope diameter of approximately 10%, which would warrant "consideration given to discarding the rope".
5. Excluding the obvious fractures, the wire rope meets the requirements for visible broken wires.
6. Examination of the wire fractures reveals that the wire rope was severely weakened by corrosion and wear. Most of the wires displayed monotonic ductile overload fractures. Some wires fractured by fatigue.
7. The primary failure mechanism of the wire rope is corrosion and wear followed by monotonic ductile overload of the remaining wire cross sections.
8. The wire rope was near the end of life and probably should have been discarded prior to the incident.

Introduction

On July 26, 2022, while conducting cargo discharging operations at the Manchester Terminal in Houston, Texas, the wire rope for the No. 1 crane aboard the Thorco Basilisk (Swiss Flag) fractured, dropping the cargo load consisting of a wind turbine nacelle to the deck from a height of about 1 meter. Additional damage was caused to the vessel's tween deck in the cargo hold. No other damage, pollution, or injuries were reported.

ESi was contracted to inspect and examine the wire rope specimens described in Table 1 and pictured in Figures 1-4. The wire rope is a Verope Verotop P steel wire rope with a 38-mm nominal diameter. The rope consists of 37 strands with 7 wires per strand in a left-hand Lang's lay with a plastic-coated core. Specimens 1 (U.S. Coast Guard tag #74) and 3 (U.S. Coast Guard tag #78) were sectioned ten feet from the block end and the fractured end, respectively. The specimens were assigned sub-specimen identifications "-1" (ten-foot section from either fracture) and "-2" (remaining length of the sectioned rope segments. Only the 10-foot sections (74-1, 76, and 78-1) were inspected. Per the NTSB Statement of Work, the following tasks were performed.

1) Visual examination of all three samples for deformation, crushing, corrosion/rottenness, and broken wires in accordance with subsections 8.5.3.1.2, 8.5.3.1.3, and 8.5.3.3.1 from DNV standard DNV-ST-0377.
2) Documentation of any locations where the condition meets the defined discard criteria of ISO 4309:2017, including nature of the condition, location relative to a reference end on each sample, and representative photographs.
3) Measurement of cable diameter in two directions approximately perpendicular to each other at two representative locations at least 3 feet apart on each rope sample and in any areas of localized diameter loss noting the measurement locations relative to a reference end on each sample.

4) Examination of the fractured ends of the wire rope to identify the fracture mechanism(s) for individual wires with overall photo documentation and representative images of individual wires.
5) Documentation of any evidence of wear, corrosion, and/or preexisting cracks that could have affected the strength of the cable at the fracture location.

Table 1 – Wire Rope Specimen Description

Specimen #	U.S. Coast Guard Evidence Tag #	Wire Rope Description	Length Received
1	00000074	Cut at one end, eye splice that was connected to a lifting block at other end	~50 feet
2	00000076	Cut at one end and the crane-side of the fracture at the other end	~10 feet
3	00000078	Cut at one end and the block-side of the fracture at the other end	~100 feet

The results of the wire rope analysis are presented herein. Numerous figures are included at the end of this report to photo-document the observations and findings.

Corrosion Inspection

The wire rope specimens were examined for external corrosion, internal corrosion, and fretting corrosion per ISO 4309:2017, especially Section 6.6. The corrosion inspection results are summarized below.

- Grease and external wear somewhat hindered the corrosion inspection. Grease obscured some surfaces and external wear smoothed some surfaces.
- Inspection was performed before and after wiping and/or brushing away grease and debris from several representative areas along the length of each sample. In compliance with ISO 4309:2017, solvent cleaning was not performed.
- The reference end is the cut end of each sample as opposed to the fractured end or the eye end.
- External Corrosion – Results are presented in Table 2.
- Internal Corrosion – Except for where the wire rope is unraveling near the fractured ends, there are no obvious signs of internal corrosion. Where unraveled, uniform corrosion of internal surfaces is generally visible.
- Fretting Corrosion – Areas with little or no grease display uniform corrosion with no obvious signs of fretting corrosion.
- See Figures 5-9 for representative images of the corrosion damage.

Table 2 – External Corrosion Inspection Results

Sample	Description	Distance (in)	Rating (%)	Comment
74-1	Eye piece	---	---	Entire length is caked with grease.
		16	20	Visually displays light roughness or pitting.
		54	20	Visually displays light roughness or pitting.
		106	0	Strands unraveling; Visually displays stains.
		Eye	60	Rough with heavy corrosion product buildup.
76	Crane-side of the fracture	---	---	Intermediate amount of grease; 3 long strands on fractured end that were likely connected to section 78-1. Displays obvious uniform corrosion.
		23	20	Visually displays roughness or pitting.
		37	60	Rough with heavy corrosion product buildup.
		55	20	Visually displays roughness or pitting.
		119	60	Strands unraveling; Visually displays more severe roughness or pitting.
78-1	Block-side of the fracture	---	---	Least amount of grease; 3 strands partially missing which were connected to section 76. Displays obvious uniform corrosion.
		32	20	Visually displays roughness or pitting.
		40	60	Two fractured strands unraveling; Visually displays more severe roughness or pitting.
		79	60	Strands unraveling; Visually displays more severe roughness or pitting.
		124	60	Strands unraveling; Visually displays more severe roughness or pitting.

Damage Inspection

The wire rope specimens were examined for damage per ISO 4309:2017, especially Sections 6.4 and 6.7. The damage inspection results are summarized below.

- Damage inspection was performed before and after scraping with plastic putty knives, wiping with rags, and brushing with plastic bristle brushes in compliance with ISO 4309:2017.
- The reference end is the cut end of each sample as opposed to the fractured end or the eye end.
- Unraveling, complete fracture at ends of rope, and partial fractures precluded inspection for some (e.g., waviness), but not all, types of damage in those areas.
- A high level of confidence was achieved in the inspection methodology for the types of damage described in Section 6.7 of ISO 4309:2017.
- The damage inspection results are presented in Table 3.
- External Wear – The wire rope reference diameter (unavailable) would be needed to assign a % severity rating based on the decrease in diameter per Paragraph 6.4.2 of ISO 4309:2017.
- Local Increase in Rope Diameter – The local increase in rope diameter at 48” for Sample 74-1 is approximately 10.3%. Per Paragraph 6.7.6 of ISO 4309:2017: “If the rope diameter increases by 5 % or more for a rope with a steel core or 10% or more for a rope with a fiber core during service, the reason for this shall be investigated and consideration given to discarding the rope”.
- See Figures 10 and 11 for representative images of the wear damage and Figure 12 for an image of the local increase in rope diameter.

Table 3 – Damage Inspection Results

Damage Type	74-1 Eye piece Distance (in)	76 Crane-Side Distance (in)	78-1 Block-Side Distance (in)
External Wear	48	All	All
Waviness	None	None	None
Basket Deformation	None	None	None
Core or Strand Protrusion or Distortion	None	None	None
Protruding Wires in Loops	None	None	None
Local Increase in Rope Diameter[1]	48	None	None
Flattened Portion	None	None	None
Kink or Tightened Loop	None	None	None
Bend in Rope	None	None	None
Damage due to Heat or Electric Arcing	None	None	None

[1] The average rope diameter in this area is approximately 43 mm versus an average diameter of approximately 39 mm for Sample 74-1. This area is also out of round by approximately 2 mm.

Dimensional Inspection

Per the NTSB Statement of Work, the diameter of the wire rope specimens was measured “in two directions approximately perpendicular to each other at two representative locations at least 3 feet apart on each rope sample and in any areas of localized diameter loss noting the measurement locations relative to a reference end on each sample”. The dimensional inspection results are summarized below.

- The reference end is the cut end of each sample as opposed to the fractured end or the eye end.
- Unraveling near fractured ends excluded dimensional measurement at those locations.
- The dimensional inspection results are presented in Table 4.
  - The measured wire rope diameters exceed the nominal diameter (38 mm), so rating for uniform decrease in diameter could not be performed per Table 5 of ISO 4309.
  - Without knowledge of the reference diameter, uniform decrease in diameter could not be calculated per Paragraph 6.4.2 of ISO 4309.
- No obvious local decrease in diameter was observed per Paragraph 6.4.3 of ISO 4309.

Table 4 – Dimensional Inspection Results

<table>
<tr><th>Sample</th><th>Description</th><th>Distance (in)</th><th>Diameter 1 (mm)</th><th>Diameter 2 (mm)</th><th>Delta (mm)</th><th>AVG (mm)</th><th>% Nominal</th></tr>
<tr><td>74-1</td><td>Eye piece</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>16</td><td>38.81</td><td>39.43</td><td>0.62</td><td>39.12</td><td>103</td></tr>
<tr><td></td><td></td><td>54</td><td>38.82</td><td>39.25</td><td>0.43</td><td>39.04</td><td>103</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>76</td><td>Crane-side of the fracture</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>11</td><td>39.22</td><td>39.52</td><td>0.30</td><td>39.37</td><td>104</td></tr>
<tr><td></td><td></td><td>49</td><td>39.96</td><td>40.17</td><td>0.21</td><td>40.06</td><td>105</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>78-1[1]</td><td>Block-side of the fracture</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>5</td><td>39.08</td><td>39.21</td><td>0.13</td><td>39.14</td><td>103</td></tr>
<tr><td></td><td></td><td>57</td><td>39.06</td><td>---</td><td rowspan="2">0.21</td><td rowspan="2">39.16</td><td rowspan="2">103</td></tr>
<tr><td></td><td></td><td>58</td><td>---</td><td>39.27</td></tr>
</table>

[1] Due to the presence of a single loose strand, Diameters 1 and 2 were measured at two locations spaced 1-inch apart.

Visible Broken Wire Inspection

The wire rope specimens were examined for visible broken wires per ISO 4309:2017, especially Section 6.2. The visible broken wire inspection results are summarized below.

- Visible broken wire inspection was performed before and after scraping with plastic putty knives, wiping with rags, and brushing with plastic bristle brushes in compliance with ISO 4309:2017. The presence of grease prevented 100% coverage for the visible broken wire inspection.
  - Roughly 50% of the external surfaces of Sample 74-1 (eye piece) could effectively be inspected for broken wires after mechanical cleaning to remove grease.
  - Roughly 80-90% of the external surfaces of the Sample 76 (crane-side fracture) and Sample 78-1 (block-side fracture) could effectively be inspected for broken wires after mechanical cleaning to remove grease.
- Excluding the areas of complete and partial fractures, no broken wires were observed.
- In areas of complete and partial fractures, no broken wires were observed except those associated with completely fractured strands.
- The visible broken wire inspection results are presented in Table 5 and compared to the discard criteria from Table 4 of ISO 4309:2017 for Rope Category Number (RCN) 23-3.

Table 5 – Visible Broken Wire Inspection Results

Sample	Description	Number Breaks over 6d (9 in)	Number Breaks over 30d (45 in)	ISO 4309:2017 Over 6d (9 in)		ISO 4309:2017 Over 30d (45 in)	
				A[1]	B[2]	A[1]	B[2]
74-1	Eye piece	0	0	3	5	6	11
76	Crane-side of the fracture	0	0	3	5	6	11
78-1	Block-side of the fracture	0	0	3	5	6	11

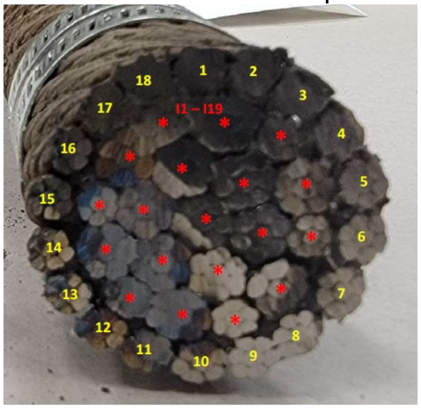
[1] Maximum allowable of visible broken wires for sections of rope working in steel sheaves and/or spooling on a single-layer drum

[2] Maximum allowable of visible broken wires for sections of rope spooling on a multi-layer drum

Fractured Ends Examination

Per the NTSB Statement of Work, the fractured ends of the wire rope Specimen 2 (76, crane side) and Specimen 3 (78-1, block side) were examined to determine fracture mechanisms for individual wires and to document any evidence of wear, corrosion, and/or preexisting cracks that could have affected the strength of the wire rope at the fracture location. The fractured end examination results are summarized below.

- The fractured wires were sectioned within a few inches of the fracture location and ultrasonically cleaned with soapy water and/or water-based degreaser to facilitate microscopic examination.
- The 18 outer strands (O1 thru O18) are numbered in sequential order (i.e., Strand O2 is located between Strands O1 and O3). Also, the mating outer strands have the same identification number [i.e., Strand O1 is the same for the crane end (76) and the block end (78-1)]. The 19 inner strands (I1 thru I19) are arbitrarily assigned numbers. The mating inner strands do NOT have the same identification number [i.e., Strand I1 is NOT the same for the crane end (76) and the block end (78-1)].



- The fractured ends of all wires were examined using a stereomicroscope and categorized as brittle fracture, ductile fracture, wear, or wear plus minor fracture. The results are summarized in Tables 6-9.
    - Brittle = Flat fracture with no visible necking. Monotonic brittle overload and fatigue fractures would fall in this category.
    - Ductile = Slant fracture with or without visible necking or plastic deformation. Monotonic ductile overload fractures would fall in this category.
    - Wear = Worn to a flat knife-like edge or to a point. Little or no visible fracture.
    - Wear plus Minor Fracture = Heavily worn but with a visible final fracture.
- Macroscale Examination
    - Most of the fractures fall into the ductile fracture category. In addition, most of the wires categorized as “wear plus minor fracture” appear to display ductile fractures. In fact, the categorization of wires as “ductile fracture” versus “wear plus minor fracture” is subjective based on the relative degree of wear damage.
    - All the fractured wires display corroded and worn surfaces.
    - No brittle fractures were observed macroscopically.
    - Stereomicroscope images were taken of representative ductile fracture, wear, and wear plus minor fracture wires.
- The same representative ductile fracture and wear plus minor fracture wires were examined using a scanning electron microscope (SEM) to identify the microscale fracture morphology.
    - All but one of the twelve wires examined with an SEM exhibited dimpled rupture fracture surface morphology, consistent with monotonic overload fractures.
    - One of the wear plus minor fracture wires exhibited a fatigue fracture surface morphology.
- See Figures 13-17 for representative images of the fractured ends.

Table 6 – Fracture Examination: Specimen 76 Outer Strands

Strand/Wire	Brittle Fracture	Ductile Fracture	Wear	Wear plus Minor Fracture	Comments
O1 Outer		4		2	
O1 Center		1			
O2 Outer		4		1	One wire not ratable.
O2 Center		1			
O3 Outer		3		2	One wire not ratable.
O3 Center		1			
O4 Outer		5		1	
O4 Center		1			
O5 Outer		6			
O5 Center		1			See images.
O6 Outer		3	3		
O6 Center		1			
O7 Outer		6			See images.
O7 Center		1			
O8 Outer		3		3	
O8 Center		1			
O9 Outer		3		3	See images.
O9 Center		1			
O10 Outer		1	4	1	
O10 Center		1			
O11 Outer		6			
O11 Center		1			
O12 Outer		5		1	
O12 Center		1			
O13 Outer		5		1	
O13 Center		1			
O14 Outer		6			
O14 Center		1			
O15 Outer		4		2	
O15 Center		1			
O16 Outer		3	1	2	
O16 Center		1			
O17 Outer		1	3	2	
O17 Center		1			
O18 Outer		4		2	
O18 Center		1			
Totals	0	90	11	23	

Table 7 – Fracture Examination: Specimen 76 Inner Strands

Strand/Wire	Brittle Fracture	Ductile Fracture	Wear	Wear plus Minor Fracture	Comments
I1 Outer		6			
I1 Center		1			See images.
I2 Outer		3	1	2	
I2 Center		1			
I3 Outer		6			
I3 Center		1			
I4 Outer		2	2	2	
I4 Center		1			
I5 Outer		5		1	See images.
I5 Center		1			
I6 Outer		4		2	
I6 Center		1			
I7 Outer		3		3	
I7 Center		1			
I8 Outer		4		2	
I8 Center		1			
I9 Outer		6			
I9 Center		1			
I10 Outer		5		1	
I10 Center		1			
I11 Outer		2		4	
I11 Center		1			
I12 Outer			4	2	
I12 Center		1			
I13 Outer		1	2	2	One wire not ratable.
I13 Center		1			
I14 Outer			2	4	See images.
I14 Center		1			
I15 Outer		2		4	
I15 Center		1			
I16 Outer		5		1	
I16 Center		1			
I17 Outer		1		5	
I17 Center		1			
I18 Outer			6		
I18 Center		1			
I19 Outer		4	1	1	
I19 Center					Not ratable
Totals	0	77	18	36	

Table 8 – Fracture Examination: Specimen 78-1 Outer Strands

Strand/Wire	Brittle Fracture	Ductile Fracture	Wear	Wear plus Minor Fracture	Comments
O1 Outer			4	2	
O1 Center		1			
O2 Outer			5	1	
O2 Center		1			
O3 Outer			4	2	
O3 Center		1			
O4 Outer		3		3	
O4 Center		1			
O5 Outer			1	5	
O5 Center		1			
O6 Outer		2		4	See images.
O6 Center		1			
O7 Outer			3	3	
O7 Center		1			
O8 Outer		5	1		
O8 Center		1			
O9 Outer		1	1	4	
O9 Center		1			
O10 Outer		1		5	
O10 Center		1			
O11 Outer		5		1	
O11 Center		1			
O12 Outer		5	1		See images.
O12 Center		1			
O13 Outer		5		1	See images.
O13 Center		1			
O14 Outer		4		2	
O14 Center		1			
O15 Outer		5		1	
O15 Center		1			
O16 Outer		5		1	
O16 Center		1			
O17 Outer		5		1	
O17 Center		1			
O18 Outer		5		1	
O18 Center		1			
Totals	0	69	20	37	

Table 9 – Fracture Examination: Specimen 78-1 Inner Strands

Strand/Wire	Brittle Fracture	Ductile Fracture	Wear	Wear plus Minor Fracture	Comments
I1 Outer		6			
I1 Center		1			See images.
I2 Outer		2	2	2	
I2 Center		1			
I3 Outer			3	3	
I3 Center		1			
I4 Outer		3		3	See images.
I4 Center		1			
I5 Outer		4		2	
I5 Center		1			
I6 Outer			5	1	
I6 Center		1			
I7 Outer		2	1	3	
I7 Center		1			
I8 Outer		1	1	4	
I8 Center		1			
I9 Outer		1	3	2	
I9 Center		1			
I10 Outer		3		3	
I10 Center		1			
I11 Outer		2	2	2	
I11 Center		1			
I12 Outer		2		4	
I12 Center		1			
I13 Outer			4	2	
I13 Center		1			
I14 Outer		4		2	
I14 Center		1			
I15 Outer			4	2	See images.
I15 Center				1	
I16 Outer		6			
I16 Center		1			
I17 Outer		5		1	
I17 Center		1			
I18 Outer		4		2	
I18 Center		1			
I19 Outer		6			
I19 Center		1			
Totals	0	69	25	39	

<<< End of Report Text >>>

Figures

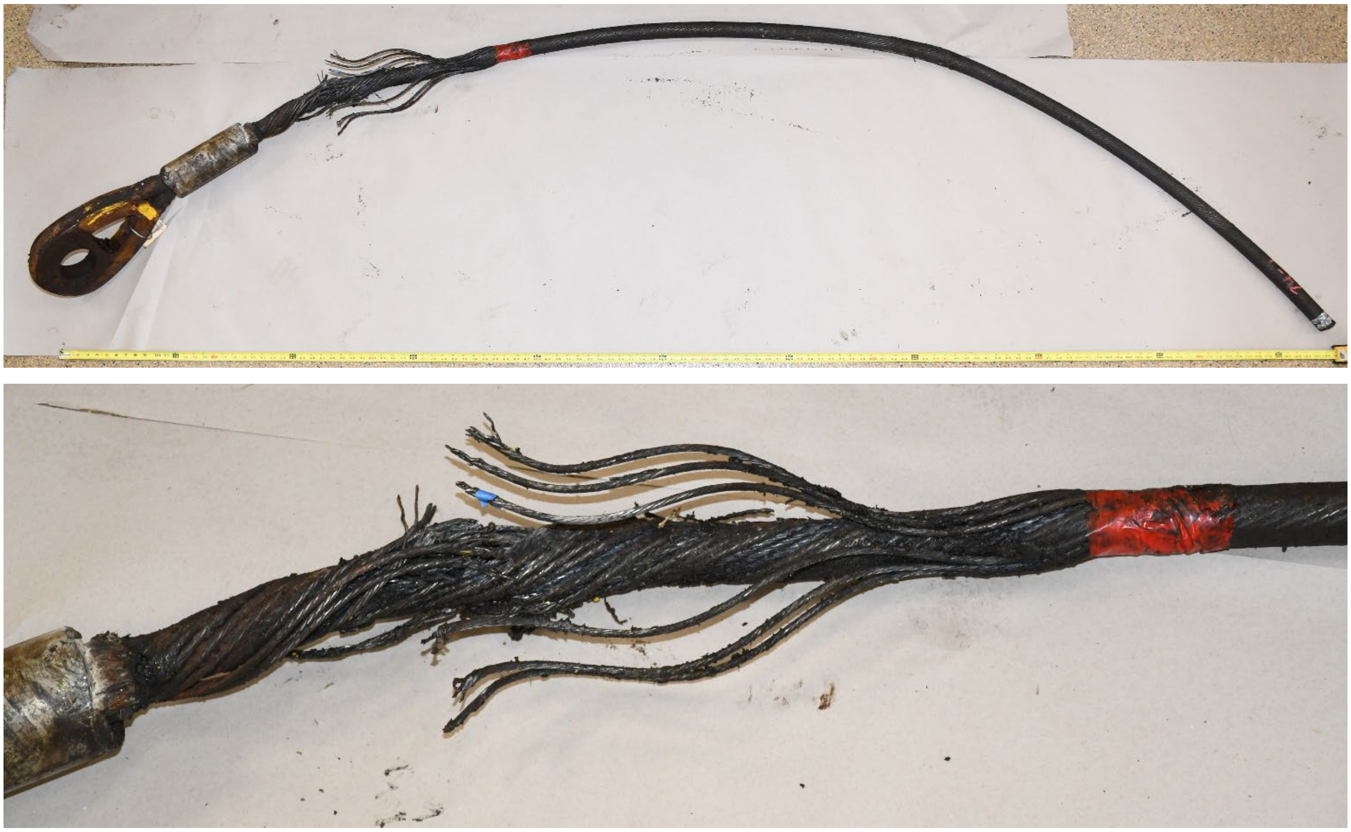


Figure 1 Images showing Specimen 1 (74-1, the eye piece) after sectioning 10 feet from the eye.

Figure 2 Images showing Specimen 2 (76, the crane-side of the fracture).

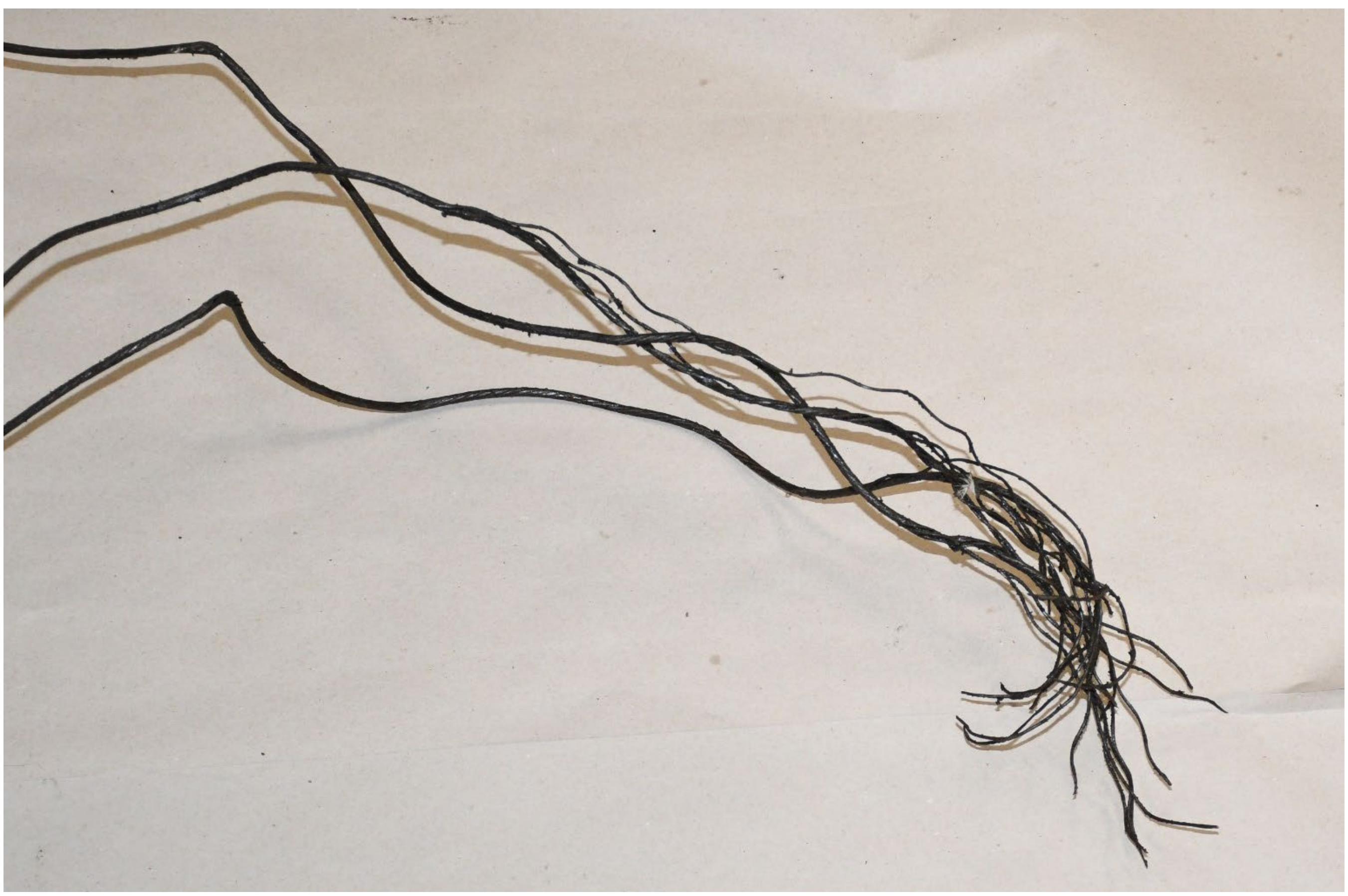


Figure 2 (Cont.) **Images showing Specimen 2 (76, the crane-side of the fracture).**

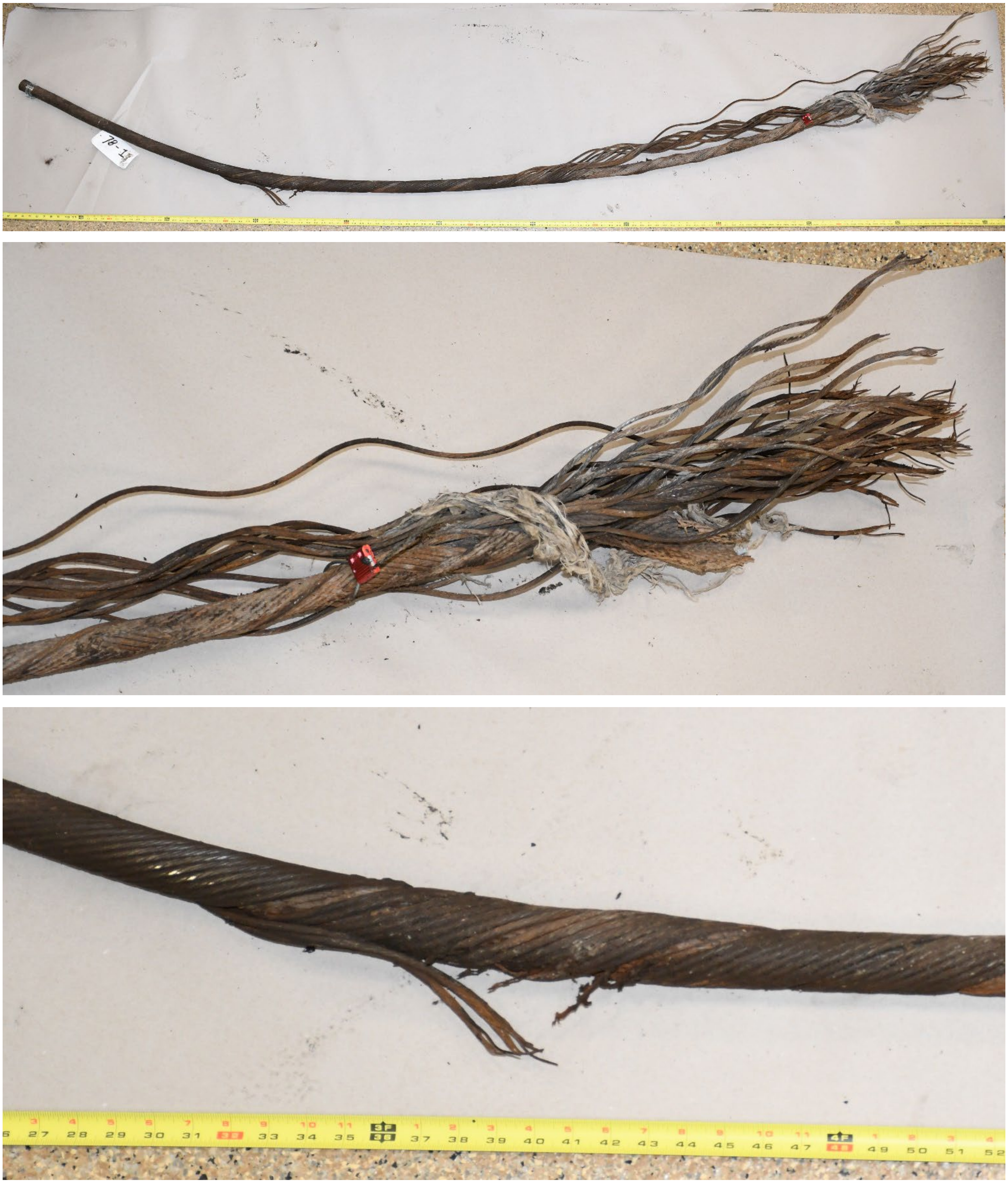


Figure 3 **Images showing Specimen 3 (78-1, the block-side of the fracture) after sectioning 10 feet from the fractured end.**

Figure 4 Images showing the excess lengths of wire rope from Specimen 1 (74-2, the eye piece, lefthand image) and Specimen 3 (78-2, the block-side of the fracture, righthand image) after removal of 10-foot sections.

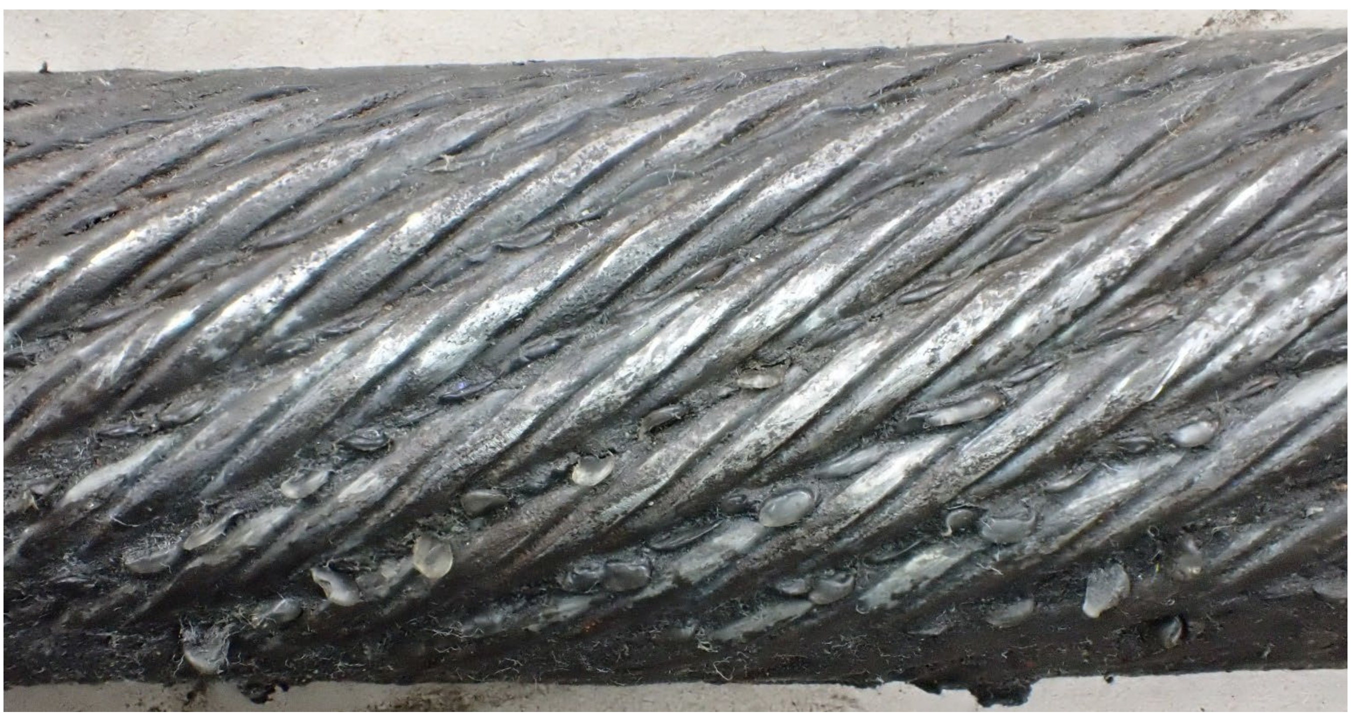


Figure 5 Representative image showing the light degree of roughness or pitting observed on Specimen 1 (74-1, the eye piece). (54-inches from reference end, Severity Rating 20%)

Figure 6 **Image showing the rough surface and heavy corrosion product buildup at the eye on Specimen 1 (74-1). (Severity Rating 60%)**

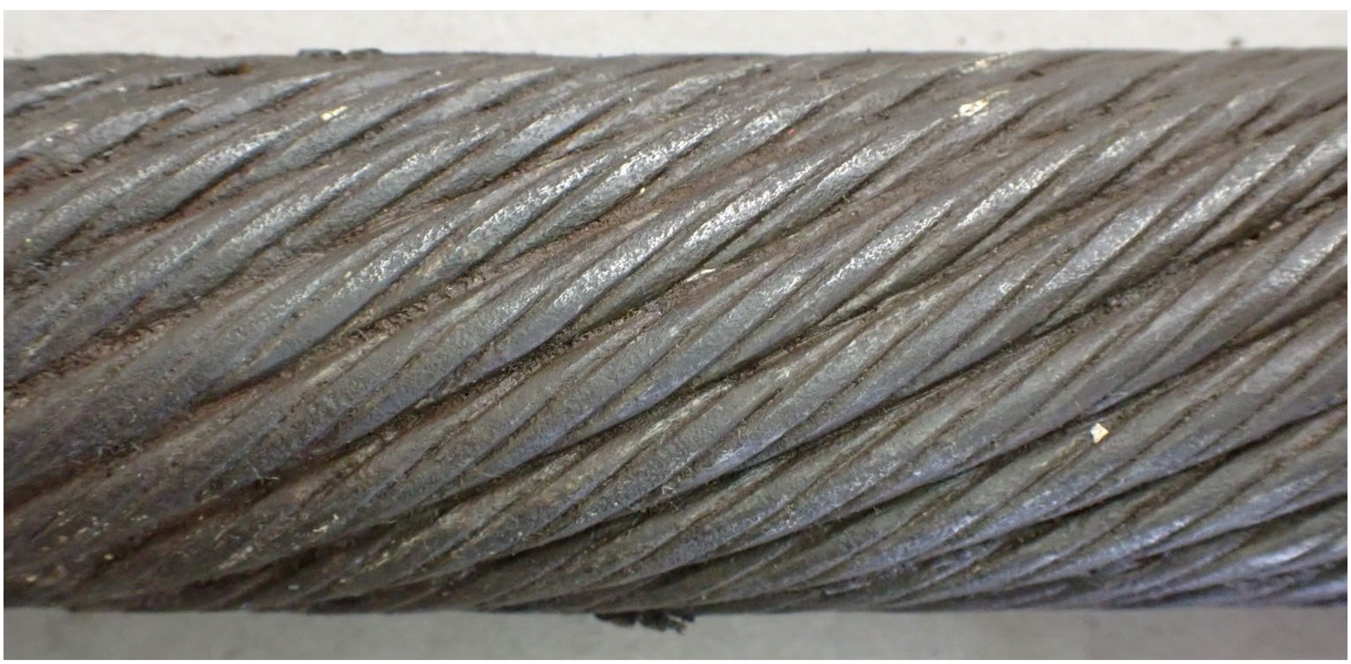


Figure 7 **Representative image showing the roughness or pitting observed on Specimen 2 (76, crane-side of fracture). (23-inches from reference end, Severity Rating 20%)**

Figure 8 Representative image showing the rough surface and heavy corrosion product buildup observed on Specimen 2 (76, crane-side of fracture). (37-inches from reference end, Severity Rating 60%)

Figure 9 Representative image showing the rough surface or pitting observed on Specimen 3 (78-1, block-side of fracture). (79-inches from reference end, Severity Rating 60%)

Figure 10 Representative image showing the external wear observed at the 48-inch mark on Specimen 1 (74-1, the eye piece).

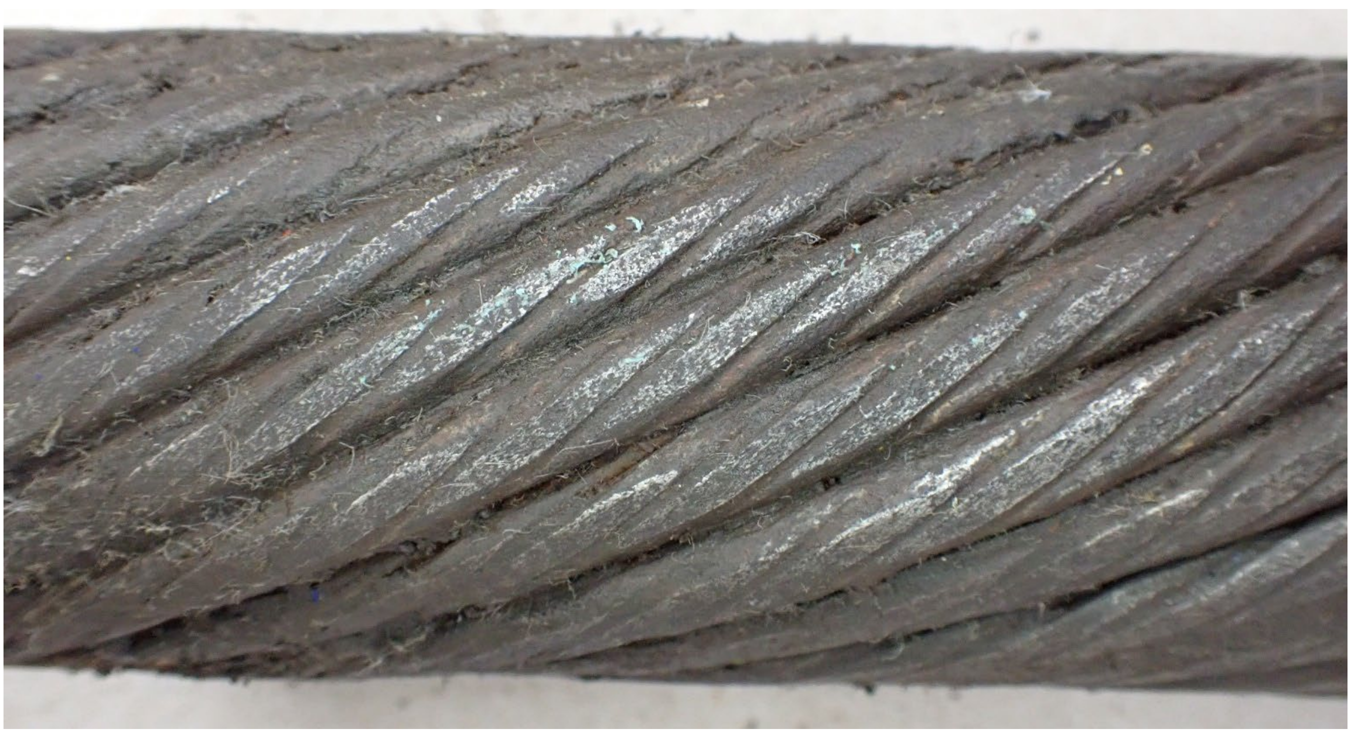


Figure 11 Representative image of the external wear observed on Specimen 2 (76, crane-side of fracture) and Specimen 3 (78-1, block-side of fracture). This image is at the 12-inch mark on Specimen 2.

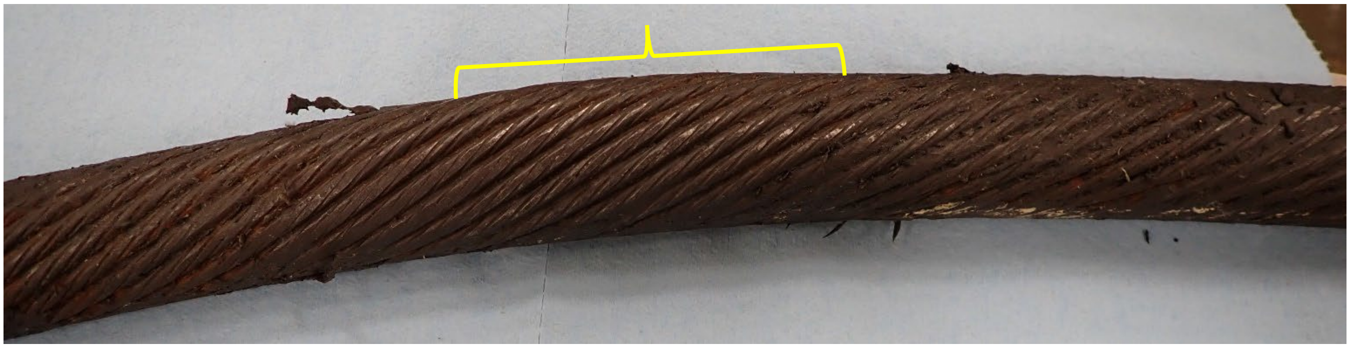


Figure 12 Image showing the local increase in rope diameter observed at the 48-inch mark on Specimen 1 (74-1, the eye piece).

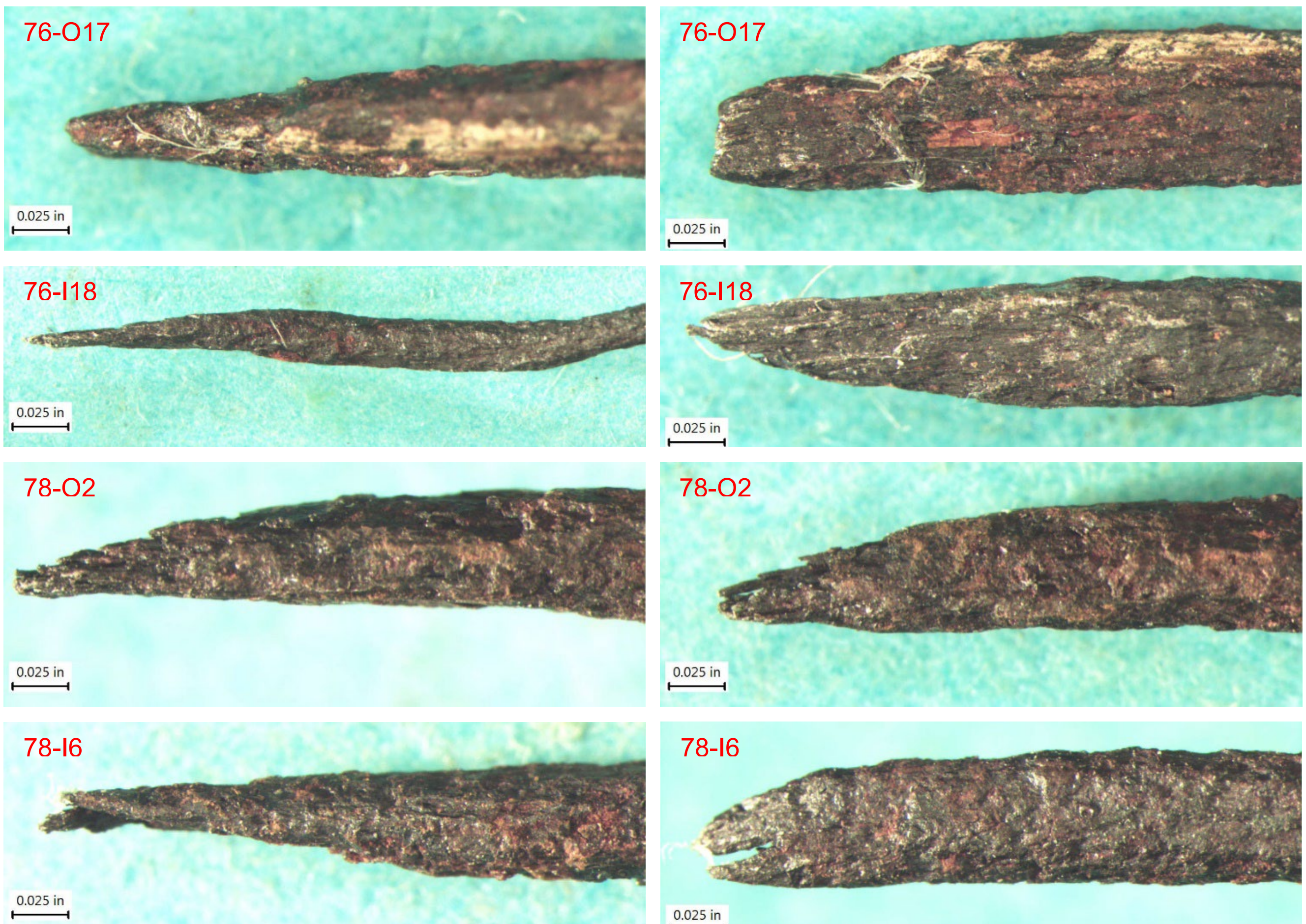


Figure 13 Representative stereomicroscope images showing wire wear failures/fractures. Two images (rotated ~90° to each other) are presented for each wire. The fractured ends are worn to a flat knife-like edge or to a point.

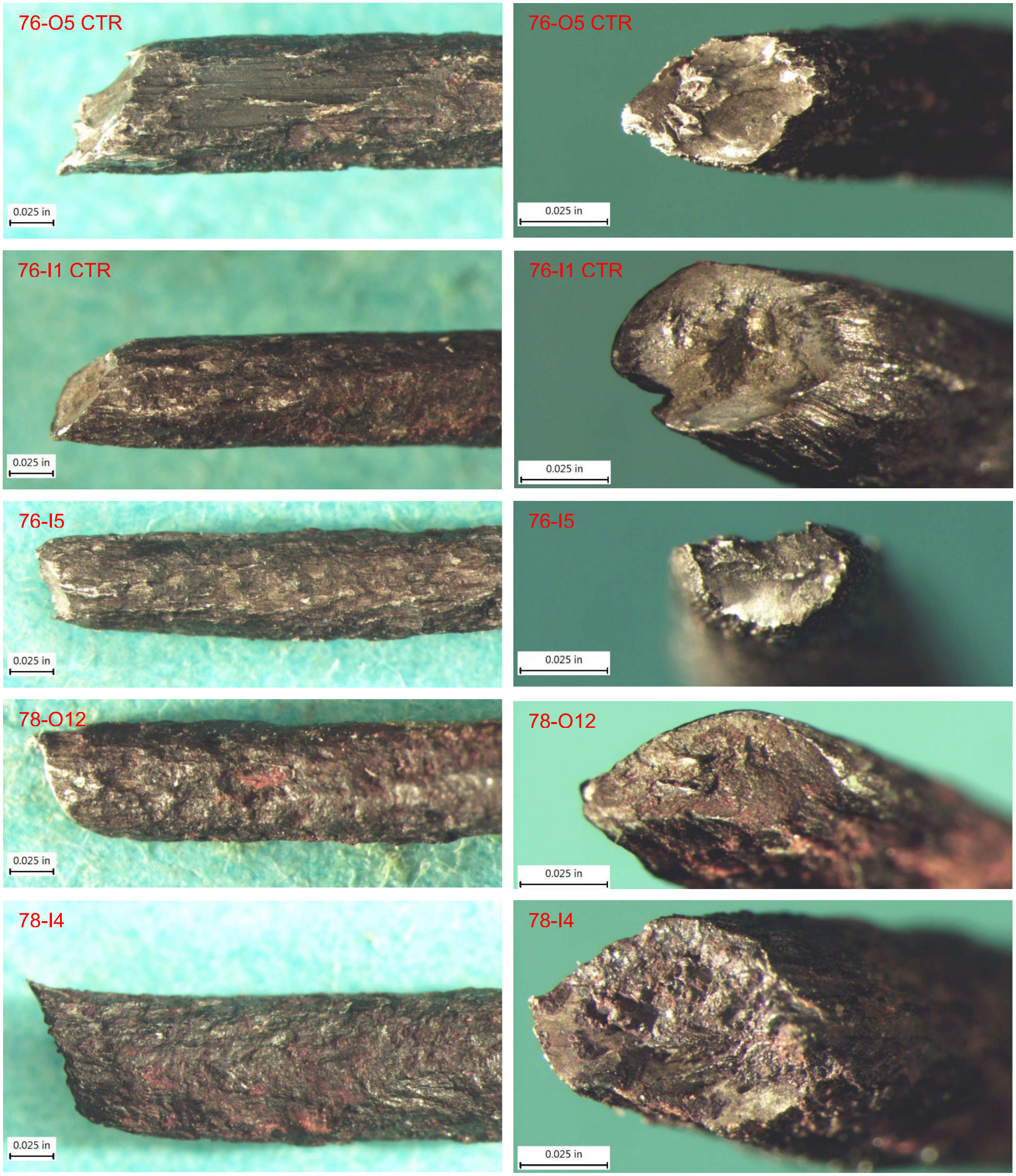


Figure 14 **Representative stereomicroscope images showing wire ductile fractures. Two images are presented for each wire, one side view and one view perpendicular to the fracture surface. These fractures are characterized by a slant fracture orientation, slight necking, plastic deformation, and/or rough surface texture.**

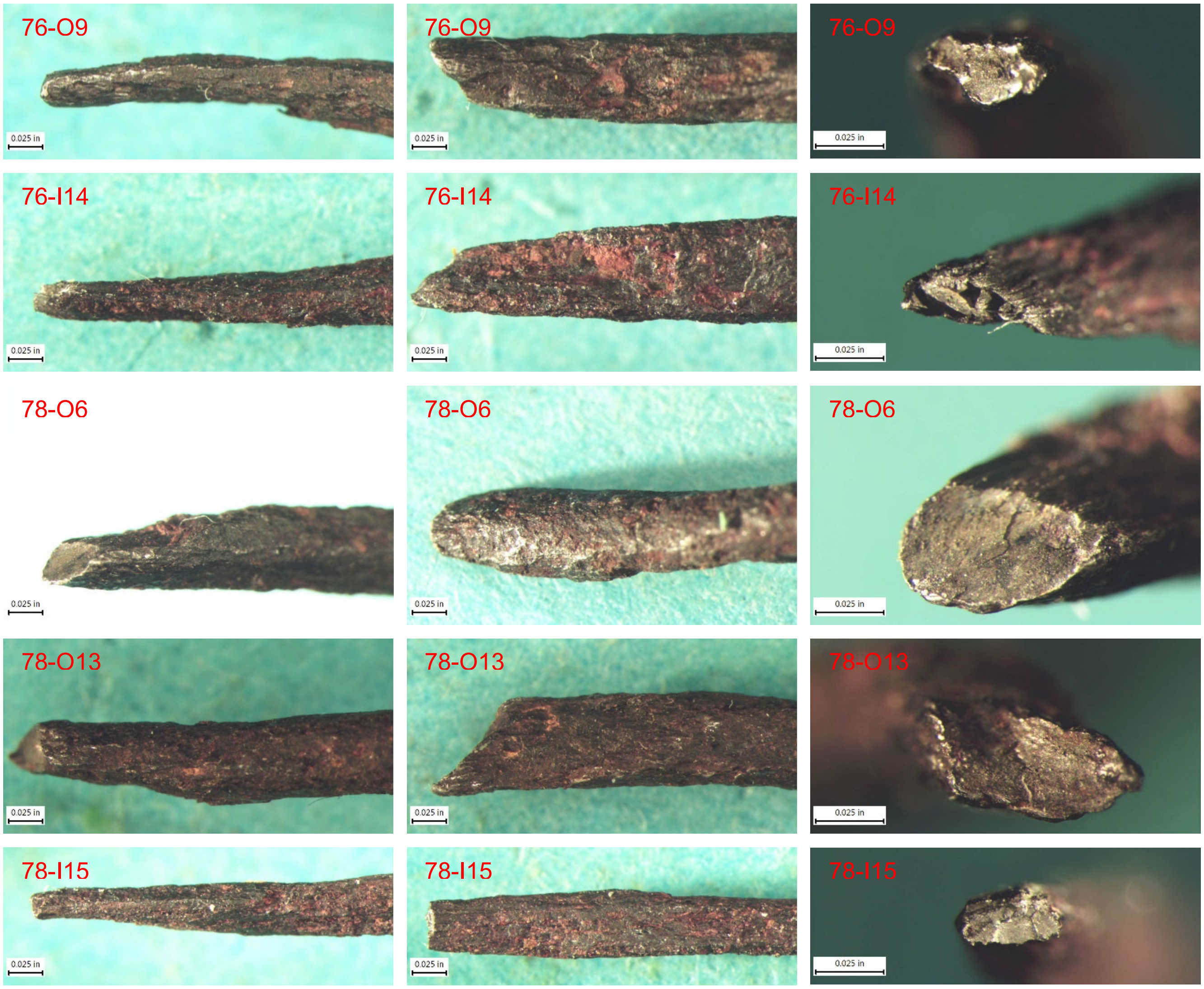


Figure 15 **Representative stereomicroscope images showing wires categorized as wear plus minor fracture. Two images (rotated ~90° to each other) are presented for each wire along with a higher magnification image of the fracture surface. These fractures are characterized by considerable wear followed by fracture of the remaining metal ligament. Most of the fractures appear to be ductile on the macroscale. Note – Wire 78-I15 (the bottom row) displays a flat fracture surface on the macroscale and fatigue fracture surface morphology on the microscale (see Figure 17).**

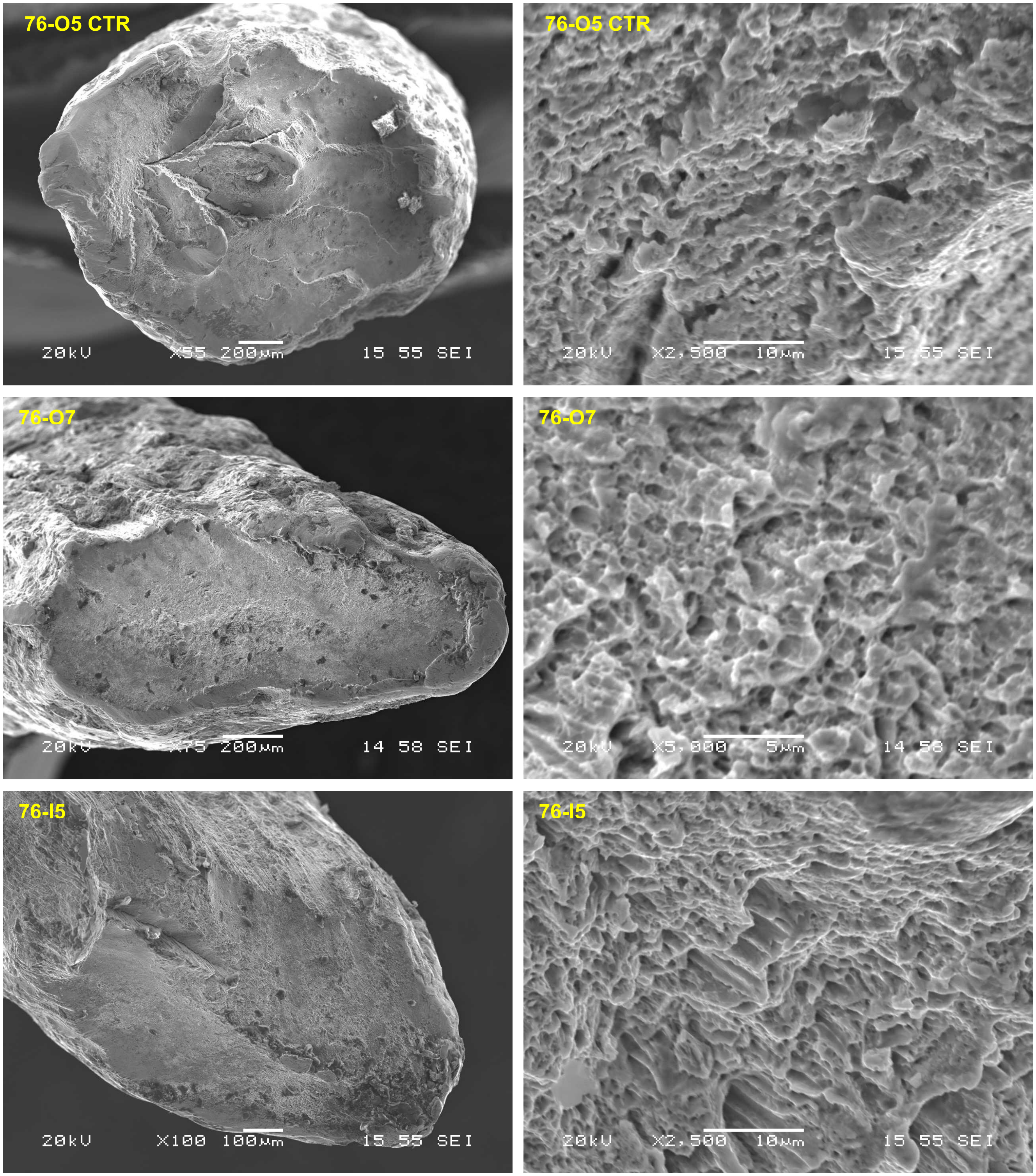


Figure 16 **Representative SEM micrographs showing the ductile dimpled rupture fracture surface morphology observed for most of the ductile fractures and the wear plus minor fracture breaks.**

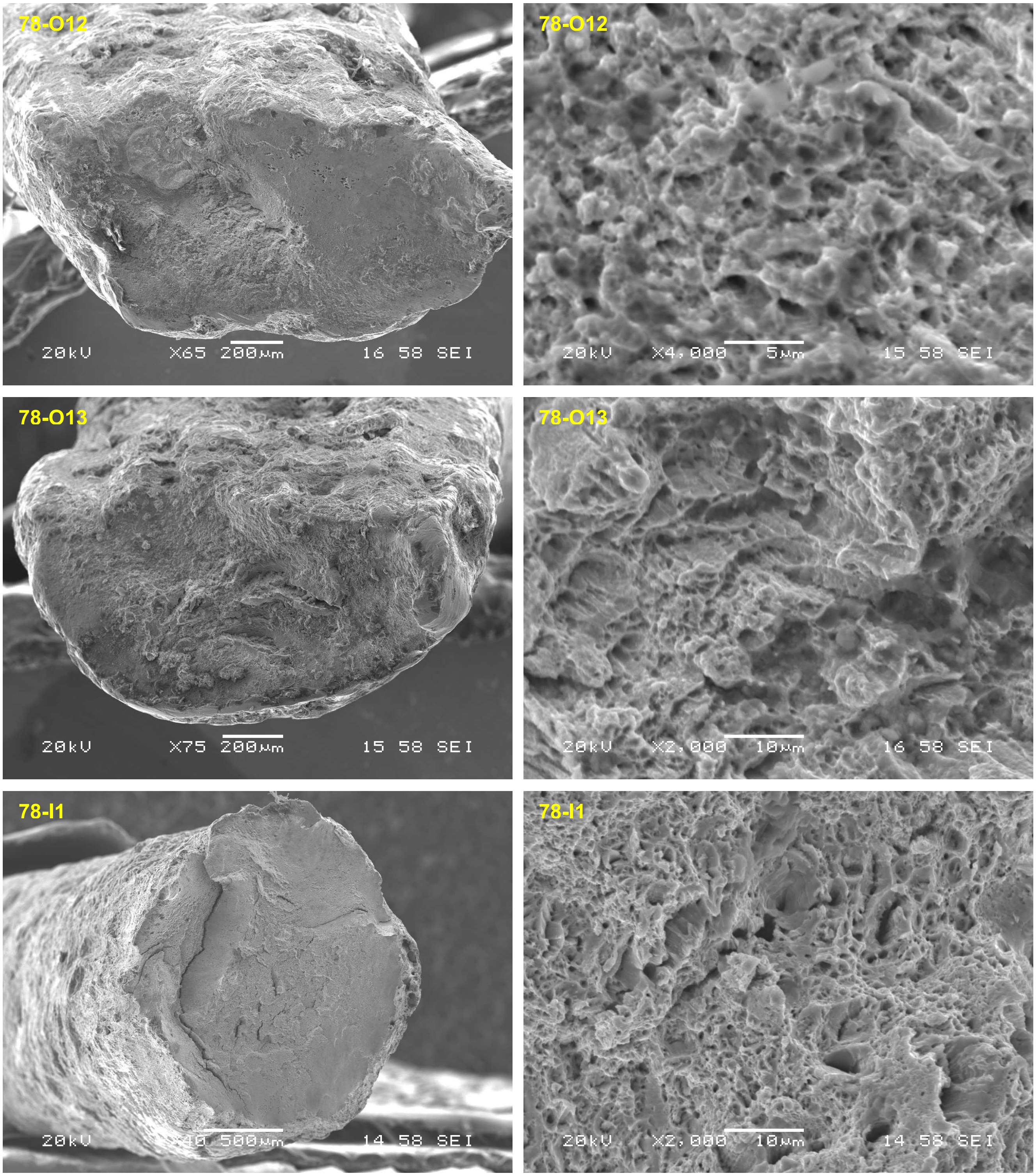
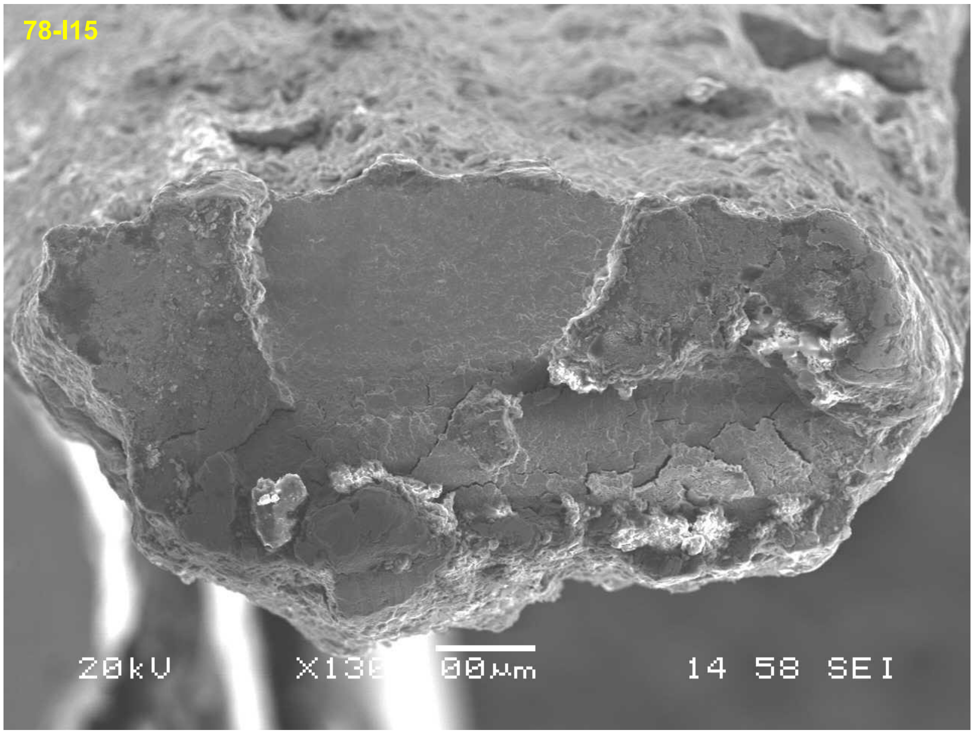


Figure 16 (Cont.) **Representative SEM micrographs showing the ductile dimpled rupture fracture surface morphology observed for most of the ductile fractures and the wear plus minor fracture breaks.**



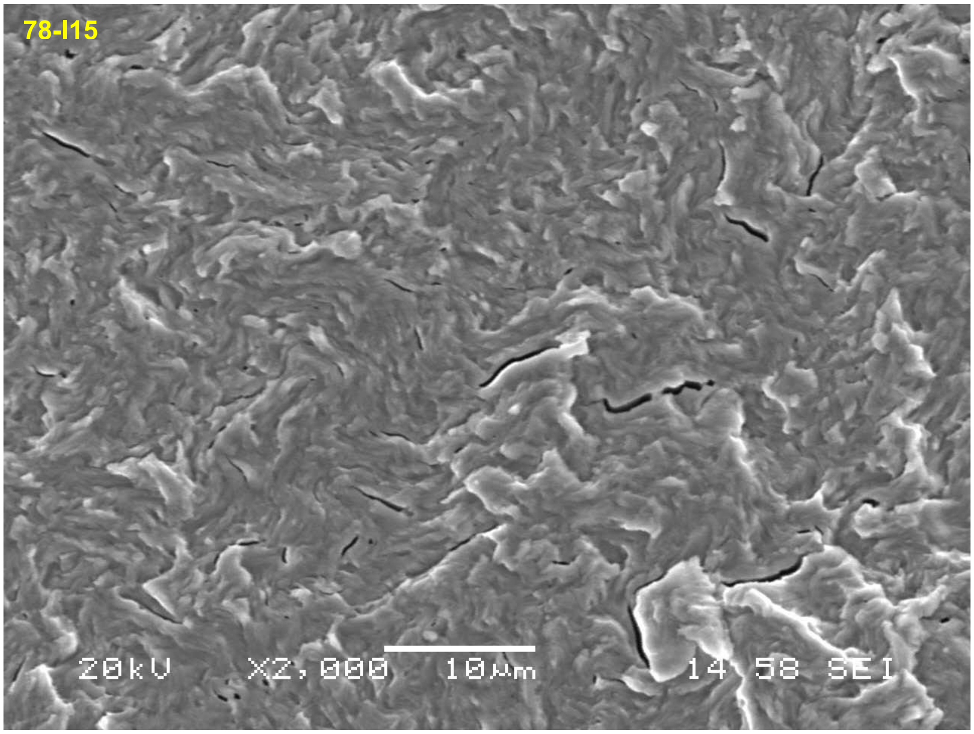


Figure 17 **SEM micrographs showing the fracture surface of Wire 78-I15, which displayed a fatigue fracture surface morphology.**