NATIONAL TRANSPORTATION SAFETY BOARD
Office of Research and Engineering
Materials Laboratory Division
Washington, D.C. 20594

May 22, 2008

MATERIALS LABORATORY FACTUAL REPORT — Report No. 07-122

A. ACCIDENT

Place	:	Carmichael, Mississippi
Date	:	November 1, 2007
Vehicle	:	Dixie Pipe Line Company, 12¾-inch outside diameter pipeline
NTSB No.	:	DCA08MP001
Investigator	:	Rod Dyck

B. COMPONENTS EXAMINED

Ruptured 12¾-inch outside diameter liquid propane transmission pipe.

C. DETAILS OF THE EXAMINATION

On-site

Figure 1 shows a photograph of the ruptured pipe. The rupture extended over a longitudinal distance of approximately 52 feet and 4¾ inches. The pipe in the area of the rupture was oriented southwest-northeast and was transporting propane liquid. The propane was flowing toward the northeast direction and the northeast end of the pipe was referred as the downstream end. The rupture was located at approximately 11:30 o'clock[1] looking upstream and intersected a circumferential (girth) weld at each end of the rupture. The distance between the girth welds measure approximately 52 feet ¾ inch. The rupture extended longitudinally approximately 1½ inch beyond the northeast (downstream) girth weld and longitudinally approximately 2½ inches (15 inches along the curved path of the fracture) beyond the southwest (upstream) girth weld. The maximum separation between the longitudinal fractures faces measured approximately 18 inches and was located in segment 2 in an area near the upstream end.

Preliminary inspection of the pipe fracture faces was made between November 4 and 7, 2007. This group consisted of the following individuals:

[1] The pipe in several areas was marked with a dot surrounded by a circle indicating the top of the pipe. For the purpose of this examination, the top of the pipe is referred as the 12:00 o'clock position. All references to a clock position along the wall of the pipe will be made looking upstream.

Frank Zakar	NTSB
Ravi Chhatre	NTSB
C. Dan Tarpley	Dixie Pipeline Company
Ron Scrivner	Stress Engineering Services Inc (consulting metallurgist for Dixie Pipeline Company)

The fracture faces were cleaned with a nylon brush and alcohol. The on-site preliminary examination of the pipe revealed the fracture faces contained no evidence of a fatigue crack origin area or fracture initiation site. The entire length of the fracture faces exhibited a uniform gray/blue tint consistent with exposure to heat from a fire, with no evidence of a distinct lighter or darker tinted band that extended from either the inside diameter or outside diameter surface. The fracture faces exhibited oxidation damage from exposure to heat from a fire. In several areas of the pipe, a layer of gray/blue-tinted oxide had partially fractured and peeled away from the metal surfaces. The exterior coating in the general area of the rupture was consumed by fire. The outside diameter of the pipe in the exposed (visible) areas showed no evidence of the location of a longitudinal weld seam. To facilitate shipping and handling, the pipe was cut into four segments, referred as segments “1” through “4”. The cut ends are indicated in figure 2. Each pipe segment was placed in a wood crate and shipped by truck to the Safety Board’s Materials Laboratory.

Background

Purchase records provided by Dixie Pipeline Company indicated that the pipe was manufactured to American Petroleum Institute (API) Standard 5LX, 9th edition[2], dated February 1960, grade X52[3], as 12¾-inch outside diameter, 0.250 inch nominal wall thickness, electric resistance weld (ERW) steel pipe. The pipe was ordered in May 1961 from Lone Star Steel Company (now owned by U.S. Steel), and rolling was scheduled from June 22, 1961 through July 3, 1961. A representative from U.S Steel indicated that at the time the pipe was ordered, the weld seam would have been made by the low frequency ERW process and reportedly would have been fully normalized after welding.

Location of the ERW Seam

Upon receiving the pipe shipment at the Safety Board’s Materials Laboratory in Washington D.C., and prior to the arrival of parties to the investigation, the pipe segments were removed from their wood crates and placed on top of their respective crates. Wood supports were installed under the pipe segments and, in turn, the supports were attached by screws to the crates to ensure that the pipe would not roll off the top of the crate. The faces of the fractures were cleaned with a soft nylon bristle brush and Alconox, a commercial detergent. A metallurgical section, prepared from the longitudinal fracture, indicated that the longitudinal fracture intersected the centerline of the ERW seam (at approximately 11:30 o’clock looking upstream). Details of how the ERW seam fracture was

[2] Standard that was in effect at the time of purchase and manufacture.
[3] Grade X52 indicates the steel for the pipe should have minimum yield strength of 52,000 pounds per square inch.

found is discussed in the section titled “Metallurgical Sections of Fractured ERW Seams”. Refer to discussion of section “A-A” which initially identified the location of the ERW seam.

Laboratory Group Examination

Metallurgical group examination of the pipe was performed between December 3 and 5, 2007, at the Safety Board’s Materials Laboratory. This examination was attended by:

Frank Zakar	NTSB
Rod Dyck	NTSB
Alan Kushner	NTSB
Joshua Johnson	US DOT, PHMSA
C. Dan Tarpley	Dixie Pipeline Company
Chris Robertson	Dixie Pipeline Company
Phil Miller	U.S. Steel (formerly Lone Star Steel Company)
Ron Scrivner	Stress Engineering Services Inc (consulting metallurgist for Dixie)

Metallurgical examination of the pipe continued after the group departed.

Longitudinal Fracture

Detailed examination of the pipe with a magnifying glass and portable binocular microscope revealed that the faces of the longitudinal fracture between the girth welds were for the most part flat and oriented on a longitudinal plane aligned at 90 degrees to the outside diameter surface of the pipe. The fracture faces showed no evidence of radial lines associated with an origin area or crack arrest marks[4]. The flat fracture face in many areas contained longitudinal, narrow, island-like fracture features that extended either above or below the flat fracture face. An island feature that extended above the flat fracture face contained a flat-topped ridge with cliff-like sides. An island feature that extended below the flat fracture face contained a valley with a flat bottom. The longitudinal flat fracture face contained many isolated island features that intersected the inside diameter and/or outside diameter surfaces as well as some that were closer to the center of the wall thickness. The texture of the flat-bottom or flat-top portion of the island features for the most part appeared smooth compared to the rough texture on the flat longitudinal fracture face. Figures 3 through 13 show examples of the different fracture features that were found on the fracture face of the ERW seam. The metallographic cross sections later showed that the majority of the longitudinal fracture (the portion at 90 degrees to the outside diameter surface of the pipe) was through the material affected by the ERW process, and that the flat top portion of the ridge or flat bottom portion of the valley of an island feature actually were fractured along the curved portion of the upturned grains created when their edges were upset (deformed) during welding. The inside diameter of the pipe segment upstream of the

[4] A crack arrest mark is a “step” on the fracture surface and indicates an intermittent stopping point during fracture propagation.

longitudinal fracture contained a longitudinal protrusion consistent with flash from the ERW process at the 7 o'clock position looking upstream.

The pipe in the area of the ERW seam fracture showed no evidence of corrosion degradation that reduced the wall thickness of the pipe. The ERW seam at the inside diameter and outside diameter surfaces of the pipe showed no evidence of grooving corrosion[5]. The pipe contained minor scratch marks in an area located 37 feet and 10 inches upstream from the downstream girth weld, as shown in figure 14. The scratch marks were nearly parallel to each other and oriented on a diagonal orientation relative to the length of the longitudinal fracture. The depth of each scratch appeared to be approximately 0.03 inch when compared to a scale that was placed next to the outside diameter surface. One end of one of the scratches was located as near as 2.5 inches from the ERW seam. There did not appear to be significant inward denting of the pipe at the scratch mark location, although deformation of the pipe associated with the fracture would have made it difficult to distinguish subtle deformation associated with the scratches from the deformation associated with the fracture. The wall of the pipe showed evidence of inward deformation at 44 feet and 8 inches, 45 feet and 3 inches, and 47 feet and 3 inches upstream from the downstream girth weld. These inward deformations were located the 3, 6, and 9 o'clock positions, respectively. The outer surface of the pipe in the area of the inward deformations showed no evidence of a gouge, impact mark, or scratch.

According to a report prepared by Kiefner and Associates[6], in-line inspection (ILI) data from the ruptured pipe joint reported finding two indications that were detected by a General Electric model PII ultrasonic crack detection tool[7]. This inspection tool was searching for longitudinal oriented ERW seam anomalies. One indication was reported to be a "notch-like feature" that was located approximately 0.66 feet upstream from the downstream girth weld, predicted to be approximately 4.6 inches long and less than 12.5 percent deep. Another indication was reported to be a geometry "not-decidable" feature that was located approximately 0.23 feet upstream from the downstream girth weld, predicted to be 2.8 inches long and 2 inches wide. Both features reportedly were associated with the longitudinal ERW seam. Examination of the fracture face in the general areas predicted to have the ILI indications was flat and revealed no evidence of a radial mark(s), crack arrest mark(s), or island-like fracture features. The inside and outside diameter surface in this area showed no evidence of a dent or loss of wall thickness that was associated with corrosion.

The downstream end of the longitudinal ERW seam fracture extended approximately 1½ inch downstream beyond the downstream girth weld, as shown in figure 15. The 1½-

[5] Grooving corrosion or selective seam weld corrosion is a type of corrosion that creates a sharp V-groove on the inner or outer surface of the pipe in an area along and centered on the bond line of the ERW seam.
[6] Final report titled "Review and Analysis of the Metal Loss, Deformation, and Ultrasonic Crack In-line Inspection Result from Hattiesburg to Demopolis", dated February 1, 2008, and prepared by Dennis C. Johnston and John F. Kiefner, PE. In this report Kiefner and Associates, Inc., provide an evaluation of several in-line inspections that were performed between 1998 and 2006.
[7] The two features detected by the GE ultrasonic crack detection tool were not detected by other inspections devices: the Magpie magnetic flux leakage ILI tool (which measures metal loss associated with corrosion) or the Magpie deformation ILI tool (which measures mechanical damage and deformation).

inch portion of the exposed fracture faces was on a slant (shear) plane, consistent with a ductile overstress separation. The ERW seam on the downstream pipe segment was located approximately at the 4:30 o'clock position looking upstream, as determined by section "B-B". Preparation of section "B-B" is discussed in the section titled "Metallurgical Section of an Intact ERW Seam." The outside diameter surface of the pipe segment 1 contained barely visible white stencil marks. The legible portions of an identification mark read "LONESTAR 7" and "38 X52E". These stencil marks indicated that the pipe was manufactured by Lone Star Steel Company and from grade X52 steel.

For the purpose of this report, the longitudinal ERW seam fracture faces were referred as the northwest and southeast face. Figure 16 shows photographs of the upstream portion of the ERW seam fracture. Examination of the northwest face of the longitudinal ERW seam fracture revealed a faint chevron-like pattern[8] in areas located approximately 2.5 inches and 4 inches away from the upstream girth weld, as shown in figure 17. Similar, but even less visible, chevron-like patterns were noted on the mating areas of the southeast face of the fracture.

The longitudinal fracture within 4.5 inches of the upstream girth weld contained several locations where portions of the fracture plane deviated from the center of the ERW seam without following the flow lines associated with the ERW seam. At distances of 4.5 inches and 2.8 inches from the girth weld, the deviations were located approximately in the center of the wall thickness, with gradual curving of the fracture plane in the circumferential direction as distance to the girth weld decreased, and then a more sudden step back to the center of the ERW seam. These two deviations are shown in close views in the upper left and upper center photographs of figure 18 and in slightly lower magnification views in the remaining photographs of figure 18. These locations are indicated in the left photograph in figure 16 and shown in a closer view in figure 18. Two additional and larger deviations in the fracture plane were located closer to the girth weld and adjacent to the outside diameter surface. The mating sides of one of these deviations, located 1.3 inches from the girth weld, are indicated by arrows "S2" and "S22" in figures 16 and 18. The mating sides of the second deviation, which was adjacent to the girth weld, is indicated by arrows "S1" and "S11" in figures 16 through 20. At deviation "S2" – "S22" there was a gradual curving of the fracture plane in the circumferential direction as distance to the girth weld decreased, and a more sudden step back to the center of the ERW seam, similar to the deviations further from the girth weld. At deviation "S1" – "S11" there was a similar gradual curving of the fracture plane in the circumferential direction as the fracture entered the girth weld, but, at the beginning of the girth weld, the fracture continued to curve onto the circumferential plane in the weld itself (with a slight jog at the edge of the girth weld). A closer view of these two deviations is shown in figure 19.

Directly adjacent to the inside diameter surface, the longitudinal ERW seam fracture and root portion of the upstream girth weld fracture intersected approximately at a right angle, as shown in figure 20. However, over approximately 2/3 of the wall thickness

[8] A chevron pattern is defined as an overstress fracture surface that contains features similar to nested letters "V", sometimes called herringbone pattern. The nested "V" point in a direction that is opposite of fracture propagation.

adjacent to the inside diameter surface, the longitudinal fracture continued upstream, undercutting the circumferential fracture, as shown in figure 19. This crack branching feature is indicative of fracture propagation in the upstream direction in this area.

Adjacent to the upstream girth weld, the wall of the pipe in the general area of the longitudinal southeast fracture face was bulged out (contained an outward deformation) relative to the wall of the intact pipe segment on the other side of the upstream girth weld. The radial distance between the outside diameter surface of the pipe in the area of the outward deformation and the outside diameter surface on the adjoining upstream pipe segment on the other side of the girth weld measured approximately 0.45 inch. The measured radial distance is indicated by arrows “R-R” in figure 22.

Circumferential Fracture

Figures 21 through 28 show photographs of the 15-inch circumferential fracture area associated with the upstream girth weld.[9] The circumferential fracture extended from the ERW seam fracture in a clockwise direction (looking upstream), across the top of the pipe, and partially down the other side. For approximately 3.3 inches adjacent to the longitudinal weld, the circumferential fracture was directly in or adjacent to the girth weld. The remainder of the circumferential fracture was in the base metal of the next upstream pipe segment, as shown in figure 23. The portion of the circumferential fracture in the base metal contained shear lips adjacent to the interior and exterior surfaces and a clear chevron pattern showing propagation in the clockwise direction, toward the tip of the fracture. A 2-inch length portion of the mating fracture faces, in the area indicated by bracket “C” in figure 23, showed evidence of compression damage, as if the faces in this area were pressed against each other. The terminus of the circumferential fracture was located approximately 4 inches away from the ERW seam in the upstream pipe segment. The remainder of this section discusses the portion of the circumferential crack in and adjacent to the girth weld.

The open flap portion of the pipe in the area of the girth weld was deformed and appeared to have a nearly circular curvature (see the right photograph in figure 23). Circle templates of different size diameter were placed on the inside diameter surface of the pipe in a transverse plane. The diameter of the deformed (curved) portion of the pipe in the area of the girth weld fracture measured between 8 and 8.5 inches, smaller than the original approximately 12 inch inside diameter of the pipe.

On the exterior surface, most of the girth weld fracture intersected the downstream toe of the weld bead. However, several small portions of the girth weld fracture extended nearly through the center of the weld bead. On the interior surface, the fracture largely intersected the downstream toe of the weld bead.

Examination of the downstream face of the girth weld fracture revealed that a 1-inch fracture portion adjacent to the ERW seam fracture contained a faint chevron-like pattern

[9] Length of the fracture when measured along the circumference of the pipe.

(see figure 24). Between the end of the possible chevron pattern and an area located approximately 3.3 inches clockwise of the ERW seam, the fracture intersected the downstream toe of the exterior and interior weld beads and was on a slanted and slightly curved plane. Closer views of three areas in this portion of the fracture are shown in figure 25. At approximately 3.3 inches clockwise from the ERW seam fracture, the girth weld fracture extended nearly longitudinally[10] across the weld, at the location indicated by arrow "W" in figures 16, 20, 23, 24, 26, 27, and 28. Figure 26 shows detailed views of the fracture at the location indicated by arrow "W". A portion of the fracture clockwise of the arrow "W" position was through the base metal portion of the upstream pipe segment, as shown in figure 27, and the chevron pattern in the remainder of the circumferential fracture extended almost up to the arrow "W" position.

The fracture faces of the girth weld showed no evidence of a preexisting crack (such as radial or crack arrest marks that originate from a specific location).

The upstream face of the fracture contained a void in the area near the longitudinal girth weld fracture (see figure 28). The wall of this void was deformed and the bottom portion showed no clear evidence of a boundary for a gas pocket (porosity). API standard 1104, titled Standard for Field Welding of Pipe Lines, 6th edition, dated August 1959, indicated that the maximum specified size of a gas pocket shall not exceed 0.0625 inch. Dixie Construction Welding Specification indicated that the maximum dimension of any individual gas pocket shall not exceed 0.125 inch. The size of the void measured as large as 0.050 inch, smaller than the maximum allowable size indicated in API and Dixie Construction Welding Specifications. The upstream face of the weld fracture contained other gas pockets. The same API standard contained a diagram that illustrated the maximum allowable distribution of gas pockets (applicable for plate thickness in the range greater than 0.25-inch to and including 0.5 inch). This diagram was intended for interpretation of X-ray images. For comparison purpose, the size and distribution of the exposed gas pockets in the fracture face of the weld were compared to the diagram, and found to be less than shown in the diagram. The more recent edition of API 1104, 20th edition, dated October 2005, contained a diagram that illustrated the maximum allowable distribution of gas pockets, but this edition showed X-ray reference standards that apply to plate thickness equal to or less than 0.5 inch. According to the 20th edition of API 1104, the maximum diameter of an individual gas pocket shall not exceed 0.125 inch or 25% of the thinner of the nominal wall thickness joined. For the accident pipe, 25% of the thinner of the nominal wall thickness was calculated to be 0.0625 inch. The size and distribution of the gas pockets found on the weld fracture face were less than the maximum permissible size and distribution shown in the API standard.

A 9-inch ring portion of the pipe that incorporated the girth weld and portion of the ERW seam fracture was saw-cut from the pipe. Additional saw cuts were made through the ring piece to facilitate examination of the fracture faces, as shown in figure 16. Examination of the inside diameter surface of the ring portion revealed semi-circular,

[10] Nearly longitudinal with respect to the length of the pipe (nearly transverse with respect to the length of the girth weld).

rainbow-like, stain patterns that were located adjacent to the ERW seam weld and girth weld on the open flap portion of the pipe, in the areas indicated by arrows labeled “stain A”, “stain B”, “stain C1”, and “stain C2” in figure 20. The stains were slightly etched into the inside diameter surface of the pipe. The inside diameter surface of the pipe on the other side of the upstream girth weld and ERW seam in the areas that corresponded to the location of the stains showed no evidence of a stain.

X-ray inspection of the girth weld

The complete circumference of the upstream girth weld was inspected by X-ray method[11] on the pieces shown on the right side of figure 16. Cut pieces shown on the right side of figure 16 were labeled pieces “1” through “7”. Examination of the x-ray images revealed that the amount of porosity in the girth weld was less than the allowable amounts in API and Dixie Construction Welding Specifications. Several circumferentially oriented linear, crack-like, indications were noted on the x-ray images, as shown in figure 29, 30, and 31. Although most of the crack-like indications were not visually noted when examining the external surfaces (inside or outside diameter) of the pipe, those that were visible were noted on the inside diameter surface and were associated with the toe of the root weld bead or were areas of incomplete penetration of the weld on the inside diameter surface. Metallurgical sections through the girth weld, including an area containing a crack-like indication, are discussed later in this report.

Metallurgical Section of an Intact ERW Seam

The inside diameter surface of pipe segment 4 at the upstream end contained a longitudinal protrusion consistent with the flash from the ERW process at the 4:30 o’clock position looking upstream (see figure 32). A transverse metallurgical section (labeled section “B-B”) was made through the ERW seam. This section served as a reference for comparison against metallurgical sections that were made from the fractured ERW seam. The section was encased in a metallurgical mount, polished, and etched with 2% Nital reagent. Figures 33 and 34 show photographs of the etched section. Examination of this section revealed the pipe contained a microstructure of ferrite and pearlite typical for low alloy steel. Away from the ERW seam, the pipe exhibited a minor banding[12] structure that was parallel to the inside and outside diameter surfaces and followed the circumference of the pipe. The ERW seam appeared in the microstructure as a white line and extended radially between the inside and outside diameter. In the area of the ERW seam, the grains in the base metal flowed toward the weld at the center of the wall thickness then fanned out (curved) toward the inside diameter and outside diameter surfaces. The grains were nearly parallel to the ERW seam at the outside and inside diameter surface. For the purpose of this report, the portion of the grains near the ERW seam that turn/curve toward the inside or outside diameter surfaces are referred as upturned grains.[13]

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[11] HYTEC Flash CT digital X-ray equipment.

[12] Banding is segregated structure consisting of alternating nearly parallel bands of different composition, typically aligned in the direction of primary hot working.

[13] Not to be confused with the term “upturned fiber imperfection or “hook cracks” that according to API Standard 5T1, titled “Standard on Imperfection Terminology”, dated November 1996, refer to metal separation, resulting

Section “B-B” contained an elongated stringer inclusion in an area near the ERW seam where the grains turned toward the inside diameter surface (see figure 34 and 35). The length of the stringer inclusion measured approximately 240 micrometer (0.01 inch), and the thickness measure approximately 10 micrometers (0.0004 inches). X-ray energy dispersive spectroscopy (EDS) analysis of the inclusion produced a spectrum that contained elemental peaks of sulfur and manganese consistent with manganese sulfide inclusion, as shown in figure 35.

Metallurgical Sections from the Fractured ERW Seam

In order to determine the location of the ERW seam relative to the position of the longitudinal fracture, the northeast cut end of pipe “segment 1”, indicated by arrow “C1” in figure 2, was ground all around the circumference with successively finer grit paper (until reaching 600 grit paper). The ground end was first etched with 2% Nital etch reagent and re-etched with 10% Nital etch reagent. This procedure did not reveal the location of an ERW seam. An approximately 3-inch ring portion was cut from the northeast end of pipe segment 1. The ring portion was further cut into four approximately equal size pieces (see figure 36). The cut pieces were cleaned again with Alconox, and this cleaning procedure revealed minor metal build-up on the inside diameter surface in the area adjacent to the length of each longitudinal fracture face consistent with flash from an ERW seam. A metallurgical section was prepared from the mating fracture faces, orientation and location is indicated by section line “A-A” in figure 36. Section “A-A” was etched with Nital reagent. Examination of the etched section revealed that the longitudinal fracture intersected the ERW seam, as shown in figures 37 and 38.

Five other transverse[14] metallurgical sections were made at various locations along the length of the longitudinal flat fracture. Each transverse metallurgical section incorporated the approximate mating fracture face. The metallurgical sections were identified as sections “1-1”, “2-2”, “3-3”, “4-4”, and “5-5” and their position relative to the downstream girth weld are indicated in table 1. The mating fracture faces were encased in a metallurgical mount. Prior to encasing the pieces in a metallurgical mount, the excised fracture faces were examined under a binocular microscope and this examination revealed the fracture faces were covered with a gray/blue-tinted layer of oxide consistent with exposure to heat from a fire. The excised fracture faces contained no evidence of crack arrest marks. Figures 39 through 45 show photographs of the fracture profile from each prepared metallurgical section and microstructure associated with several of these metallurgical sections.

Examination of metallurgical sections “1-1”, “2-2”, “3-3”, “4-4”, “5-5” and “A-A” revealed the pipe contained fracture profiles that were classified into two categories. In the first category, the fracture extended in a radial orientation between the inside and outside diameter surfaces and was for the most part through center of the ERW seam. Sections

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from imperfections at the edge of the plate or skelp, parallel to the surface, which turn toward the I.D. or O.D. pipe surface when the edges are upset during welding.

[14] Transverse section is oriented in the radial-circumferential plane.

“1-1” and “A-A” were classified in the first category; see figures 37, 38, 39 and 40. In the second category, a fracture at the inside diameter and/or outside diameter surfaces was parallel or nearly parallel to the ERW seam and extended partially around the upturned grains, resembling the outline of the letter “J”. There was a cross-grain fracture ligament between the end of each “J” fracture portion and the ERW seam fracture. Figure 41 identifies the “J” fracture portion, the cross-grain potion, and the ERW seam portion of the longitudinal fracture on section “2-2”. Sections “2-2”, “3-3”, “4-4”, and “5-5” were classified in the second category, see figure 41 through 46. The depth of the “J” portion of the fracture when measured from inside diameter or outside diameter surfaces was expressed as a percent of the wall thickness, noted in the appropriate figures that contained a “J” fracture.

The microstructure in the wall portion of the sections “1-1” through “5-5” and “A-A” appeared as fine grain. The grains in the ERW seam for the most part appeared uniform and their size appeared similar to the size of the grains in the wall of the pipe. The wall of the pipe in the area of the ERW showed no evidence of an hour glass-like heat-affected-zone on both sides of the ERW. These observations are consistent with an ERW seam that was subjected to heat treatment at a normalizing temperature. The surfaces of the wall and fractures contained a layer of oxide consistent with exposure to heat from a fire.

Metallurgical Sections of the Upstream Girth Weld

A metallurgical section was prepared from an intact portion of the girth weld at the upstream end of the longitudinal fracture. The section was taken at the bottom of the pipe, approximately at the 6:00 position, at the location and orientation indicated by section line “7-7” in figures 16 and 22. The metallurgical section was encased in a metallurgical mount and etched with 2% Nital reagent. The prepared metallurgical section is shown in figure 47. Examination of the section revealed no evidence of a weld defect, such as a crack, void, porosity, incomplete penetration, delamination or undercut at the toe of the weld.

API standard 1104, dated August 1959, specified angular and vertical offset between pipe segments, and size of the welds. The angular and vertical offset between pipe segments, and size of the welds were measured from the prepared section. The vertical offset between the walls of the pipe in the area of the girth weld measured between 0.040 and 0.043 inch, less than the maximum specified for a root portion of the weld (0.0625 inch). The angular offset between the two pipe segments in the general area of the weld joint measured approximately 3 degrees, with each pipe segment angled up relative to the weld. Prior to making the metallurgical section, the angular offset was measured with an inclinometer directly on a longitudinal strip of material that was cut from the 9-inch ring portion (strip portion is shown in figure 16). The difference in the angle between the inside diameter surfaces of the wall was determined to be between 0.1 and 0.3 degrees, with each pipe segment angled up relative to the weld.

The height of the weld bead is defined as the vertical distance between the surface of the bead and the toe of weld. The height of the weld bead was measured on the inside and outside diameter surfaces of the pipe. Two height measurements were reported for

each weld joint. The smallest measurement reflected the shorter height difference between the bead and the toe of weld on one side of the girth weld and the larger measurement reflected the greater height difference between the inboard portion of the bead and the toe of the weld on the other side of the girth weld. Thus, a lower and upper range was reported for each joint. The height of the bead on the inside diameter surface measured between 0.027 and 0.052 inch. The height of the weld bead at the outside diameter surface of the pipe measured between 0.0270 and 0.0620 inch. All measured weld bead heights were less than the maximum allowable height (0.0625 inch).

A metallurgical section was prepared from the fractured portion of the upstream girth weld near the top of the pipe, location and orientation indicated by sections line “6-6” in figure 20. Figures 48 and 49 show photographs of the etched section. Examination of the etched section revealed that approximately half of the fracture adjacent to the outside diameter surface for the most part extended through the base metal in the heat affected zone, and that the remainder of the fracture, adjacent to the inside diameter surface, extended through the boundaries of the weld fusion zone. The inside diameter weld bead contained a slight overlap on both sides of the weld. The height of the weld bead on the inside diameter measured approximately 0.055 inch, less than the maximum allowable height (0.0625 inch). The toe of the inside diameter weld bead contained a crack, indicated by arrow “K” in figure 20 and 48, that extended from the nearly longitudinal girth weld fracture (arrowed “W” in figure 20). The extension of this crack in the circumferential direction is denoted in the x-ray image (s) in figure 30. A void was found in the fusion weld zone near the base metal in an area that was located midway between the inside and outside diameter surfaces of the pipe (see figure 48). One end of the void was located in an area that contained manganese sulfide stringer inclusions. The length of the void measured approximately 0.02 inch. Purchase records provided by Dixie Pipeline Company indicated that the mill bevel (referred as the bevel angle) at the edges of the plate[15] was specified to be in the range between 30 and 35 degrees.[16] A representative from US Steel indicated that root face (non-beveled portion of the groove face adjacent to the root of the joint) is to be between 0.031 and 0.093 inch. The bevel angle and root face can be measured at the mill or any time before the joint is welded. The angle of the mill bevel and size of the root face could not be determined because the joint was fused by weld metal. The fracture at the weld joint appeared to follow a general angle of inclination. The angle inclination[17] of the fracture face measured between 42 and 43 degrees, as shown in figures 47 and 48.

Chemical Composition

At the time the pipe was ordered, steel for the pipe would have been produced by the open-hearth, non-expanded process, according to a representative from U.S. Steel. The check chemical composition for the pipe is carbon 0.34 max, manganese 1.40 max,

[15] The mill bevel edges of the plate eventually are joined and form a single “V” butt weld joint that later is joined by the ERW process.
[16] Bevel angle is measured at the root of the weld joint and extends between the mill bevel face and a vertical (radial) imaginary line in the joint.
[17] Measured in the same manner as a bevel angle.

phosphorus 0.05 max, and sulfur 0.06 max. Chemical analysis was performed by the Safety Board's Materials Laboratory using a LECO model GDS500 Glow Discharge Optical Emission Spectrometer at two different locations on the outside diameter surface of the pipe. One analysis was performed on the outside diameter surface of an excised piece of the wall from segment 4 near section "B-B" in the area indicated in figure 32, and another analysis was performed on the outside diameter surface of an excised piece of the wall from pipe segment 1 in the area indicated in figure 36. The analysis was performed in an area that was ground with grit paper. The results of the analysis indicated the composition of the ruptured pipe was within the limits described in the 1960 issue of API 5LX, for grade X52 pipe. The result of the chemical analysis is shown in table 2.

Dimensions of the Pipe

The thickness of the wall at the northeast saw cut end of pipe segment 1 (marked "C1" in figure 2) and the southwest torch cut end (marked "C0" in figure 2) were measured with a point micrometer. The wall thickness of the ruptured and intact pipe pieces measured between 0.254 inches and 0.255 inches, which was within the specified tolerances for 0.250-inch nominal wall thickness pipe (0.219 and 0.288 inch). The circumference of the outside diameter of the intact pipe at the cut southwest end measured approximately 3 feet, 4 inches and 5/16 inches. This calculates to an outside diameter of 12.83 inches, which was within the API 5LX specified range (between 12.62 and 12.88 inches).

Tensile Testing

The March 1960 issue of API Standard 5LX indicated that the ultimate tensile strength, yield strength (at 0.5% of gage length when measured with an extensometer), and elongation for grade X52 pipe should be no less than 66,000 pounds per square inch (psi), 52,000 psi, and 18%, respectively. The API specification indicated that for welded pipe, in sizes 8 and 5/8 inch and larger, the tensile properties shall be determined by tests on transverse specimens. The transverse body-tensile specimens shall be taken from an area that is located opposite the weld. Transverse weld specimens shall be taken with the weld at the center of the specimen. The specification also indicated that transverse weld specimens shall be tested for ultimate tensile strength only.

A 3-foot long ring piece of pipe was excised from the downstream end of "segment 4". Two transverse[18] body-tensile specimens and two transverse weld-tensile specimens were machined from the ring portion of the pipe. Each tensile specimen was manufactured with a gauge length of 2 inches and a width of 1.5 inches at the gauge length area, in accordance with API and American Society for Testing and Materials (ASTM) A370, titled "Standard Methods and Definitions for Mechanical Testing of Steel Products". Tensile specimens were machined and tested at Lehigh Testing Laboratories, New Castle, Delaware.

[18] Oriented circumferential with respect to the length of the pipe.

The results of the tensile testing are shown in table 3A for the base metal and table 3B for the ERW seam. The measured ultimate tensile strength and yield strength for the two base metal tensile specimens was within the specified range. The measured elongation values for the two base metal tensile specimens were greater than the minimum specified value (18%). The measured ultimate tensile strength for the two ERW seam tensile specimens was within the specified range. As indicated earlier, testing for the yield strength and elongation of the ERW seam was not required, but was recorded for information purpose. The measured yield strength of the ERW seam tensile specimens was within the range that was specified for the base metal, but the measured elongation value of the two tensile specimens (4% and 10%) was significantly less than the minimum elongation that was specified for the base metal (18%).

Charpy V-Notch Impact Testing

March 1960 issue of API Standard 5LX did not specify Charpy V-notch impact testing and minimum values for Charpy V-notch specimens. In order to gain information on the impact properties of the pipe, Charpy V-notch specimens were prepared from the base metal and the ERW seam. ASTM A370-07a and Specification for Line Pipe - API Specification 5L, 43rd edition, March 2004, indicated that for ERW seam pipe, transverse[19] Charpy specimens for the base metal are to be prepared from an area of the pipe that is located 90 degrees circumferentially away from the ERW seam. Sub-size Charpy specimens (approximately 1/3 the thickness of a standard specimen) were prepared to accommodate the wall thickness of the pipe (0.250 inch [6.35 mm]).[20] Specimens were machined to 3.3 mm x 10 mm x 55 mm. The specimens were tested at room temperature (approximately 68 degrees Fahrenheit). Non-notch specimens also were prepared from the ERW seam (same size and orientation as the sub-size Charpy specimens) but without the notch. API does not specify testing of non-notch specimens. The test specimens were prepared and tested by Lehigh Testing Laboratories, New Castle, Delaware. The results from the tests are shown in table 4. The values shown in table 4 are for sub-size specimens (approximately 1/3 thickness of the standard size specimen).

Flattening Tests

According to March 1960 issue of API Standard 5LX, a ring piece shall be flattened between parallel plates. No cracking shall take place in the weld until the distance between the plates is less than two thirds of the original outside diameter of the pipe (greater than one third reduction of the original outside diameter). No cracking shall take place in the wall (base metal) until the distance between the plates is less than one third of the original outside diameter of the pipe (greater than two thirds reduction of the original outside diameter).

Two ring pieces of the pipe, each ring measured approximately 3 inches wide, were subjected to a flattening test as described in API. The ring pieces were cut from

[19] Length of a Charpy specimen is parallel to the circumference of the pipe.
[20] The size of a standard Charpy specimen is about 0.394 inch x 0.394 inch x 6.67 inch (10mm x 10mm x 55mm).

the downstream end of pipe segment 4. One ring piece labeled #1 was positioned in the hydraulic press so that the ERW seam was rotated 90 degrees away from the flat plates (point of maximum bending). The pipe was compressed between flat plates until the plates were approximately 8.5 inches apart (corresponded to one third reduction of the original outside diameter). After this amount of deformation, no evidence of cracking was found in the weld or base metal. The pipe was further compressed and a crack instantaneously extended through a major portion of the weld when the outside diameter measured approximately 5.375 inch. The ring was further compressed until the outside diameter measured approximately 4.25 inch (corresponded to approximately two thirds reduction of the original outside diameter). No evidence of a cracking was found in the base metal. Ring piece #1 passed the flattening test that was specified in API.

Another ring, labeled #2, was positioned between flat steel plates such that the ERW seam was oriented zero degrees (the ERW seam was touching one plate). The pipe was compressed between flat plates until the outside diameter measured approximately 4.25 inch (corresponded to approximately two thirds reduction of the original outside diameter). No evidence of cracking was found in the ERW seam or the base metal. Ring piece #2 passed the flattening test that was specified in API.

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Senior Metallurgist

Table 1. Features of Interest that were Found Along the Length of Pipe

Distance as measured **Downstream** from the Downstream Girth Weld	Pipe Segment No.	Point Of Interest	Outward Bend Deformation at Fracture Face		Inward Deformation	Metall-urgical Section
			S.E. Fract. Face	N.W. Fract. Face		
8' and 10 ½" downstream from downstream girth weld	4	Torch cut downstream (northeast) end of pipe Segment 4				
8' and 6½" downstream from downstream girth weld	4	(section taken 4" from cut end)				Section B-B, ERW seam located at 4:30 o'clock looking upstream
0	4	Location of Downstream Girth Weld				

Distance as Measured **Upstream** from Downstream Girth Weld	Pipe Segment No.	Point Of Interest	Outward Bend Deformation at Fracture Face		Inward Deformation	Metall-urgical Sections
			S.E. Fract. Face	N.W. Fract. Face		
0	4	Location of Downstream Girth Weld				Sections 6-6 and 7-7
Between 0" and 10.5"	4			x		
7.5"	4		x	none		
7' and 7"	between 4 & 3	Reciprocating field saw cut through pipe between pipe segments 4 & 3				
9' and 7"	3		none	x		
19' and 2.5"	3			x		

20’ and 1”	3			x		
20’ and 8.5”	3			x		
22’ and 5”	between 3 & 2	Reciprocating field saw cut through pipe				
24’ and ¼”	2		x	x		
29’ and 8”	2			x		
29’ and 11”	2		x			Section 3-3
34’ and 1”	2			x		
34’ and 2”	2		x			
36’ and 4”	2	Picture OD and center islands				Section 2-2
37’ and 10”	2	Greatest separation between fractures (picture of fracture face)	x	x		Section 1-1
37’ and 10”	2	Several scratches on outer surface				
39’ and 8”	2 & 1	Reciprocating field saw cut through pipe between pipe segments 2 and 1				
39’ and 11”	1	Determined that fractured ERW seam was at 11:30 o’clock looking upstream				Section A-A
40’ and 6”	1		x	x		
42’ and 3”	1					Section 4-4
44’ and 8”	1		x	x	X (3 o‘clock looking upstream)	
45’ and 3”	1				X (6 o‘clock looking upstream)	
45’ and 5”	1	Picture OD island		x		

46” and 9”	1					Section 5-5
46’ and 10”	1		x			
47’ and 3”	1				X (9 o’clock looking upstream)	
52’ and ¾”	1	Location of Upstream Girth weld				
55’ and 4”	1	Torch cut end southwest (upstream) End of pipe segment 1 (ID surface shows longitudinal ERW seam feature at 7:00 o’clock looking upstream)				

Abbreviations used in the table:
S.E.- Southeast
N.W.-Northwest
(‘ and “) – (feet and inches)

Table 2. Chemical Composition of Coupons

Element	Specified For Open Hearth, Killed Deoxidized Non-Expanded Pipe (weight %)	Measured Results for Segment #1 That contained the major portion of the rupture (weight %)	Measured Results for pipe segment #4 portion that was located downstream from the downstream girth weld (weight %)
Aluminum	Not specified	0.00	0.00
Boron	Not specified	0.00	0.00
Carbon	**0.34 max**	**0.222**	**0.290**
Chromium	Not specified	0.024	0.027
Copper	Not specified	0.420	0.427
Manganese	**1.40 max**	**1.14**	**1.18**
Molybdenum	Not specified	0.009	0.010
Niobium[21]	Not specified	0.00	0.00
Nickel	Not specified	0.055	0.058
Phosphorus	**0.05 max**	**0.024**	**0.029**
Sulfur	**0.06 max**	**0.026**	**0.034**
Silicon	Not specified	0.033	0.033
Tin	Not specified	0.00	0.025
Titanium	Not specified	0.001	0.002
Vanadium	Not specified	0.002	0.001
Iron	Remainder	Remainder	Remainder

[21] Formerly know as the element columbium.

Table 3A. Tensile Properties of the Base Metal[22]

Property	**Minimum Specified**	Specimen #1 **Measured**	Specimen #2 **Measured**
Yield Strength, 0.5% EUL (psi)[23]	52,000	63,500	65,000
UltimateTensile Strength (psi)	66,000	85,100	84,900
Elongation, (%)	18	28	28

Table 3B. Tensile Properties of the ERW Seam

Property	**Minimum Specified**	Specimen #1 **Measured**	Specimen #2 **Measured**
Yield Strength, the stress required to produce a total elongation of 0.5% of the gage length (psi)	Not required for a weld	65,600	66,800
UltimateTensile Strength (psi)	66,000	80,900	88,100
Elongation, (%)	Not required for a weld	4	10

Table 4. Impact Properties (tested at 68°F)

Specimen Type	Specimen Identification	Impact Energy (ft-lbs)	Lateral Expansion (Mils)	Shear (%)
Notched ERW Seam	A	7	20	90
	B	4	15	90
	C	12	24	100
	D	12	25	100
Not Notched ERW Seam	A	30	36	80
	B	20	28	80
	C	14	21	90
	D	29	35	90
Notched Base Metal	1	12	29	90
	2	17	31	90
	3	19	53	90

[22] Results are for the pipe portion that was located downstream from the downstream girth weld.
[23] Extension under load (EUL) method - stress required to produce a total elongation of 0.5% of the gage length.

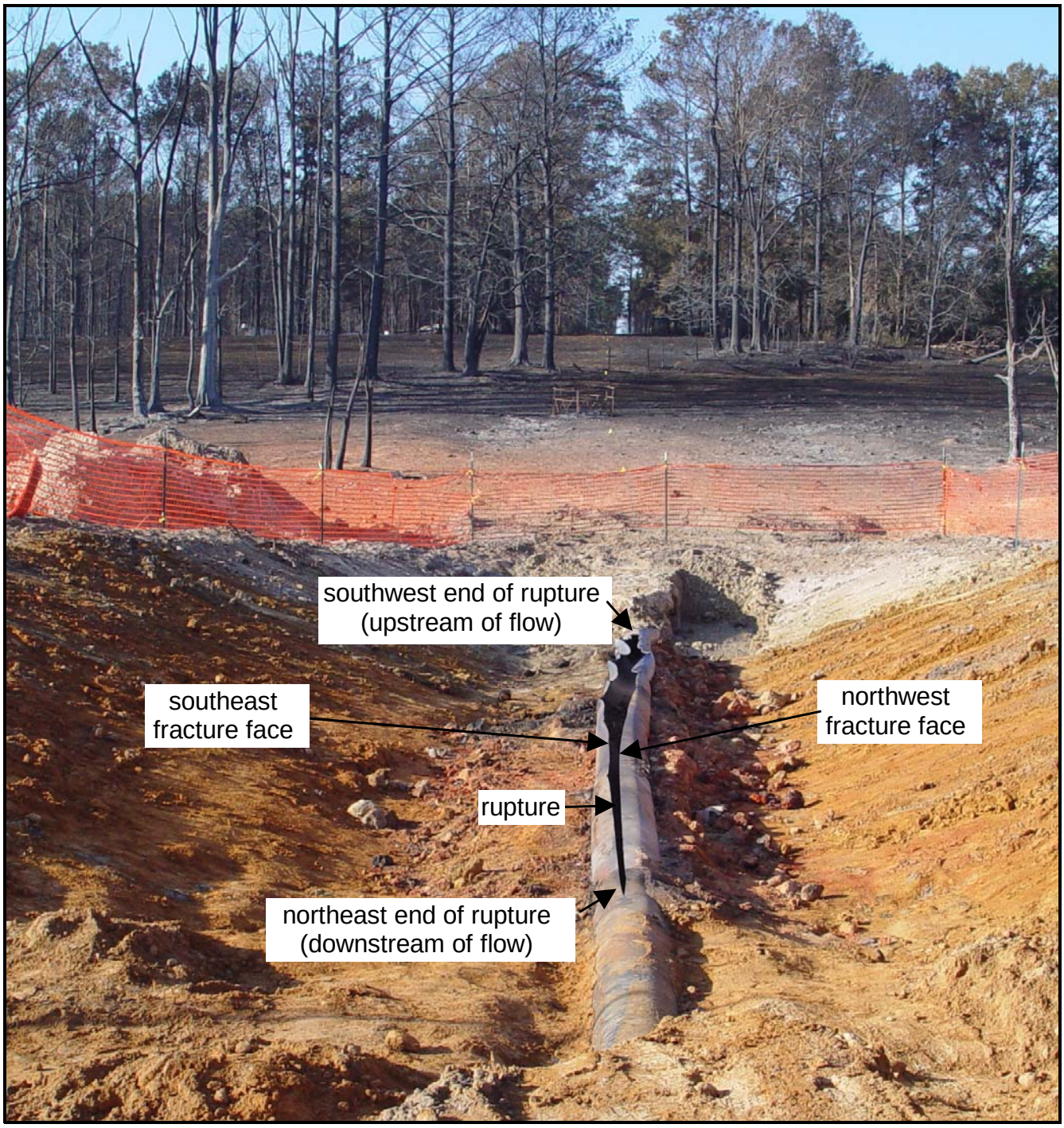

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Figure 1. View looking southwest at the ruptured pipe. The soil has been removed from around the pipe to facilitate on-site examination.

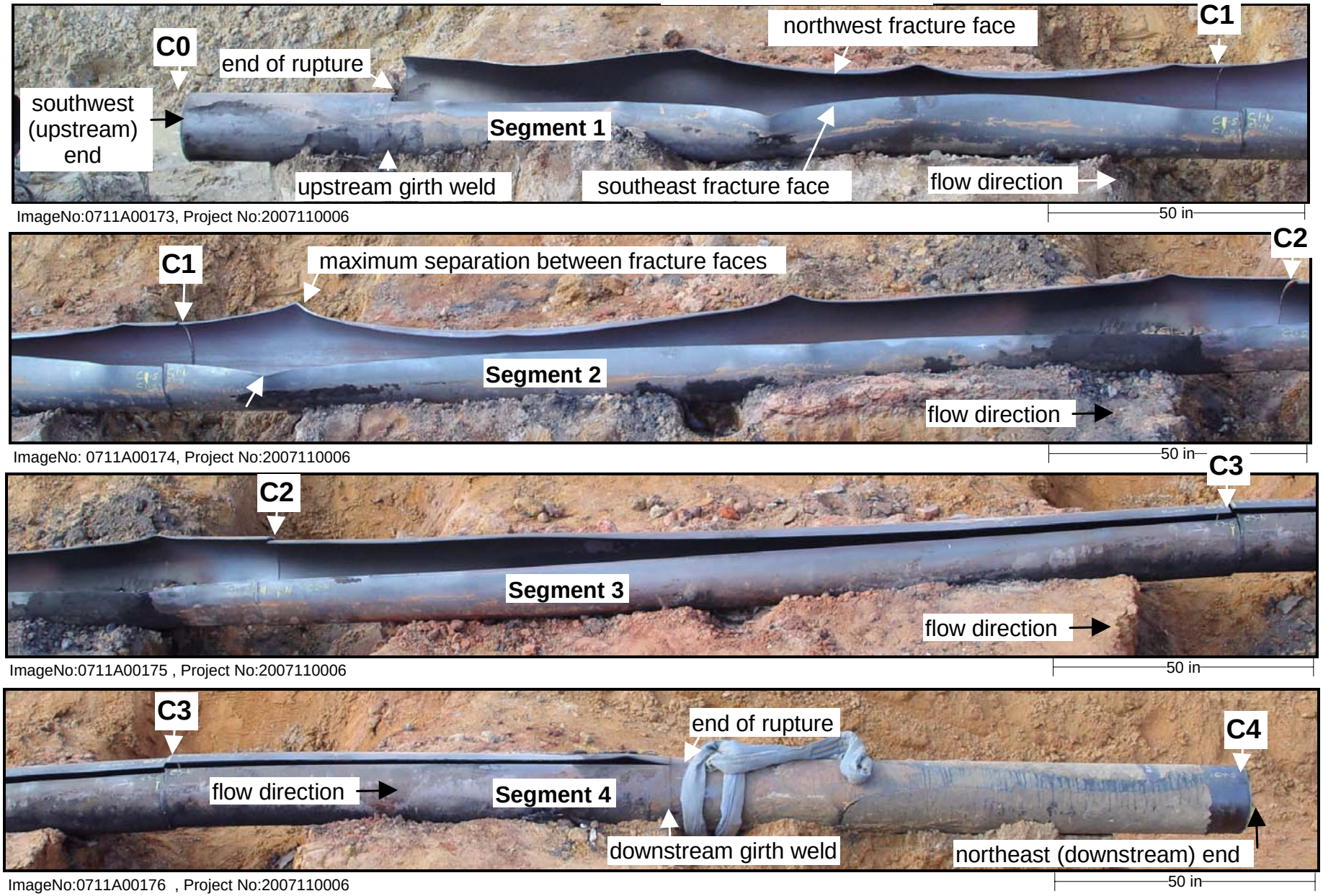

Figure 2. Ruptured pipe that was cut into four segments to facilitate shipping. The circumferencial saw cut areas are indicated by arrows "C1", "C2", and "C3". The circumferencial torch cuts ends are indicated by arrows "C0" and "C4". A strap was wrapped around pipe "segment 4" in preparation for lifting.

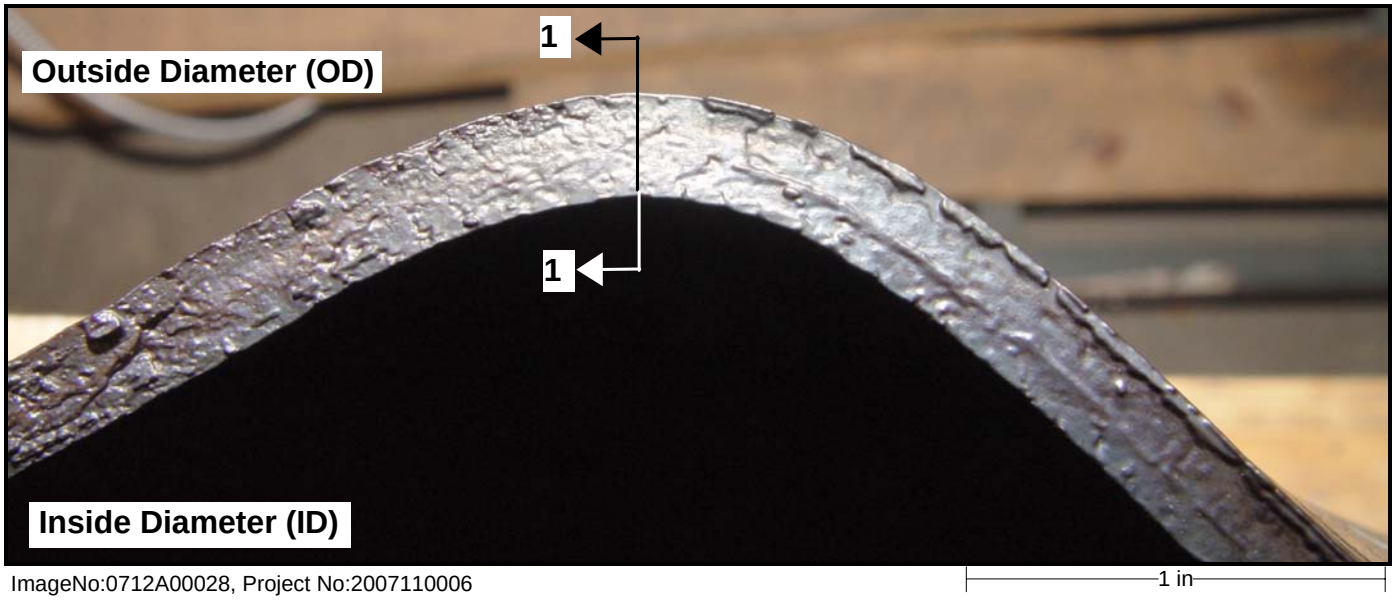

Figure 3. Longitudinal fracture face that was located approximately 37 feet and 10 inches upstream from the downstream girth weld. The upstream end is located on the left side of the photograph. A metallurgical section was taken from the area and orientation indicated by section line "1-1". The wall in this area of the pipe was deformed outward relative to the overall longitudinal fracture.

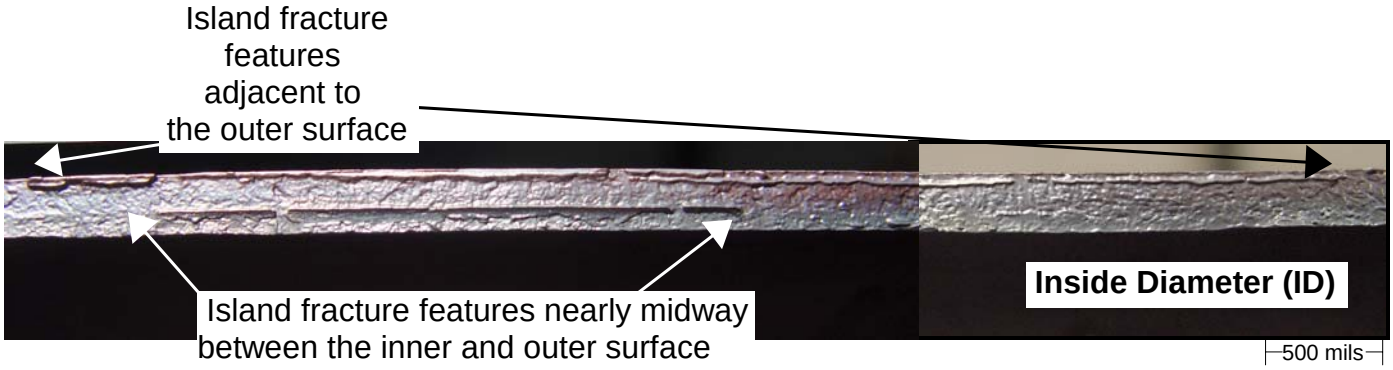

Figure 4. Longitudinal fracture face that was located approximately 36 feet and 1 inch upstream from the downstream girth weld. Upstream end is on the left side of the photograph. This flat fracture face contained island fracture features near the center of the wall (nearly midway between the inner and outer surface) and island fracture features adjacent to the outer surface. The combined length of all the island features adjacent to the outer surface in this area of the wall measured approximately 5.5 inches. The combined length of the island fracture feature that were located nearly midway between the inner and outer surfaces measured approximately 2.38 inches.

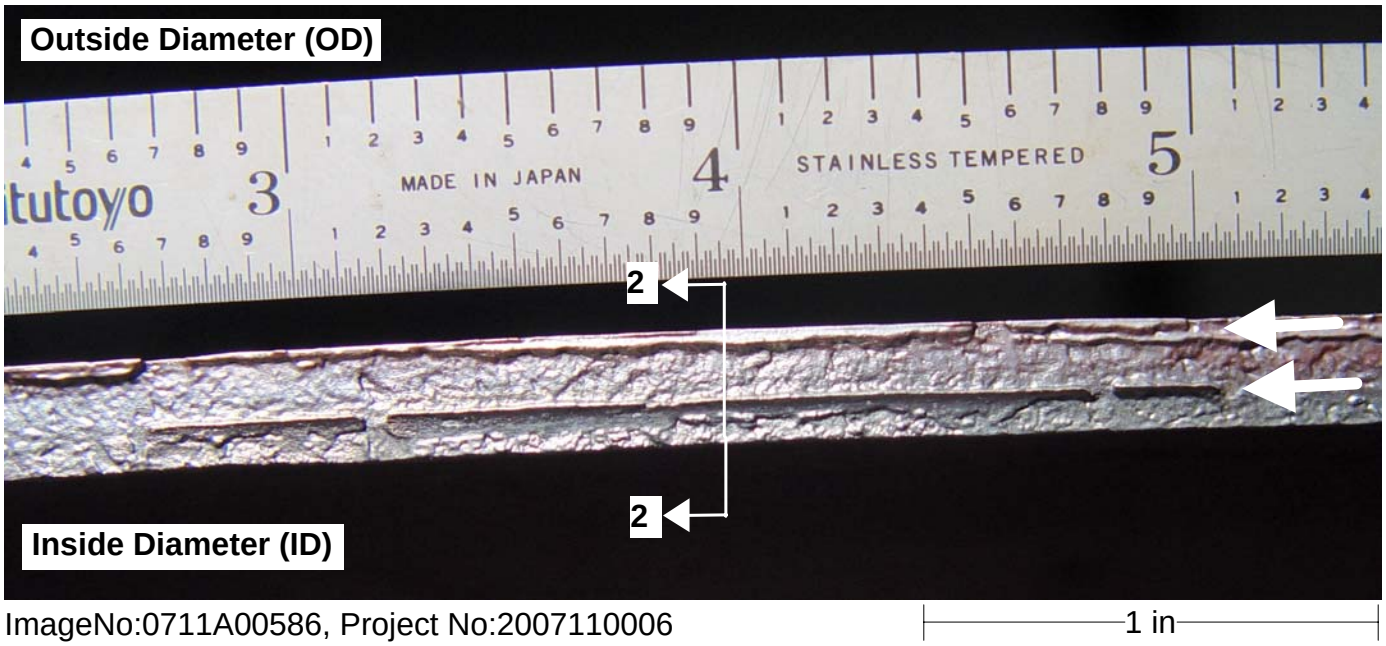

Figure 5. Closer view of a portion of the photograph in figure 4. Inside diameter is located at the bottom and the upstream end is on the left. A metallurgical section was taken from the area and orientation indicated by section line "2-2". Unlabeled arrows indicate the location of island fracture features that extended above the longitudinal flat fracture face.

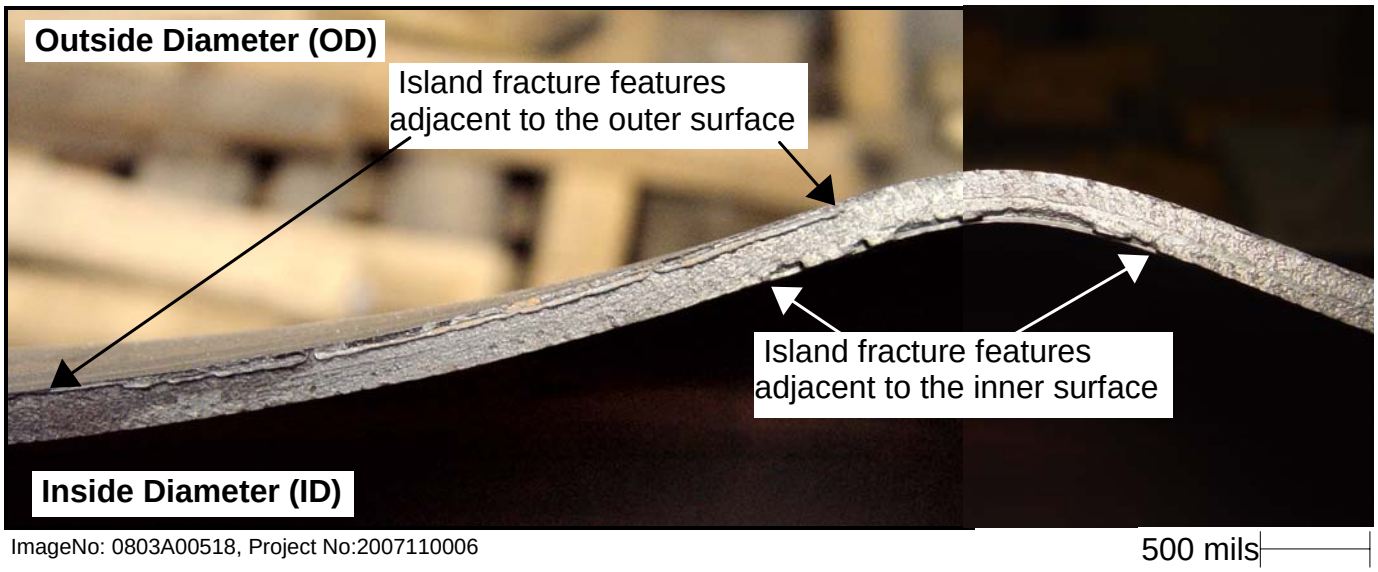

Figure 6. Longitudinal fracture face that was located approximately 29 feet and 11 inches upstream from the downstream girth weld. Upstream end is located on the left side of the photograph. The fracture face contained island fracture features adjacent to the outer surface and inner surface. The island fracture features adjacent to the outer face extended above the longitudinal fracture and those adcent to the inner surface extended below the longitudinal flat fracture face. The combined length of the island features at the outer surface measured approximately 4.3 inches and the greatest width of this island feature measured approximately 0.07 inch (28% of the wall thickness). The length of the island features adjacent to the inner surface measured approximately 3.3 inches.

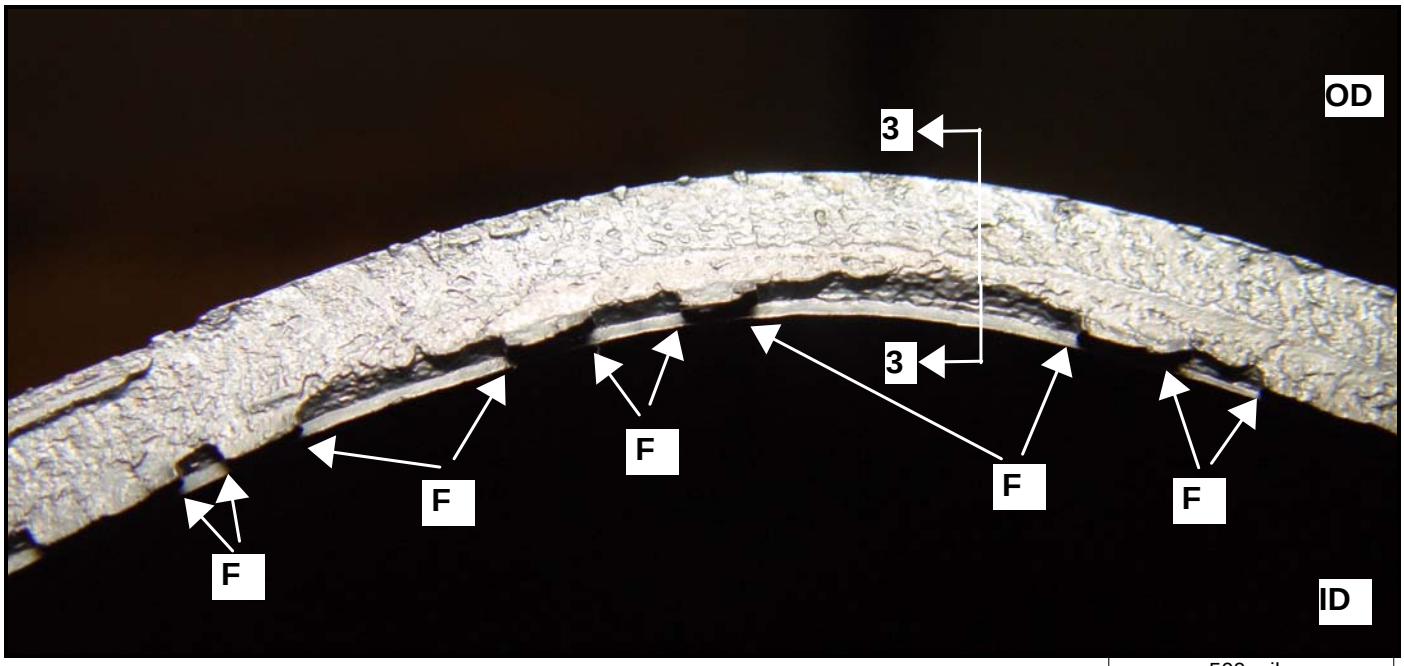

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Figure 7. Longitudinal fracture face located 29 feet and 11 inches upstream from the downstream girth weld. Inside diameter is located at the bottom and the upstream end is located on the left. A metallurgical section was taken from the area and orientation indicated by section line "3-3". Arrows "F" indicate the ends of several isolated flat fracture planes on the inner surface that extended below the longitudinal fracture face. The isolated fracture planes are not connected to each other.

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Figure 8. Longitudinal fracture face located 28 feet upstream from the downstream girth weld. Inside diameter is located at the bottom and the upstream end is on the left. No section was taken from this fracture face. The fracture face in this general area was for the most part flat.

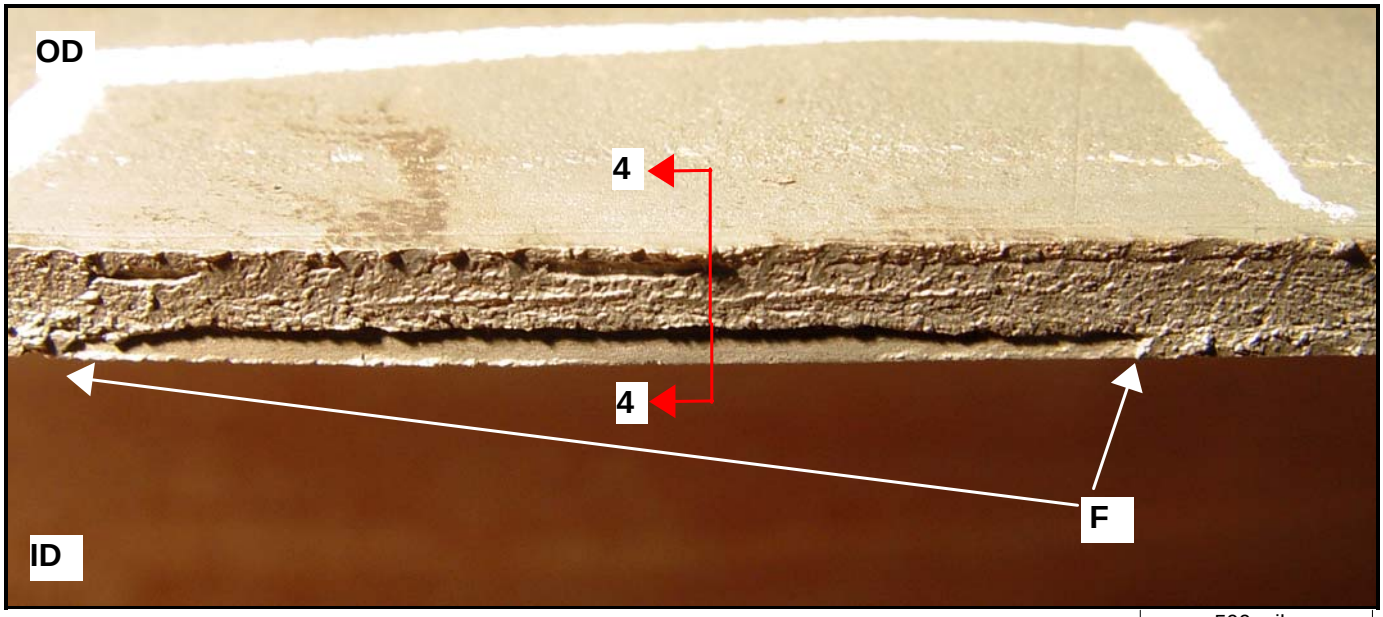

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Figure 9. Longitudinal fracture face located 42 feet upstream from the downstream girth weld. Inside diameter is located at the bottom and the upstream end is on the left. A metallurgical section was taken from the area and orientation indicated by section line "4-4". Arrows "F" indicate the ends of the flat fracture plane on the inner surface that extended below the longitudinal fracture face. The length of this island feature measure approximately 2.4 inches.

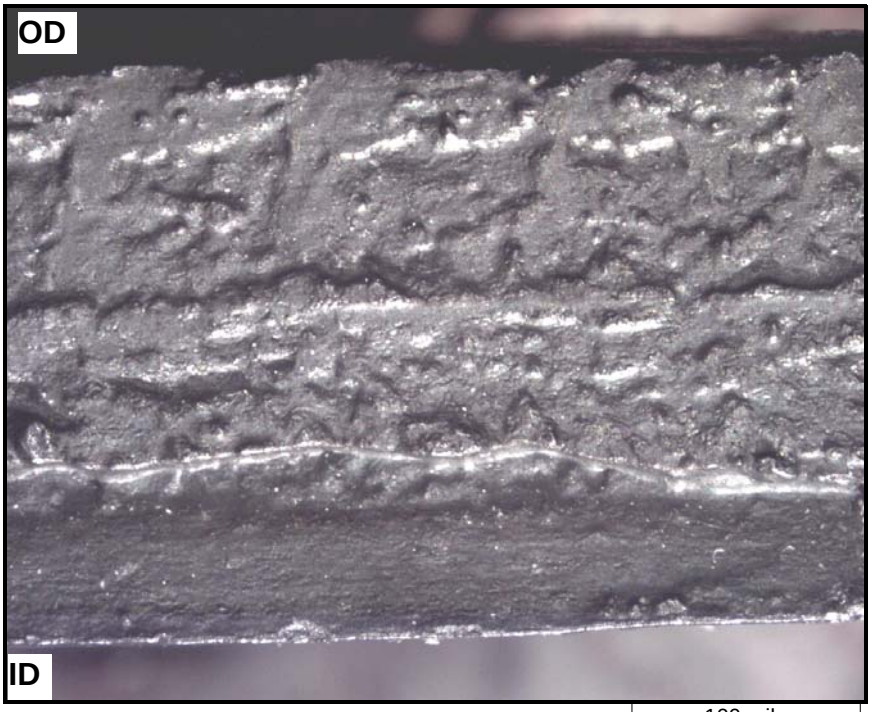

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Figure 10. Close-up photograph of the fracture face in the general area indicated by section line "4-4" in figure 9.

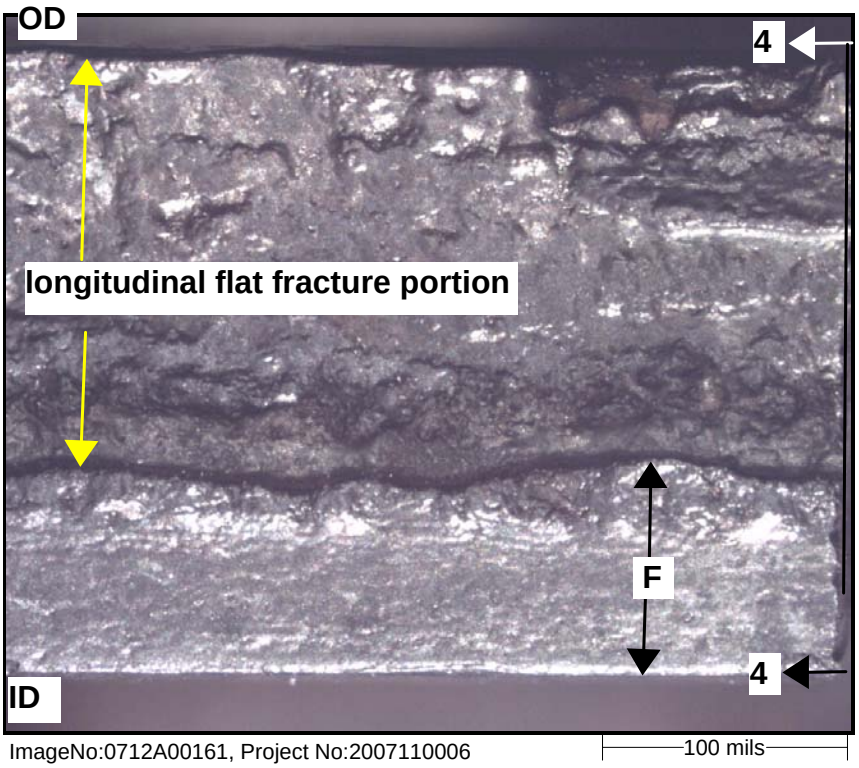


Figure 11. Close-up photograph of the approximate mating fracture that is shown in figure 10. Inside diameter is on the bottom side. Metallurgical section was taken in the orientation and location indicated by section line "4-4". Isolated fracture plane that extended above the longitudinal fracture face is located between arrows "F".

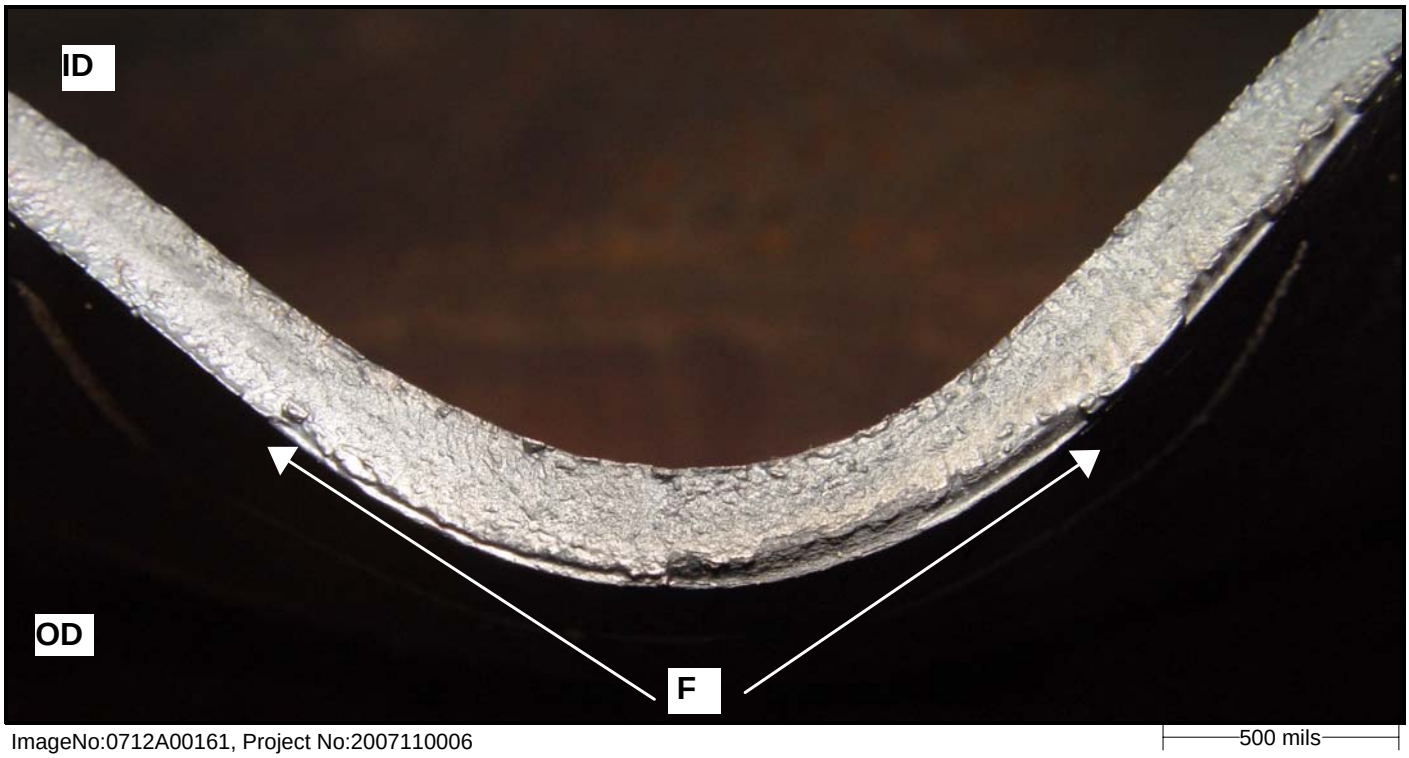


Figure 12. Longitudinal fracture face located 46 feet and 5 inches upstream from the downstream girth weld. Inside diameter is located at the top and the upstream end is on the left. No section was taken from this fracture face. Arrows "F" indicate the ends of an isolated flat fracture plane on the outer surface that extended below the longitudinal fracture face.

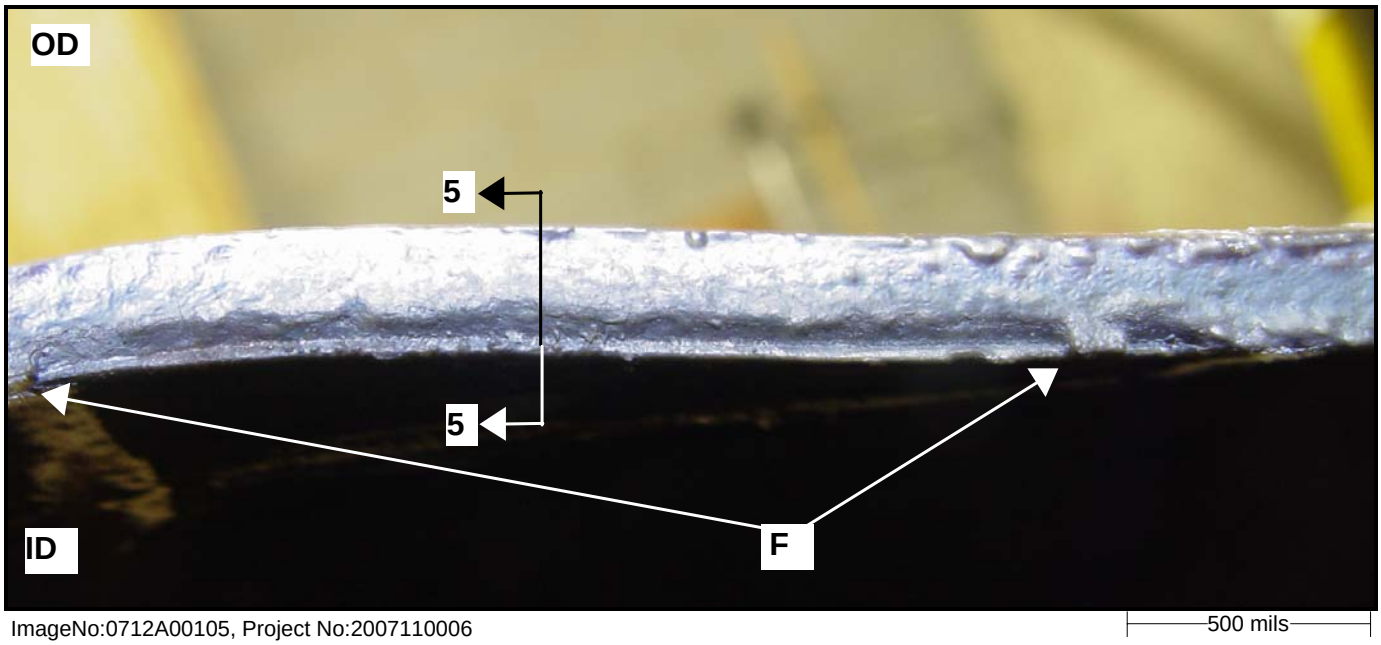


Figure 13. Longitudinal fracture face that was located 47 feet and 2 inches upstream from the downstream girth weld. Inside diameter is located at the bottom and the upstream end is on the left. A metallurgical section was taken from the area and orientation indicated by section line "5-5". The ends of arrow "F" indicate an isolated fracture plane on the inner surface that extended below the longitudinal fracture face. The length of this island feature measured approximately 2 inches.

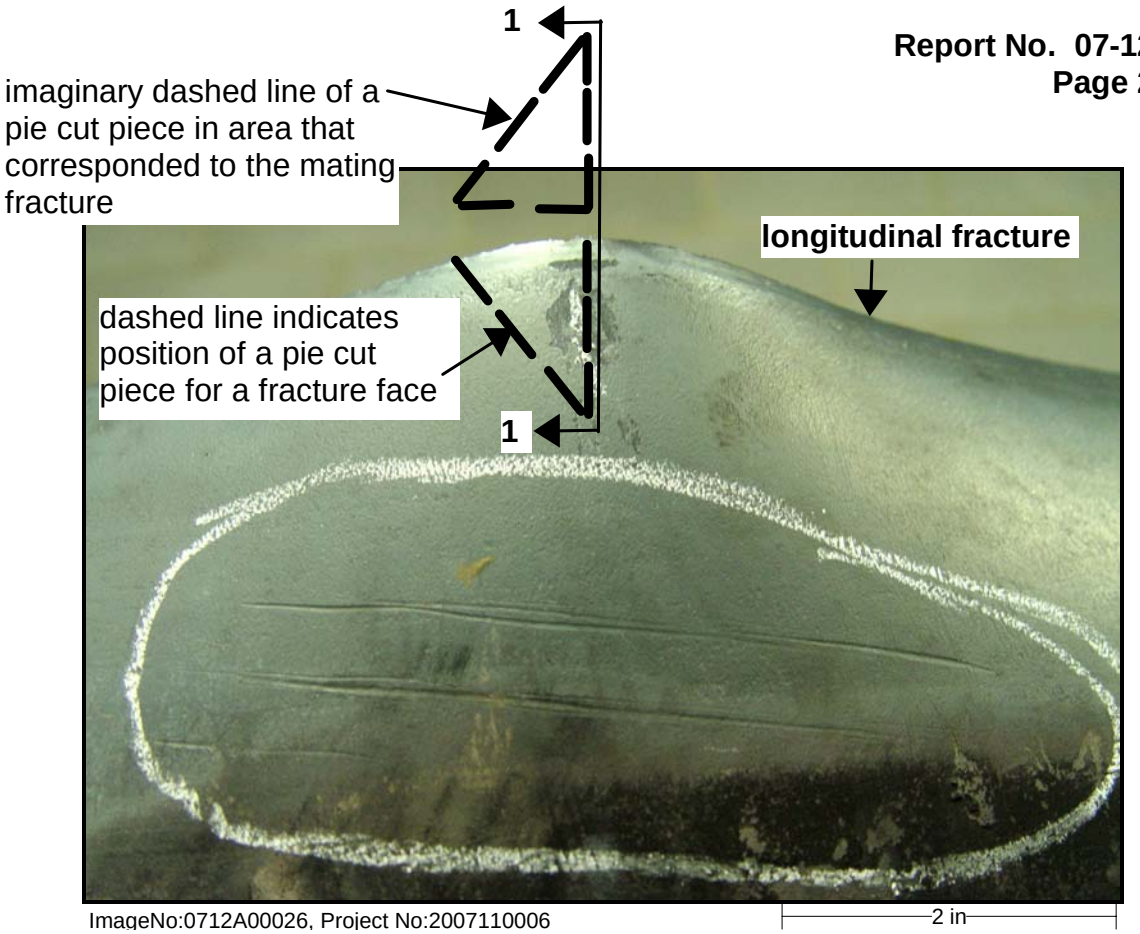


Figure 14. Photograph of the outer surface of the pipe showing parallel scratch marks, within the the area marked with white chalk, that were located near the longitudinal fracture face at an area 37 feet and 10 inches upstream from the downstream girth weld. Metallurgical section was prepared from the location and orientation indicated by section line "1-1". Section "1-1" incorporated mating fractures from the pie cut pieces shown in this figure.

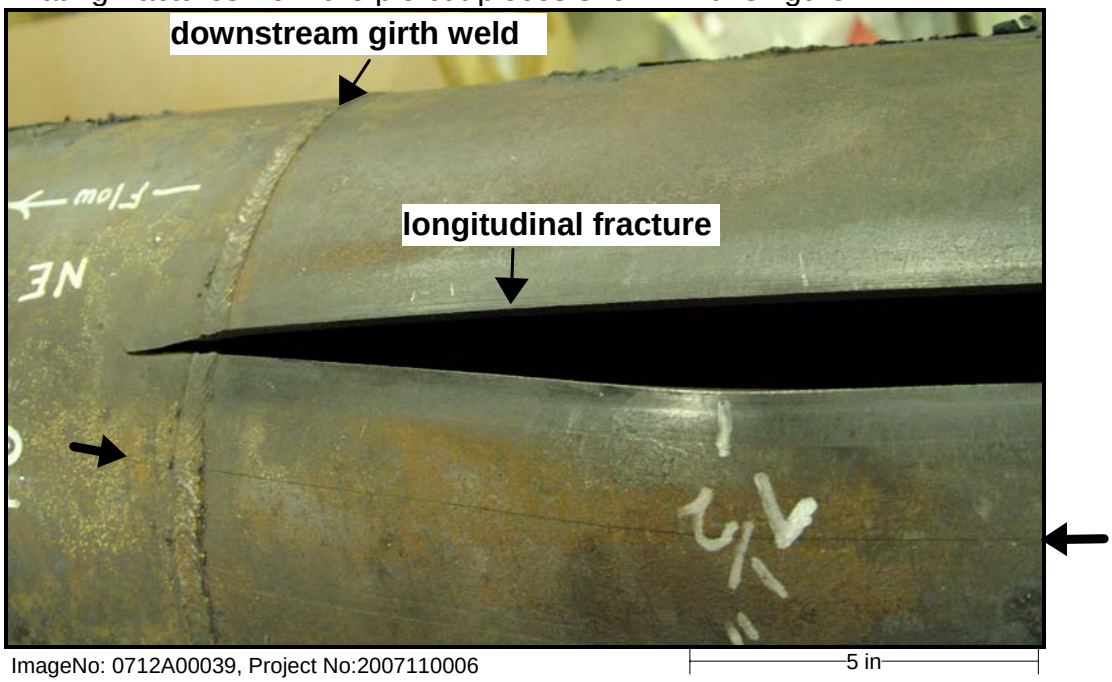


Figure 15. Photograph of the downstream end of the rupture. A fine longitudinal scratch line was found near the longitudinal fracture in the area between unlabelled arrows. The scratch line was located approximately 2 inches from the fracture face and the length measure approximately 13 inches.

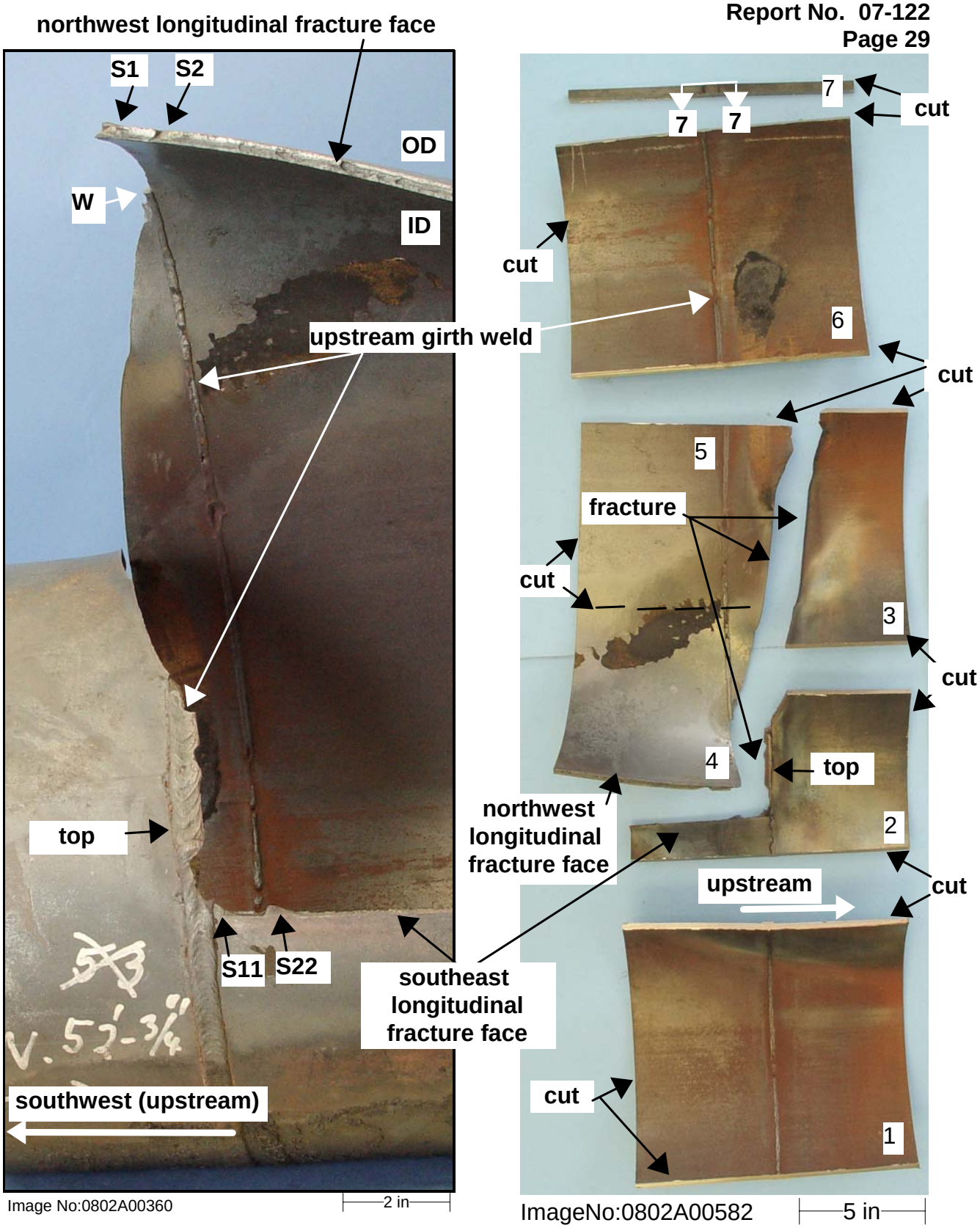
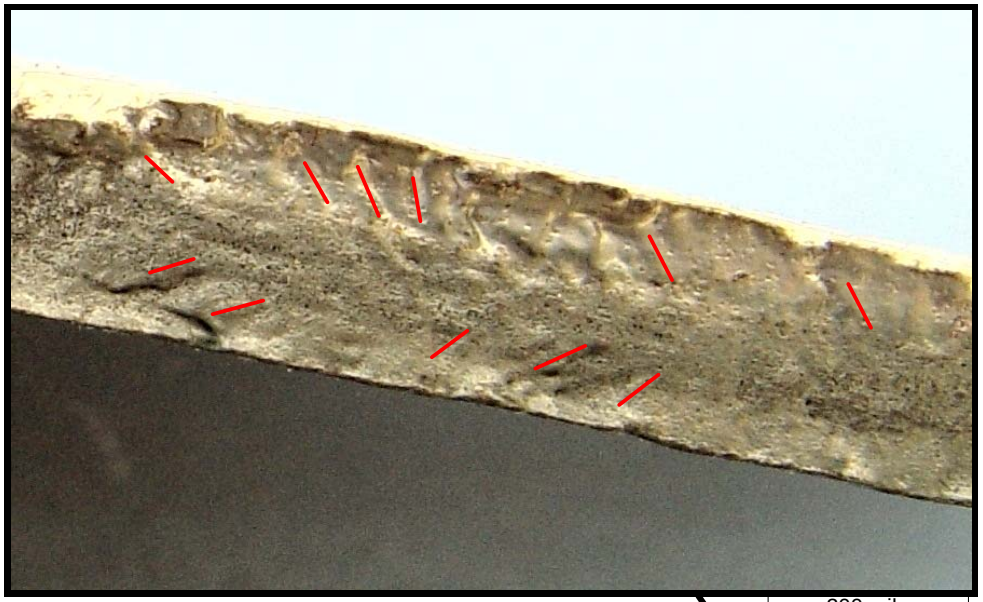


Figure 16. Photograph on the left side shows a side view of the upstream girth weld. Photograph on the right shows the inner surface of the pipe after several pieces were cut from the pipe in the general area of the girth weld to facilitate examination of the fractures. Pieces on the right side photograph were assembled next to each other as if intact. Arrow "W" indicates a small portion of the girth weld fracture on a longitudinal plane. Arrows "S1" and "S2" indicate shear, trough-like, features at two locations that were recessed below the flat fracture plane, and arrows "S11" and "S22" indicate mating shear, ridge-like, features on the mating fracture face that correspond to the shear, trough-like, features "S1" and "S2", respectively



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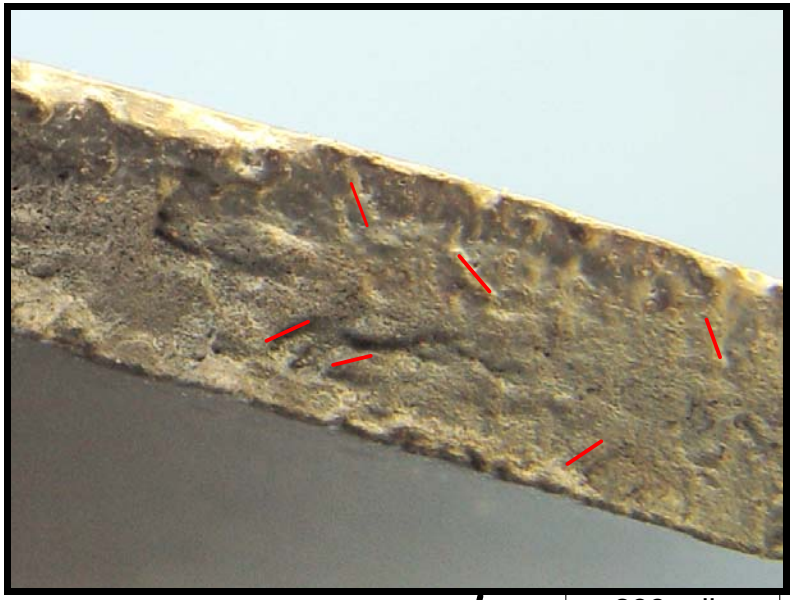

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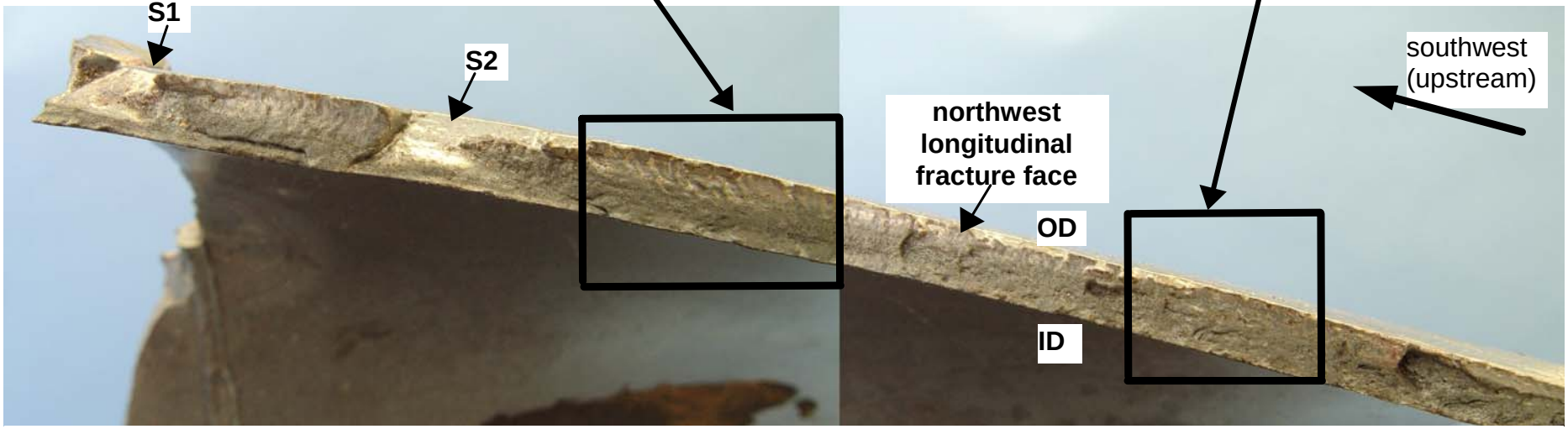

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Figure 17. Photograph (bottom of page) of a portion of the northwest longitudinal fracture face in the area near the upstream girth weld showing two areas that contained a faint chevron-like pattern. The photographs on the upper left and right corners of the page show higher magnification views, with red dashed lines indicating some of the chevron-like marks.

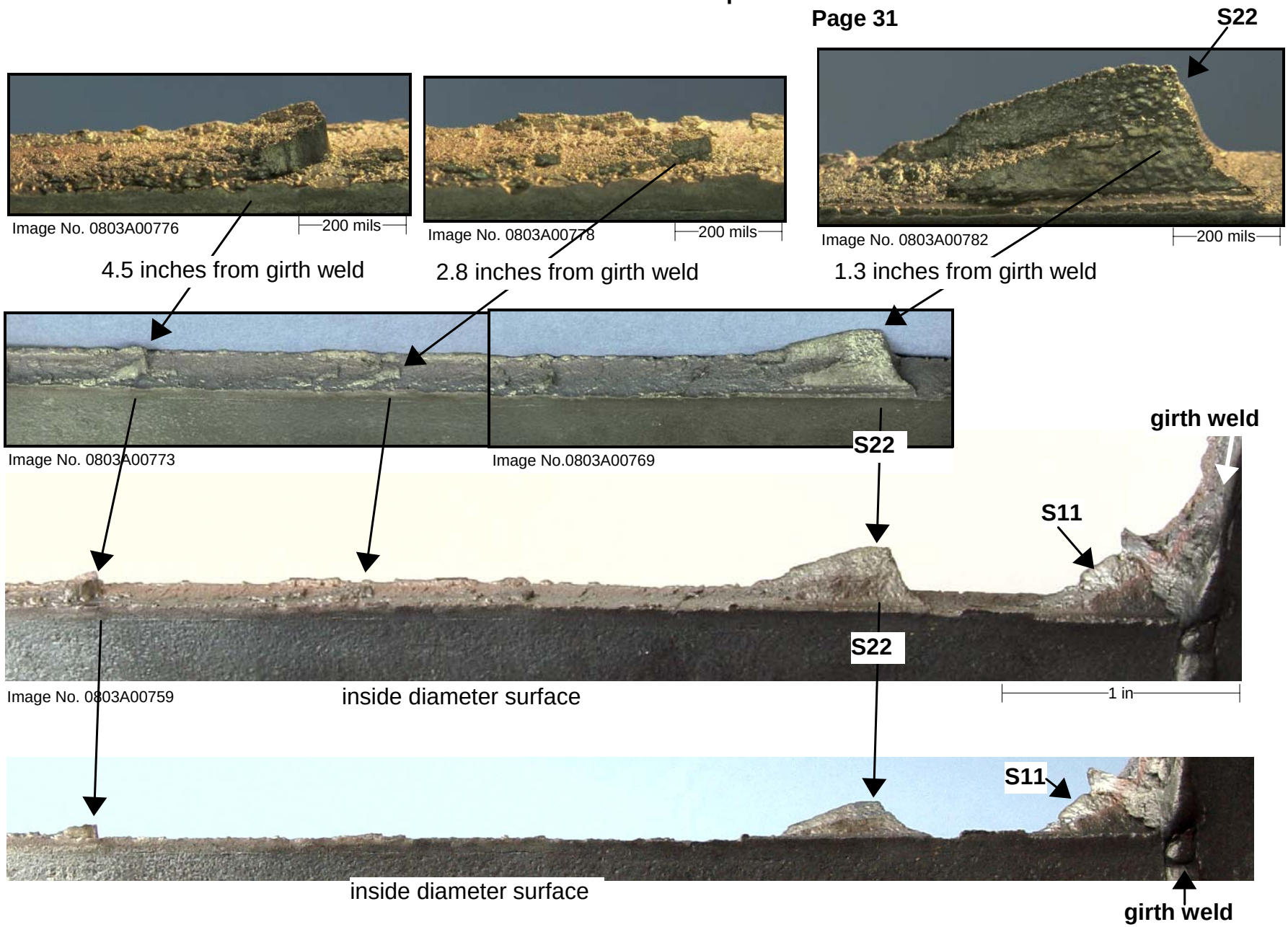


Figure 18. Photographs that were taken from the inside diameter surface at different angles of the longitudinal ERW seam fracture face in the area near the upstream girth weld showing various ridge features (fracture feature plane that deviated from the center of the ERW weld).

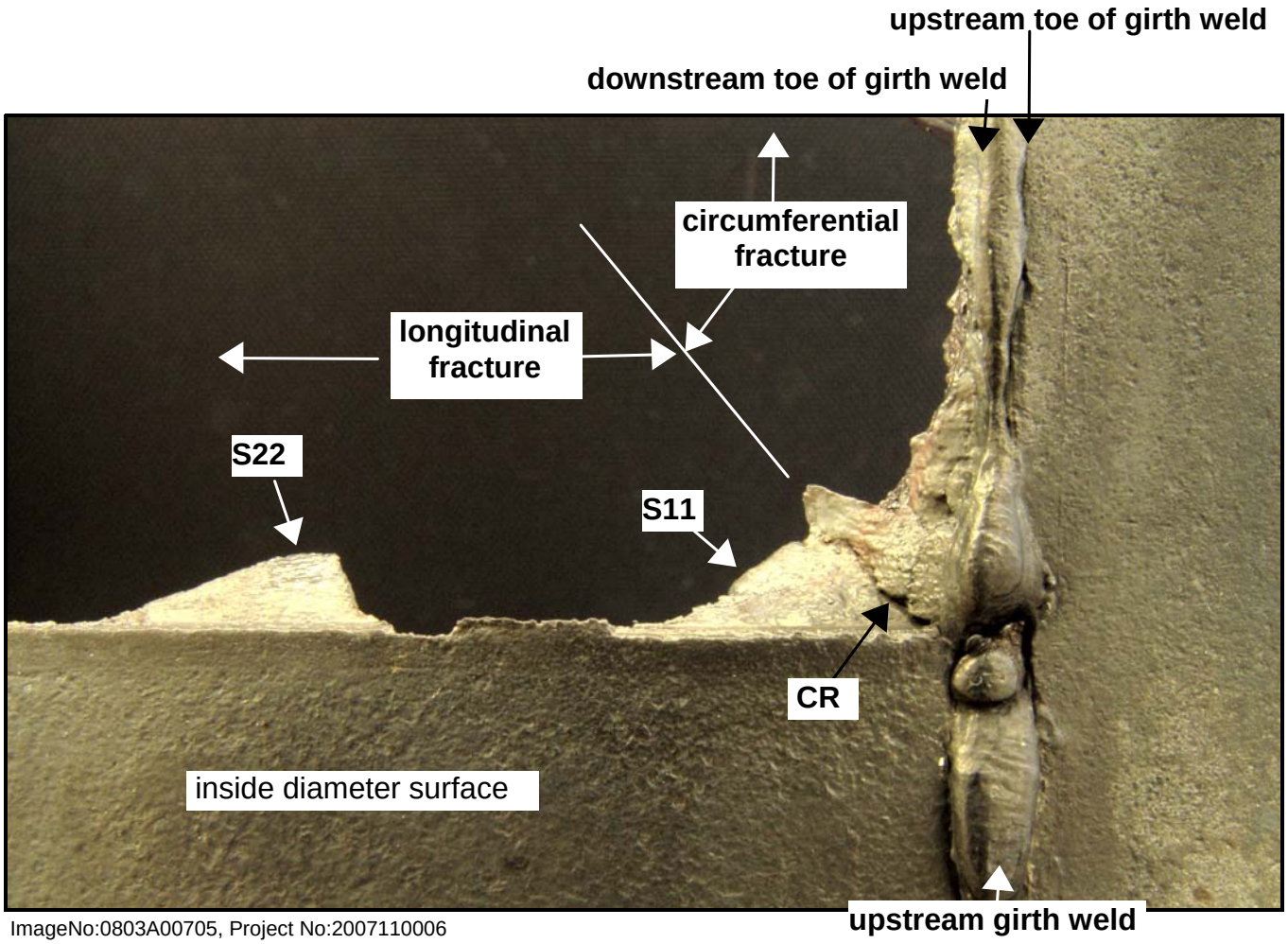
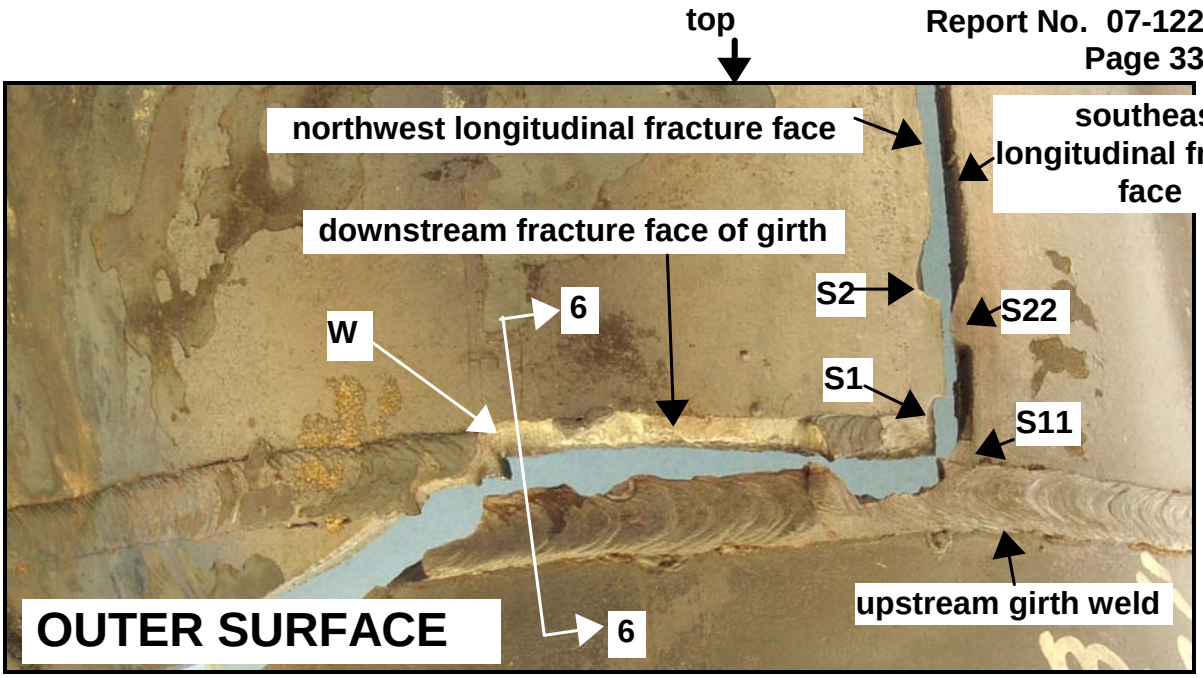


Figure 19. Photograph of the fracture face at the corner between the longitudinal ERW seam and the upstream girth weld. Arrow "CR" indicates a branching crack.



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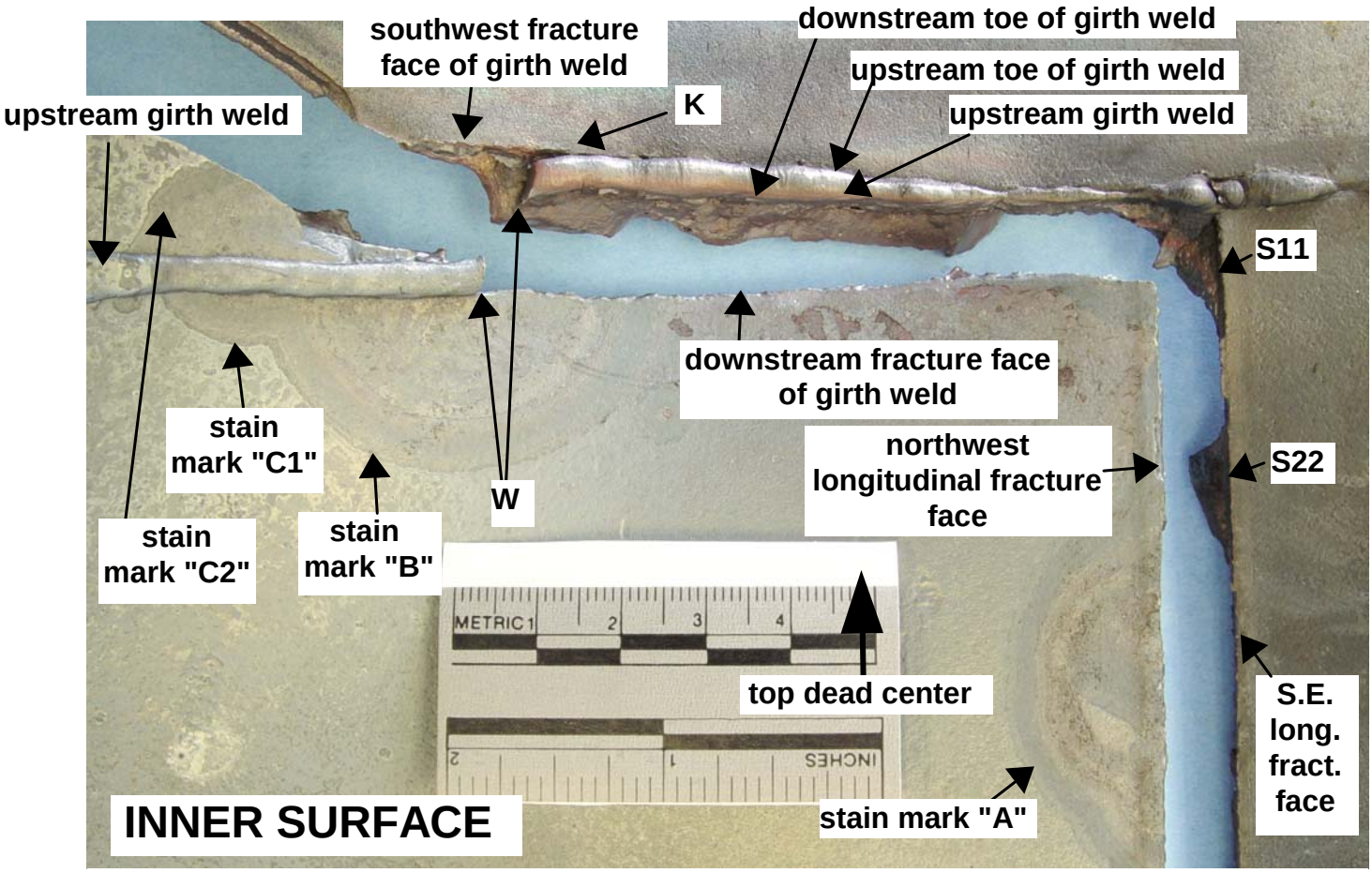

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Figure 20. Photographs of the fracture in the area where the longitudinal ERW seam fracture intersected the upstream girth weld as viewed from the outside diameter surface (upper photograph) and inside diameter surface (lower photograph). Arrow "W" indicates the location of the nearly longitudinal girth weld fracture. Arrow "K" indicates a crack that extended from the nearly longitudinal girth weld fracture.

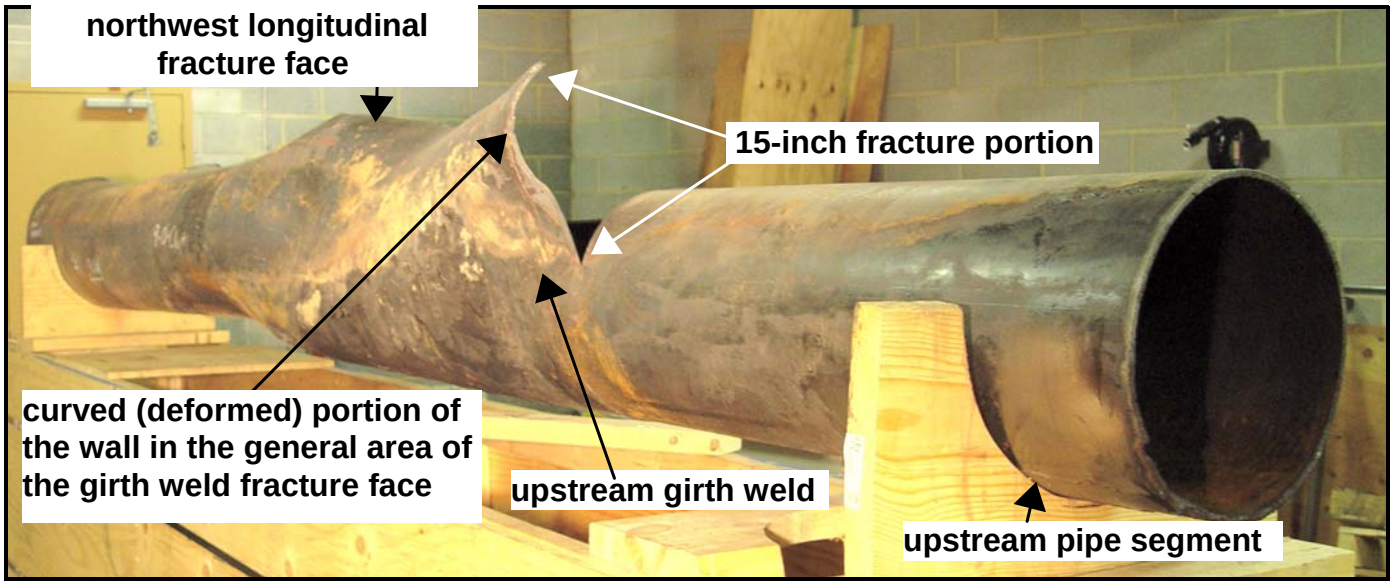

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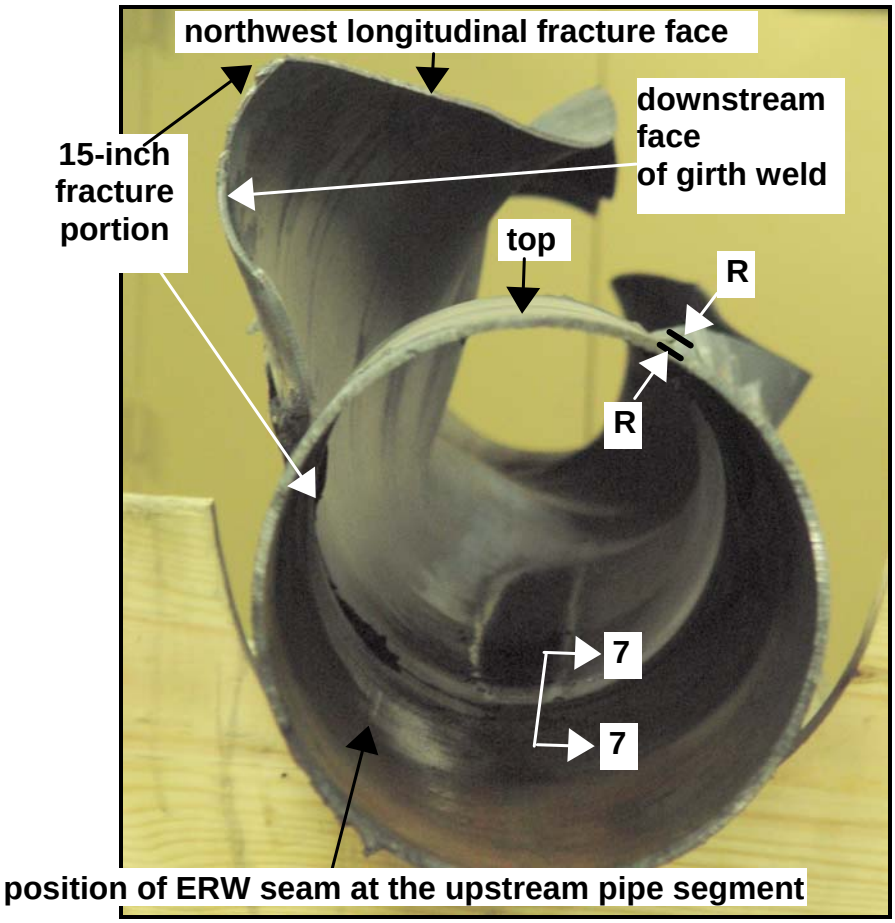
Figure 21. View of pipe segment 1 showing the location of the upstream girth weld and the 15-inch fracture that extended from the longitudinal fracture. The upstream end of the pipe segment is on the right side of the photograph.



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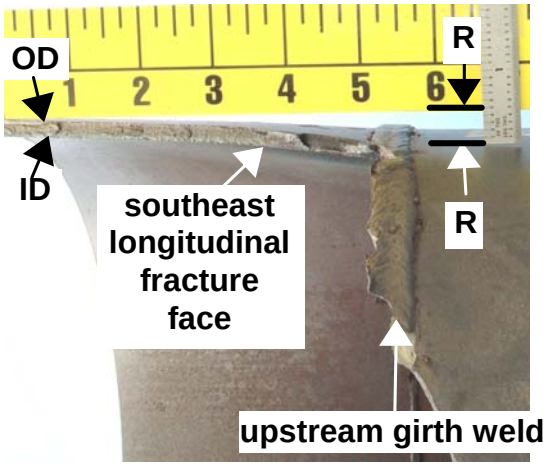
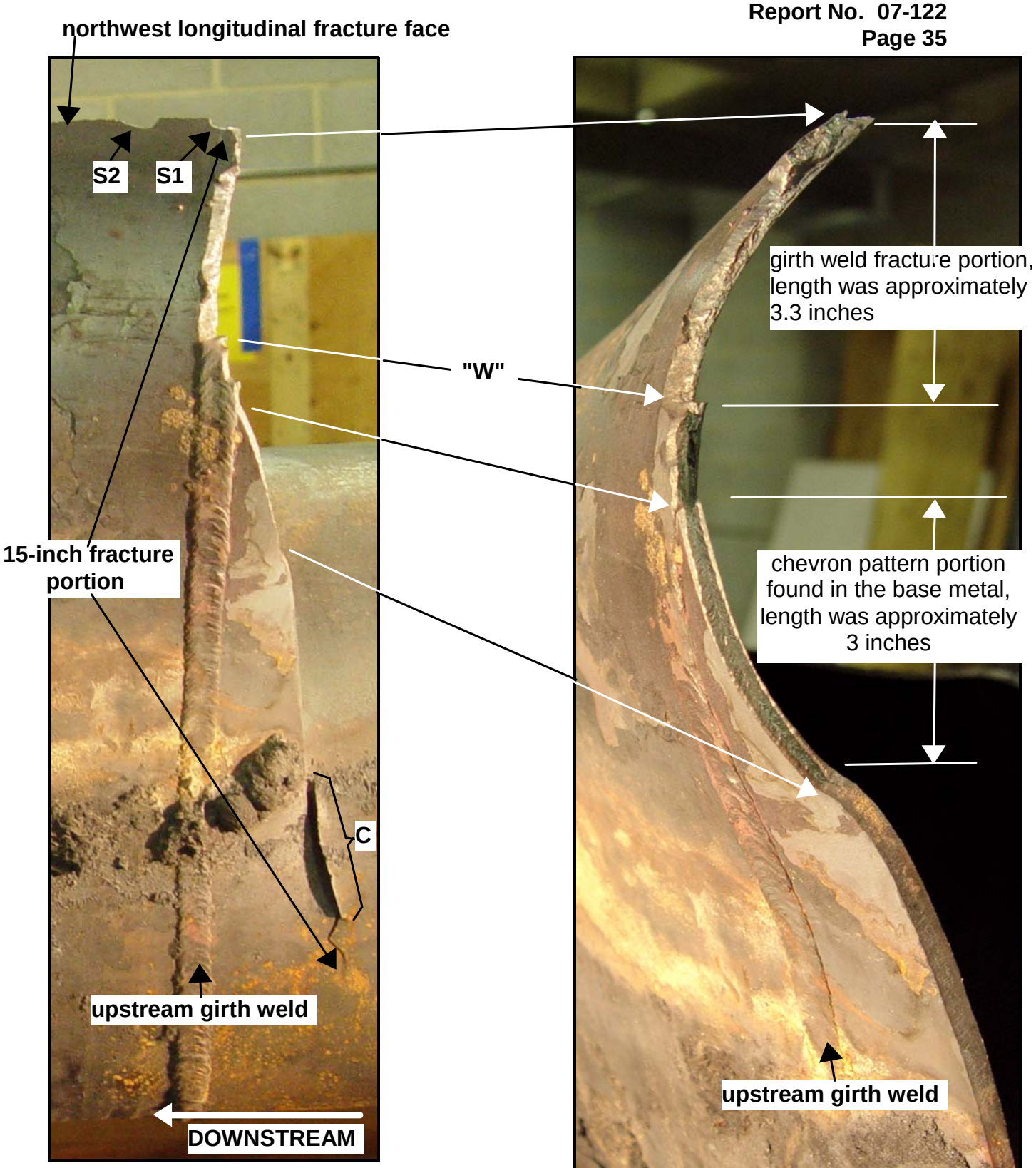


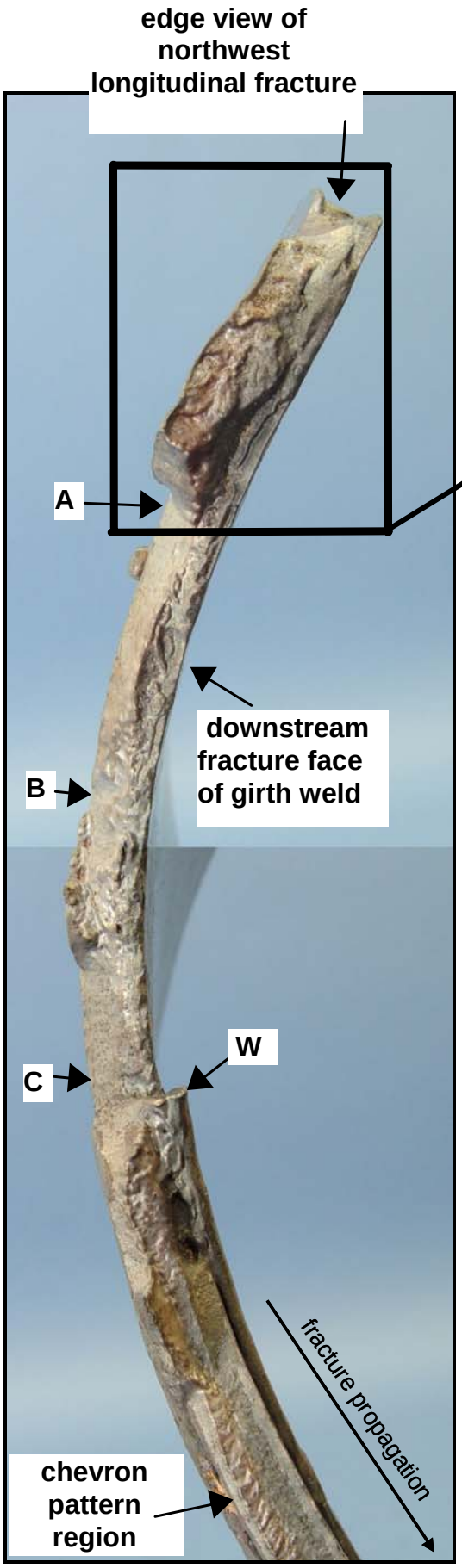
Figure 22. View looking downstream at the upstream end of pipe segment 1 showing the 15-inch fracture that extended from the longitudinal fracture (photograph on the left side). Side view of the pipe in the area of the upstream girth weld showing a portion of the southeast longitudinal fracture (photograph located at the right center portion of the page).



ImageNo:0712A00331, Project No:20071100

ImageNo: 0712A00345, Project No:2007110006

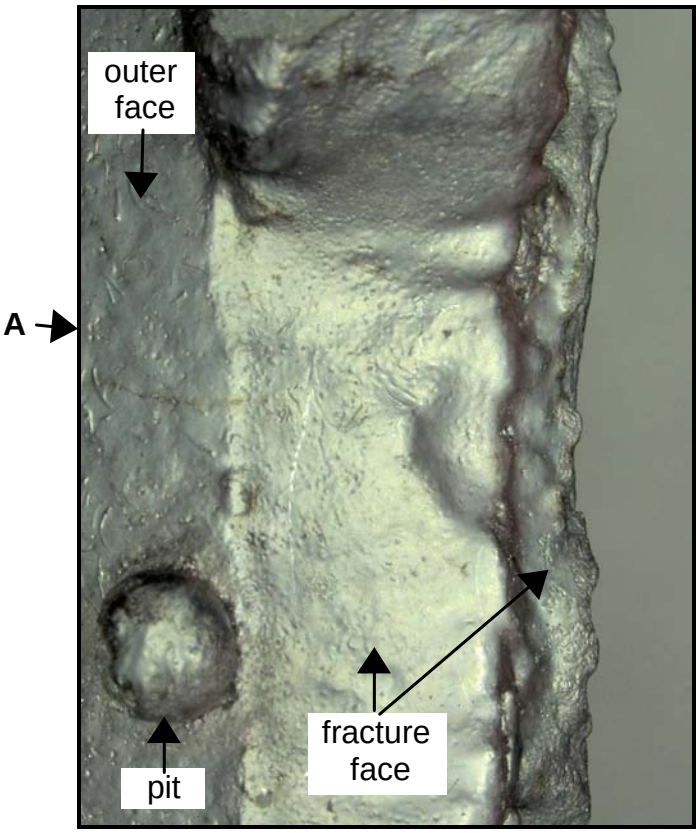
Figure 23. Side view (left photograph) and view looking downstream (right photograph) at the fractured portion of the upstream girth weld. Arrow "W" indicates the position of the nearly longitudinal girth weld fracture. Bracket "C" indicates a portion of the mating fracture faces that showed compression damage (fracture faces pressing against each other). The 15-inch fracture was measured along the circumference of the pipe.



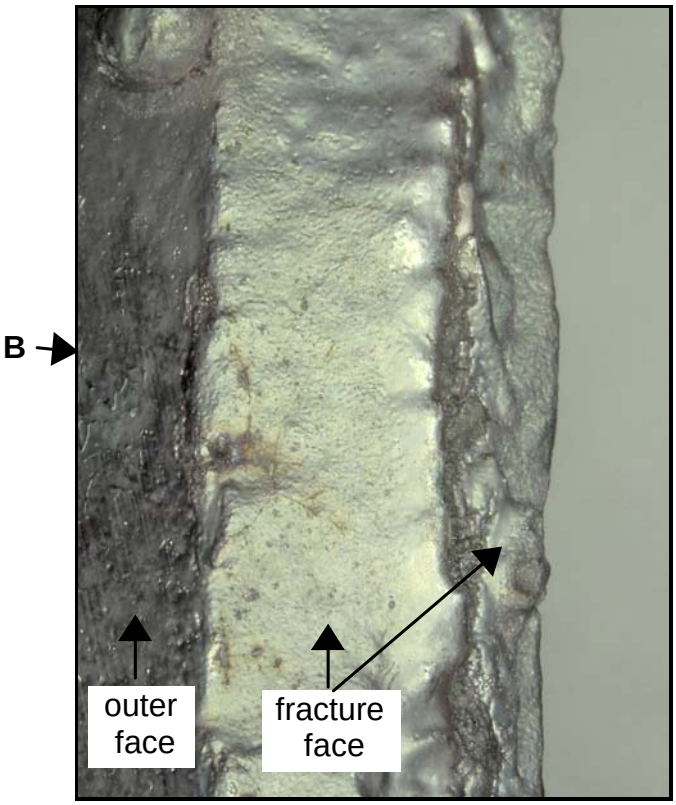
ImageNo:0802A00361, Project No:2007110006

ImageNo:0802A00361, Project No:2007110006

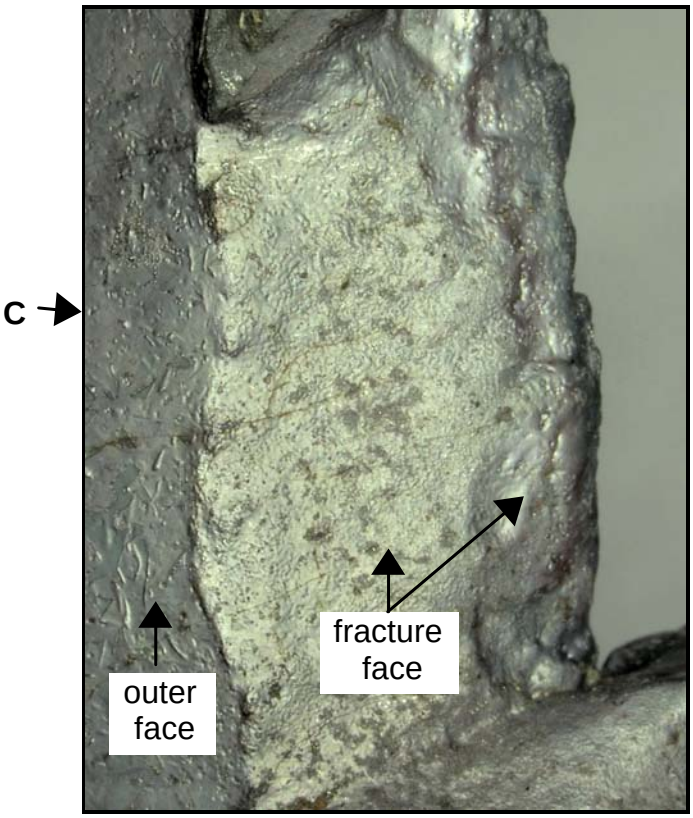
Figure 24. Composite photograph (left) of the downstream fracture face of the upstream girth weld showing chevron-like pattern adjacent to the longitudinal fracture. Red lines indicate location of the nested "V" pattern. Arrow "W" indicates the location of the nearly longitudinal girth weld fracture. Photograph on the upper right corner is at higher magnification.



ImageNo:0802A00649, Project No:2007110006

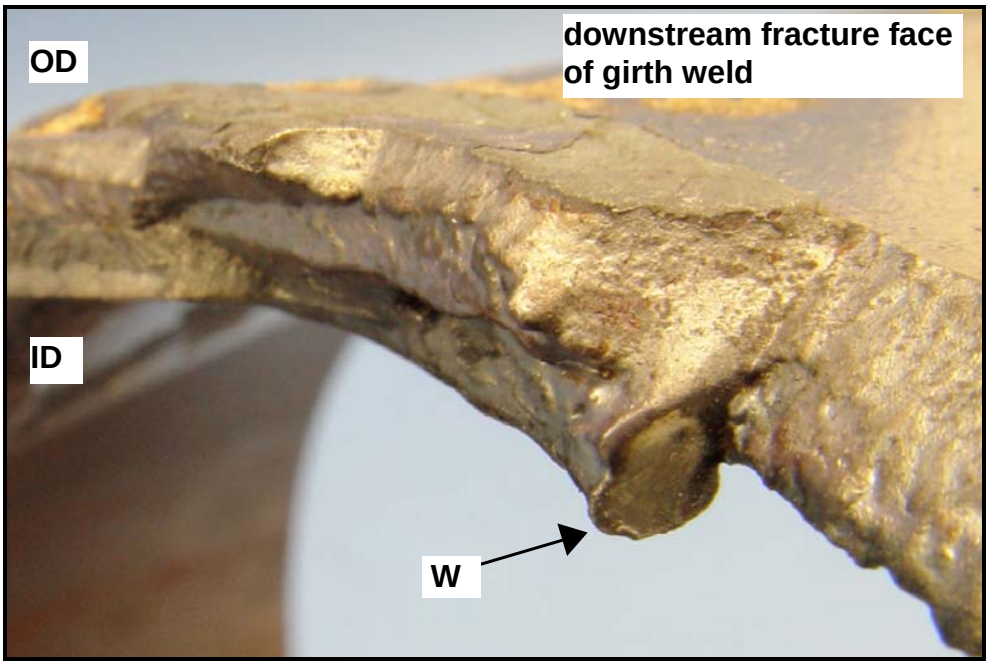


ImageNo:0802A00662, Project No:2007110006

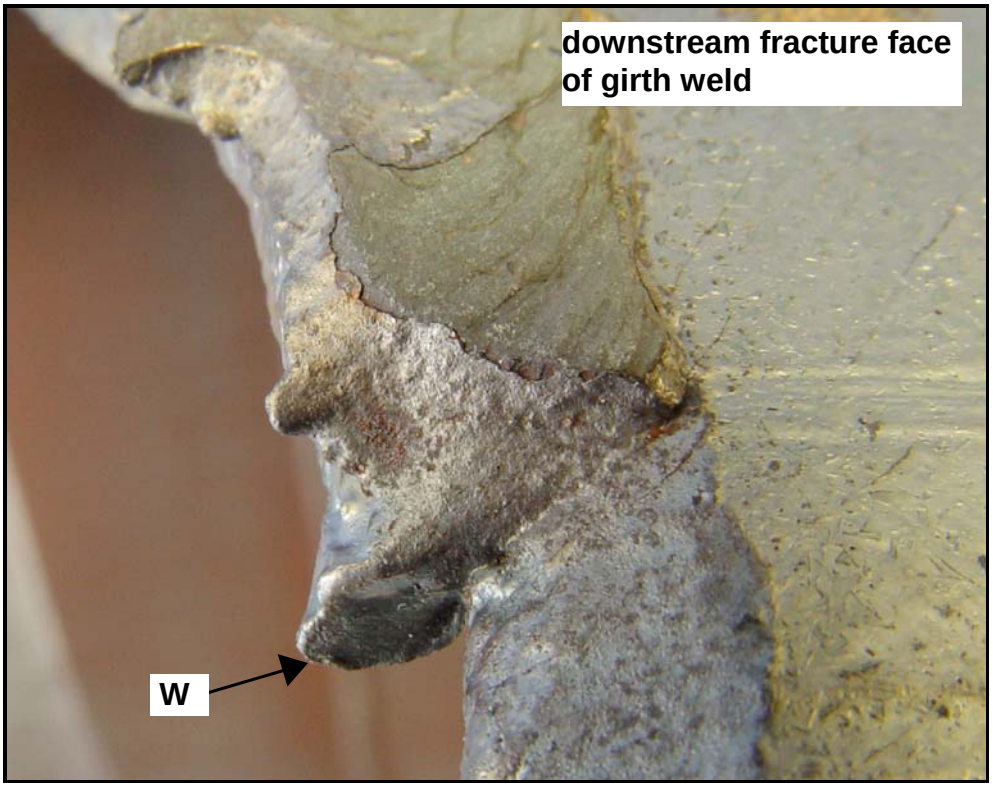


ImageNo: 0802A00657, Project No:2007110006

Figure 25. Close-up photographs of the downstream face of the girth weld fracture face in areas indicated by arrows "A", "B", and "C" in the previous page.

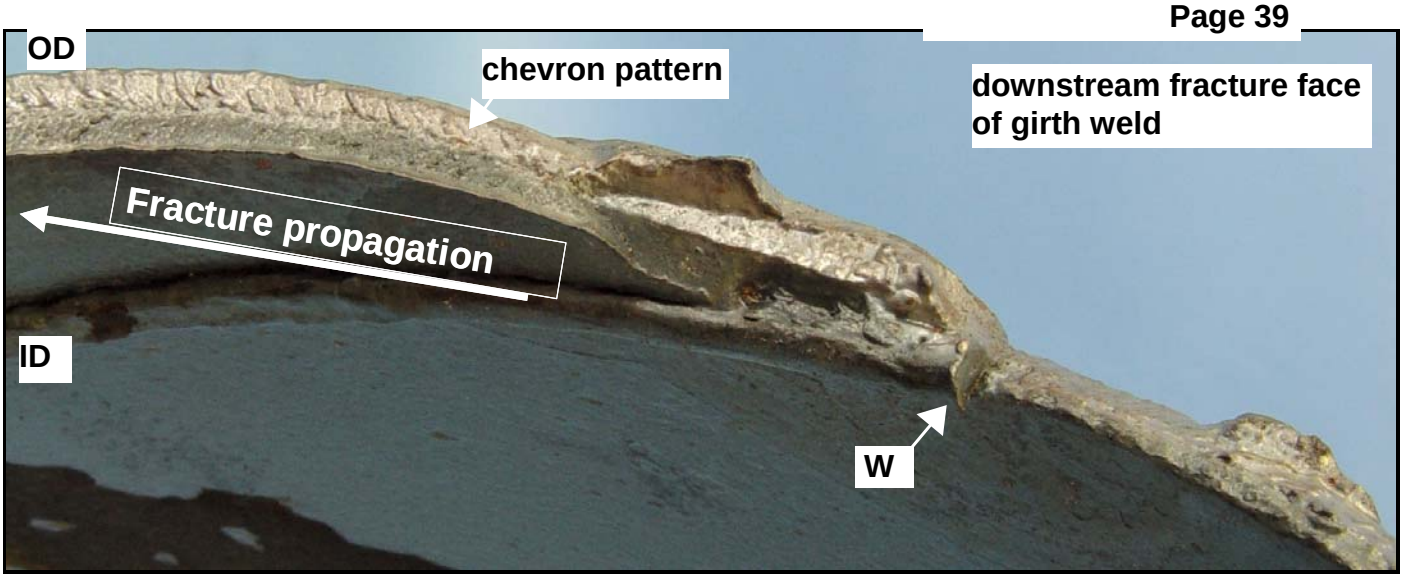


ImageNo:0802A00384, Project No:2007110006



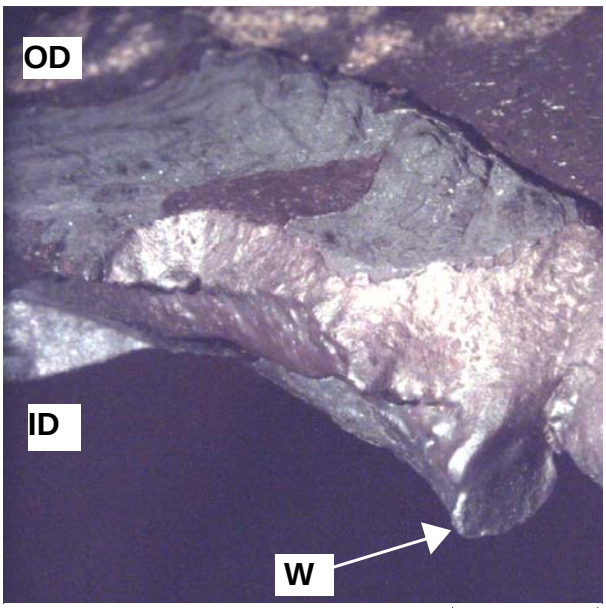
ImageNo: 0802A00386, Project No:2007110006

Figure 26. Close-up views of a portion of the downstream fracture face of the girth weld in the area of the near longitudinal girth weld fracture (indicated by arrow "W").



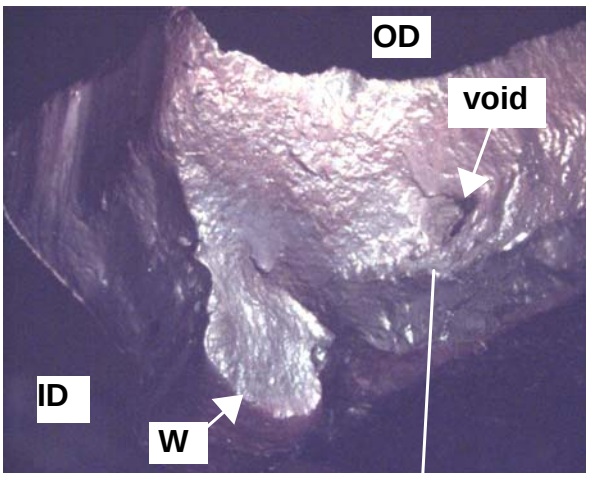
ImageNo:0802A00378, Project No:2007110006

ImageNo: 0803A00037, Project No:2007110006



ImageNo: 0803A00047 200 mils

Figure 27. Close-up views of a portion of the downstream fracture face of the girth weld in the area of the near longitudinal girth weld fracture (arrowed "W").



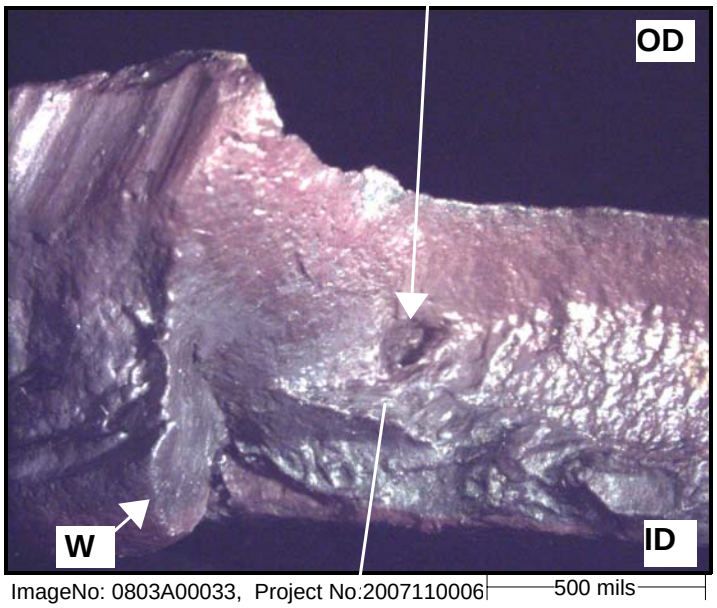
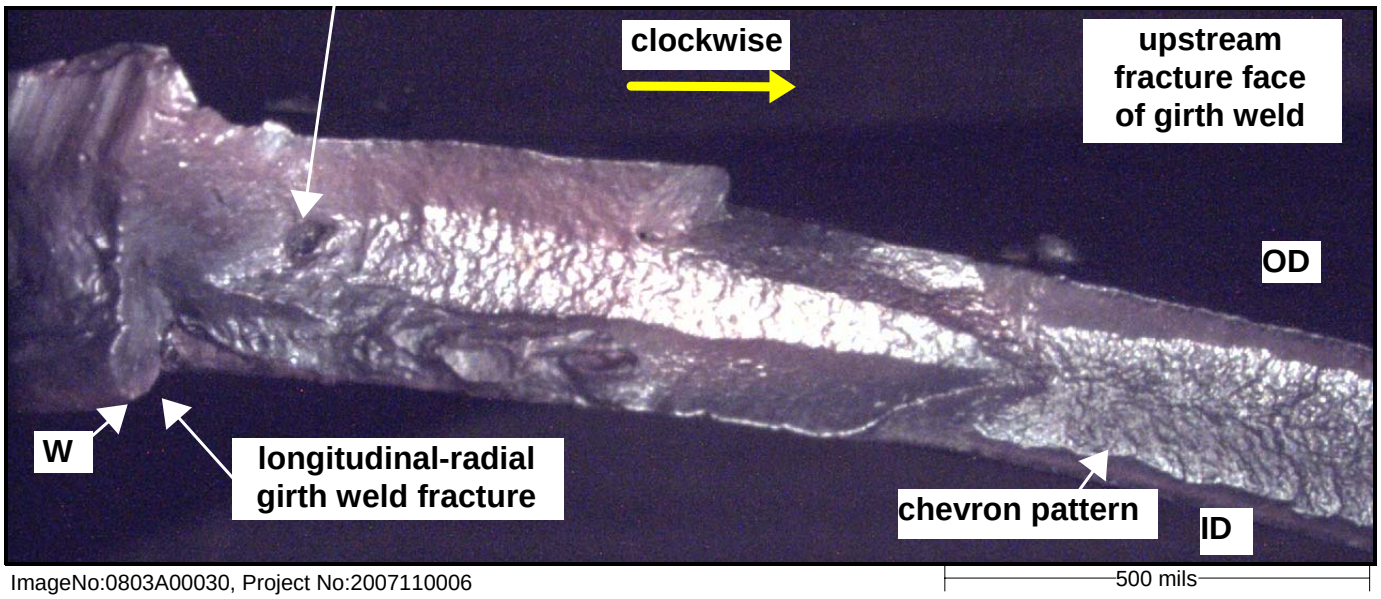
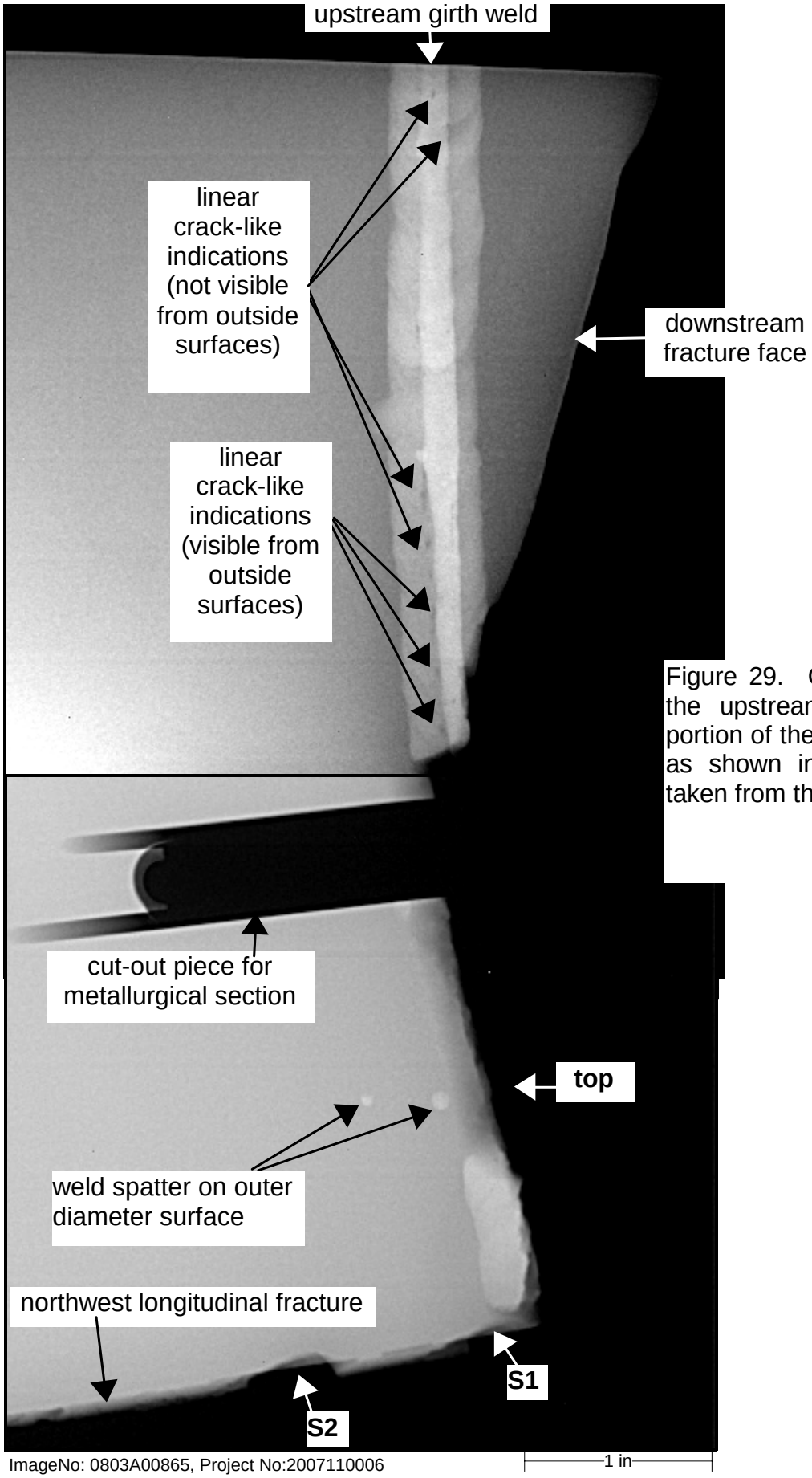


Figure 28. Photographs of a portion of the upstream fracture face of the girth weld in the area of the nearly longitudinal girth weld fracture (arrowed "W"). A void was found between the inner and outer surface and measured as large as approximately 0.05 inch.

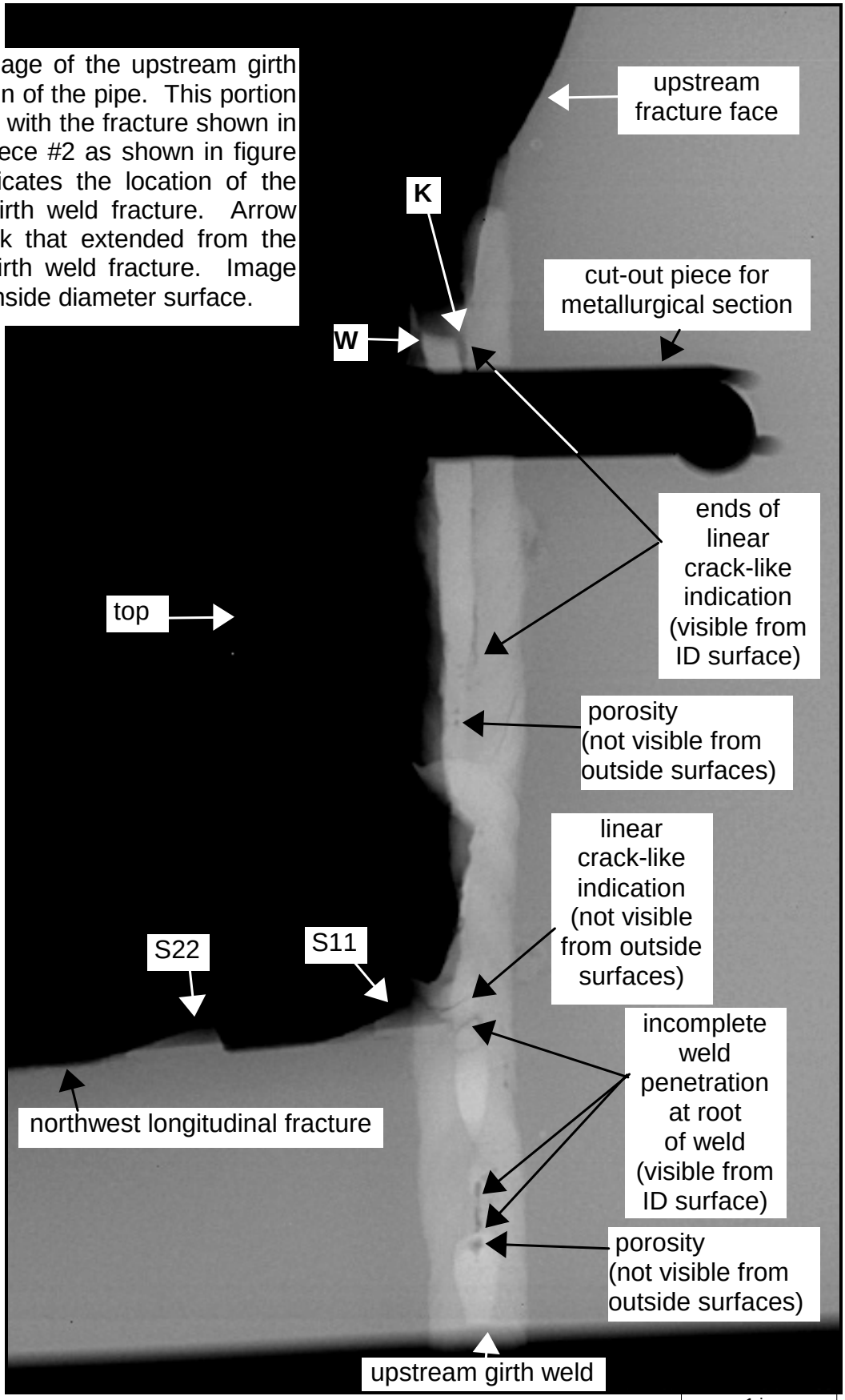




ImageNo: 0803A00865, Project No:2007110006

Figure 29. Composite X-ray image of the upstream girth weld at the top portion of the pipe. This is cut piece #4 as shown in figure 16. Image was taken from the inside diameter surface.

Figure 30. X-ray image of the upstream girth weld at the top portion of the pipe. This portion of the fracture mates with the fracture shown in figure 29. This is piece #2 as shown in figure 16. Arrow "W" indicates the location of the nearly longitudinal girth weld fracture. Arrow "K" indicates a crack that extended from the nearly longitudinal girth weld fracture. Image was taken from the inside diameter surface.



ImageNo:0803A00871, Project No:2007110006

1 in

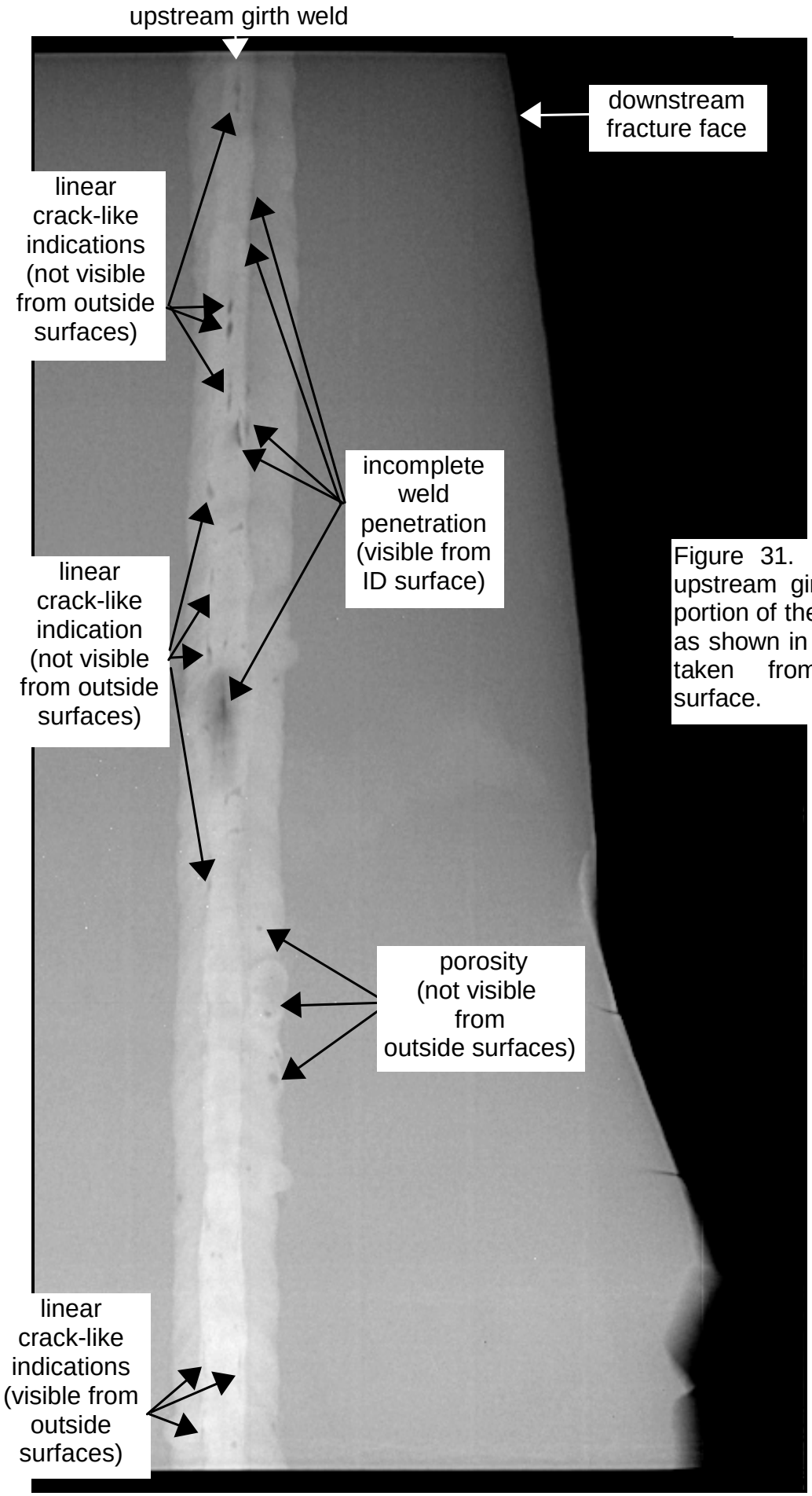


Figure 31. X-ray image of the upstream girth weld near the top portion of the pipe. This is piece #5 as shown in figure 16. Image was taken from outside diameter surface.

ImageNo:0803A00859, Project No:2007110006

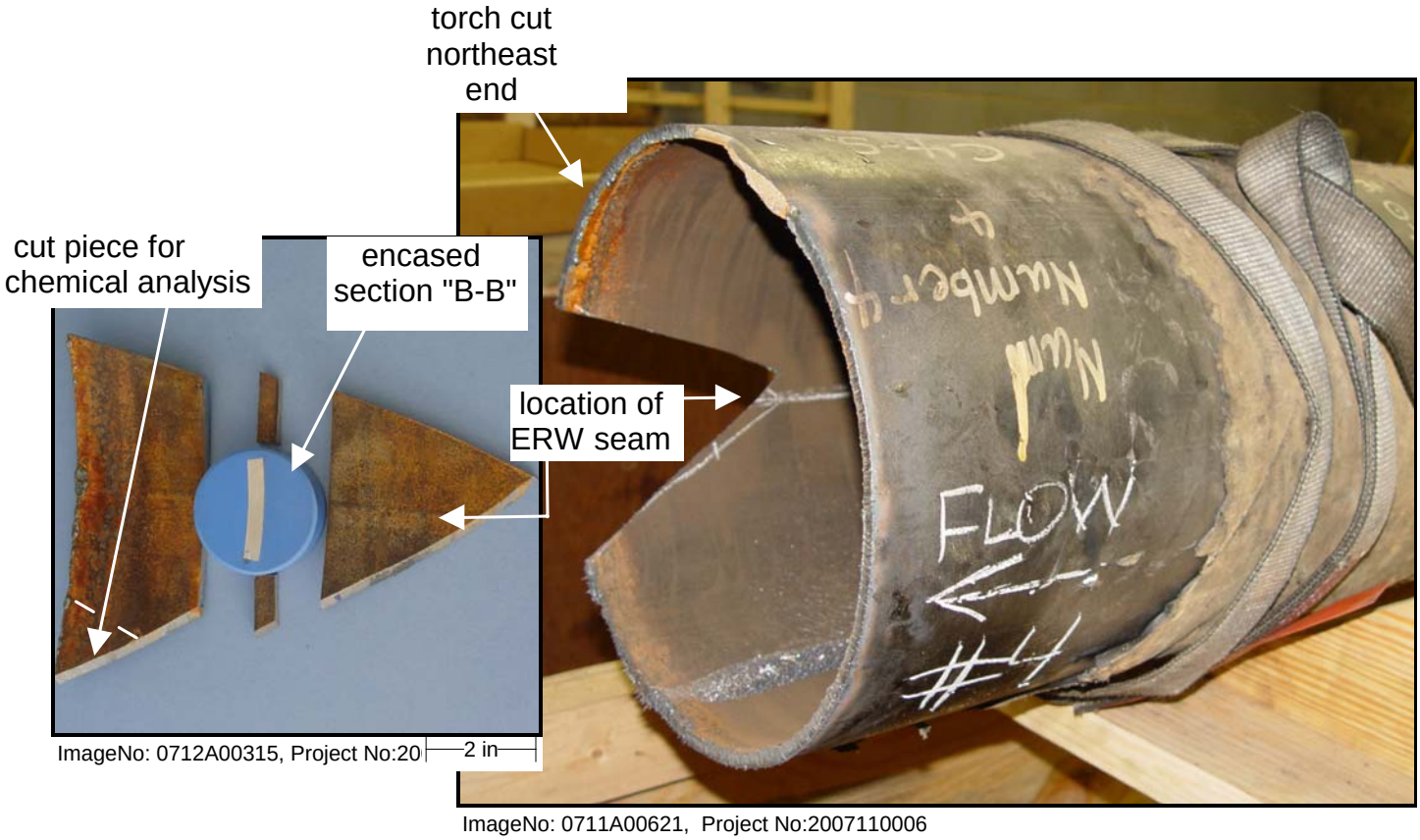


Figure 32. View of the torch cut end of segment 4 (photograph on right side) in the area that did not rupture. A pie cut piece (photograph on the left side) was removed from the torch cut end and metallurgical section "B-B" (shown encased in blue mount material) was prepared from the cut pieces.

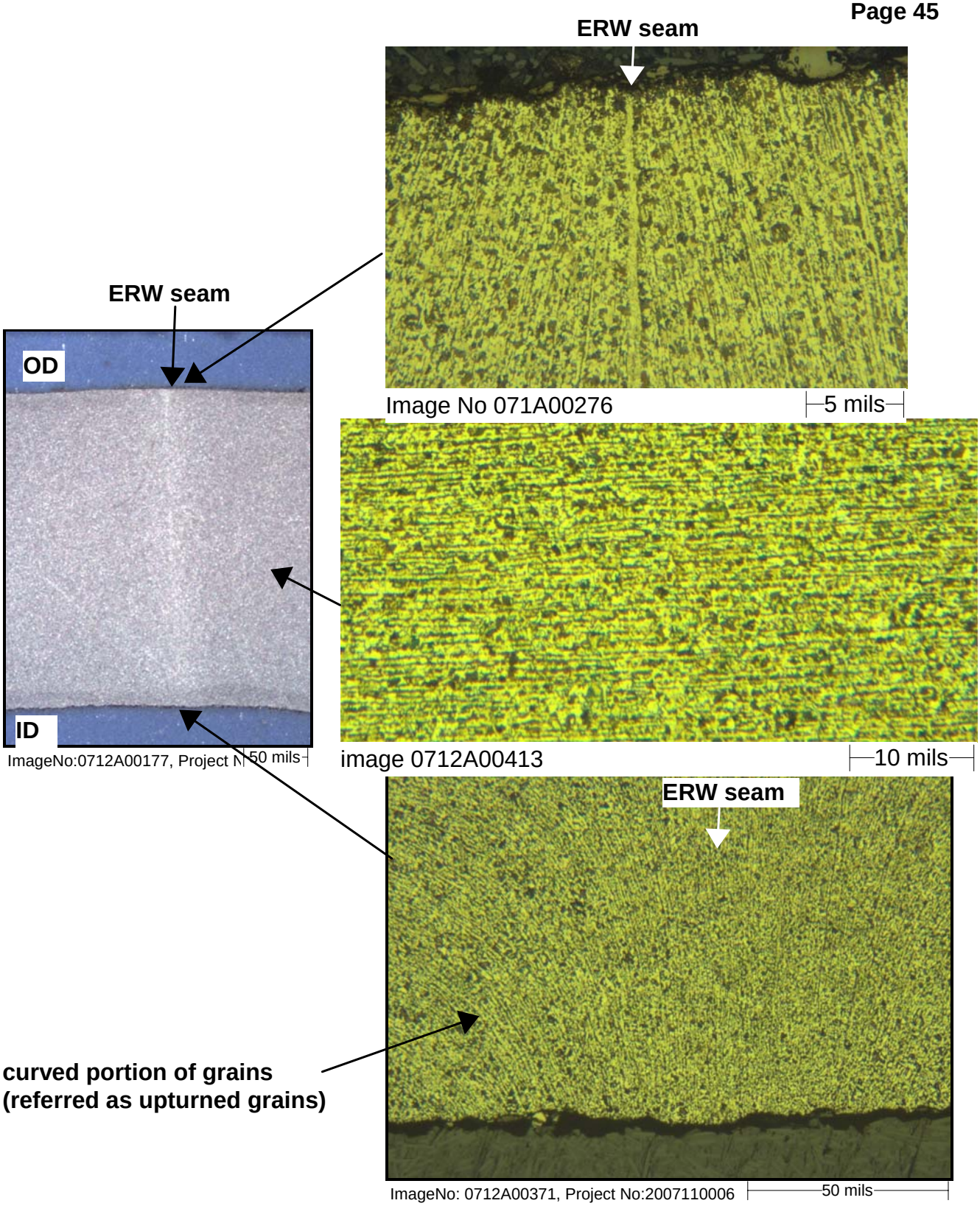


Figure 33. Photograph of a portion of metallurgical section "B-B" showing the ERW seam that extended radially between the inside and outside diameter. On the left photograph, the tint of the ERW seam appeared lighter compared to the tint of the microstructure in the wall portion . This section was taken approximately 8 feet and 6 1/2 inches downstream from the downstream girth weld. The inside diameter is on the bottom. Etched with 2% Nital reagent.

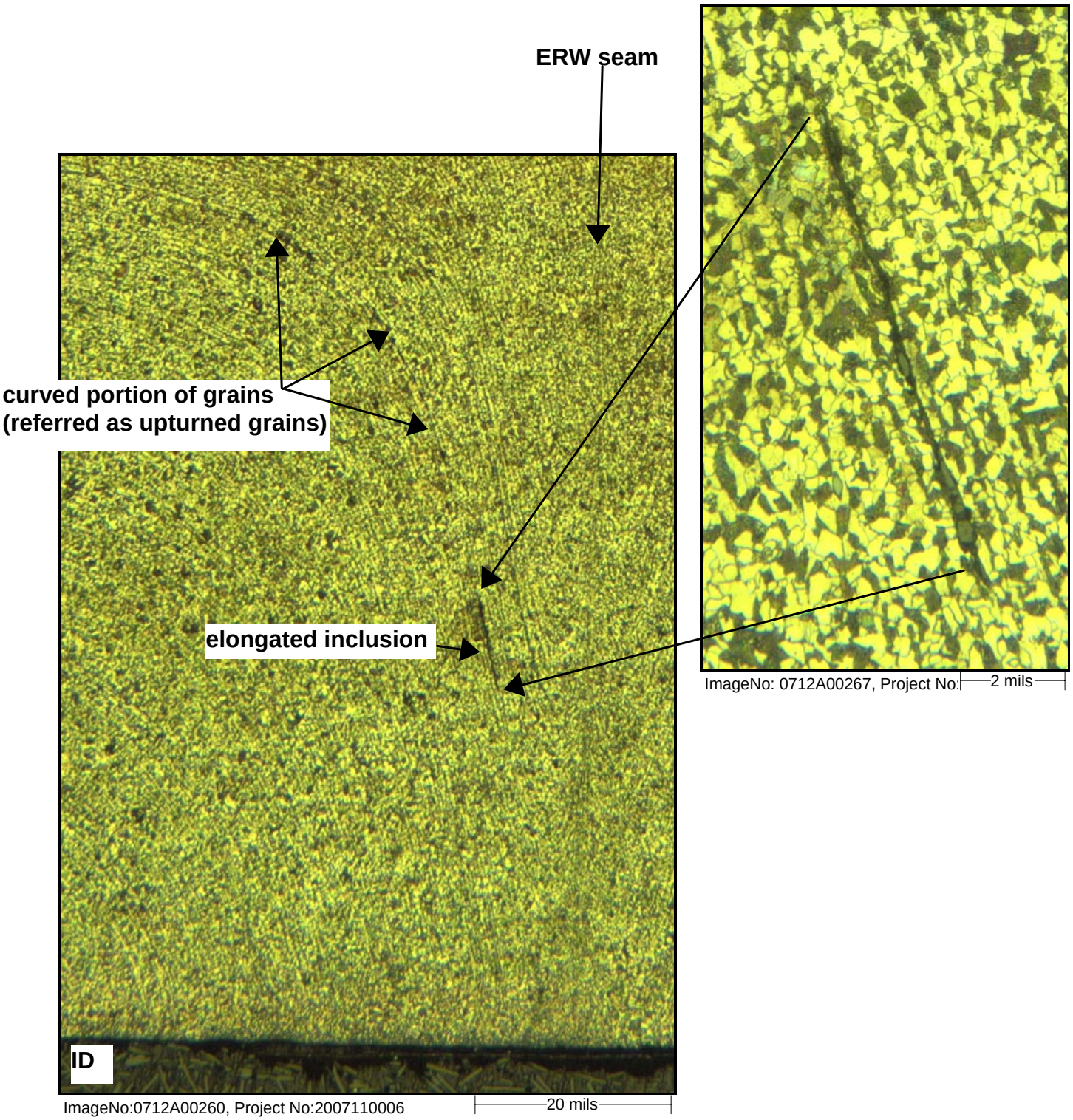
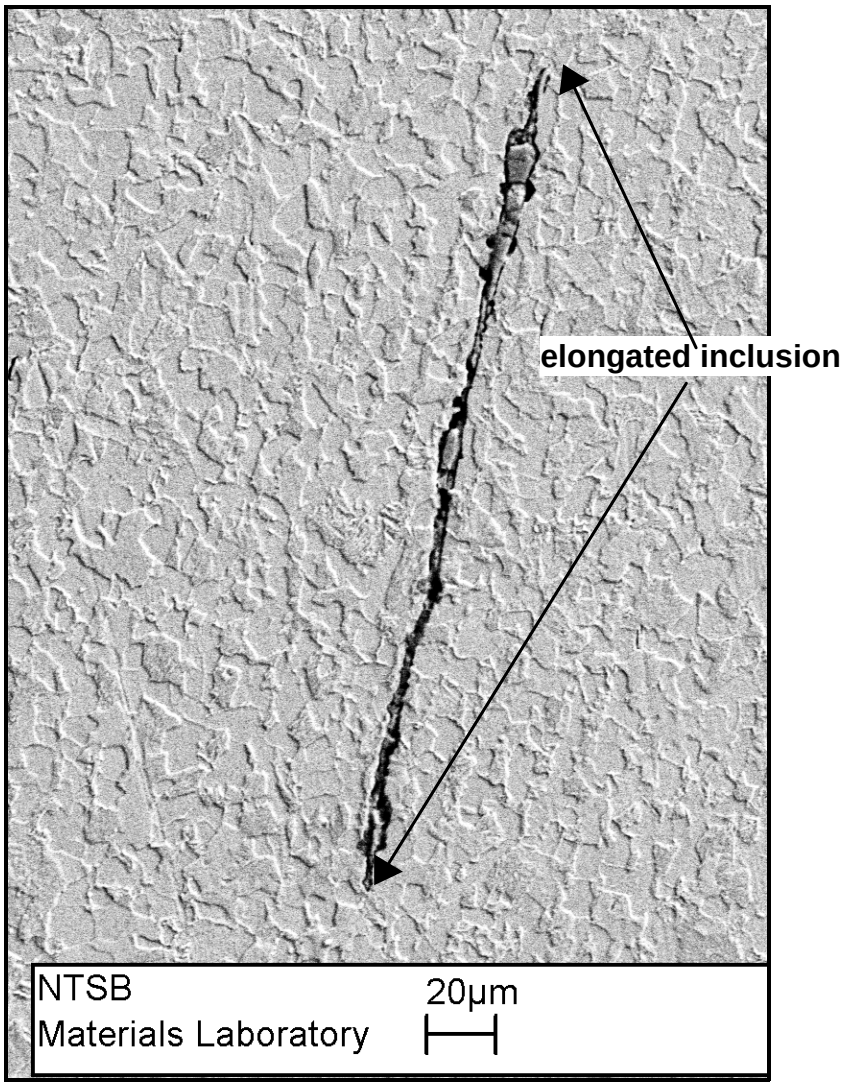


Figure 34. Photograph of a portion of section "B-B", after polishing and etching for a second time. An elongated inclusion (manganese sulfide) was found near the ERW seam.

Reminder: The photographs from the metallograph microscope are a mirror image of those shown from a bench binocular or scanning electron microscope.



ImageNo: 0712A00313, Project No:2007110006

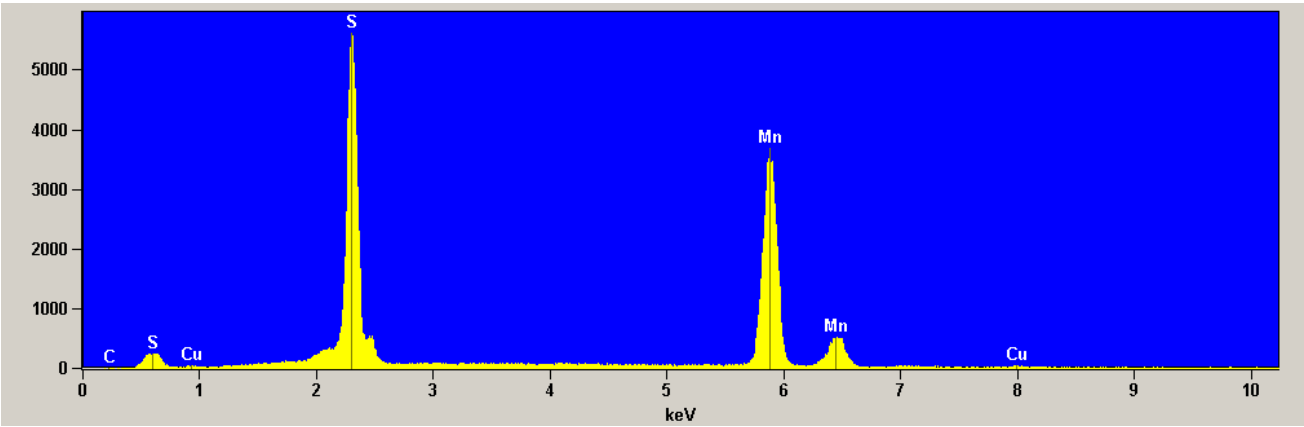


Figure 35. Scanning electron microscope photograph (above) of a portion of etched section "B-B" showing an elongated manganese sulfide inclusion. The length of this inclusion measured approximately 240 micrometers (0.01 inch), and thickness measured approximately 10 micrometer (0.0004 inch). Arrows indicate the ends of the elongated manganese sulfide inclusion. The EDS spectrum (below) of the inclusion showed elemental peaks of sulfur and manganese, consistent with manganese sulfide.

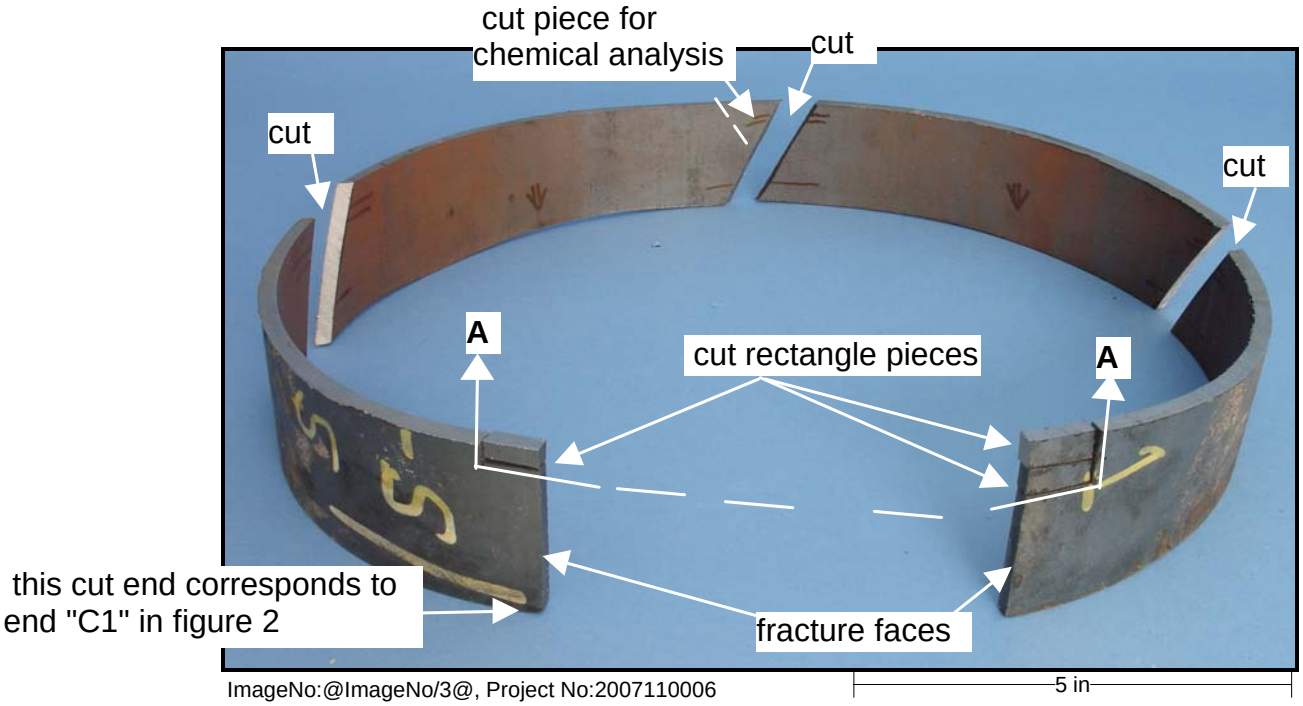


Figure 36. Three-inch ring piece that was cut from the saw cut end of segment 1. This ring piece was further cut into 4 pieces. Three rectangle pieces also were cut from the fracture surface. Location and orientation of metallurgical section "A-A" is indicated by section line "A-A". The metallurgical section portion on each side of the fracture face appears to be at different areas of the ring but in actuality correspond to mating fracture features.

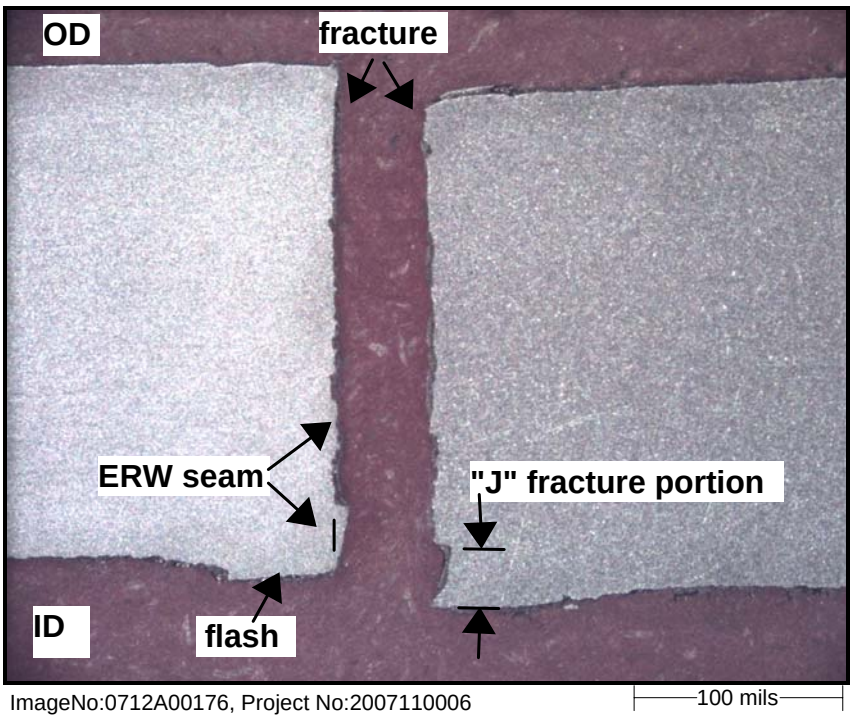
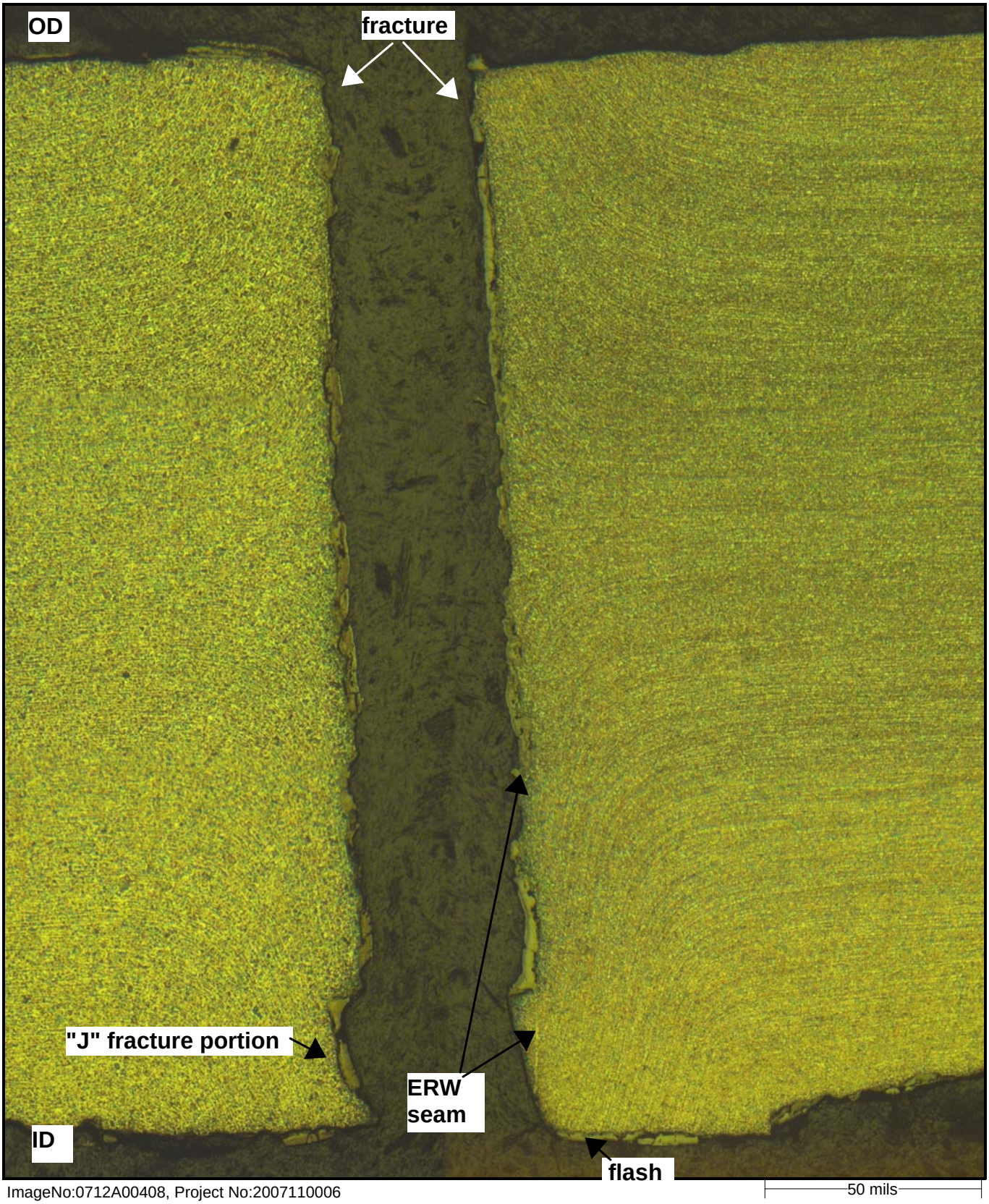


Figure 37. Photograph of a portion of metallurgical section "A-A" showing the near mating longitudinal fracture faces. The inside diameter is located at the bottom of the photograph. Line indicates position of ERW seam. Depth of the "J" fracture is about 10% of wall thickness. The depth of the "J" fracture was calculated based on a wall thickness of 0.250 inch. Etched with 2% Nital reagent.



ImageNo:0712A00408, Project No:2007110006

Figure 38. Photograph of a portion of section "A-A". Etched with 2% Nital reagent. Fracture was for the most part through the ERW seam (fusion) line.

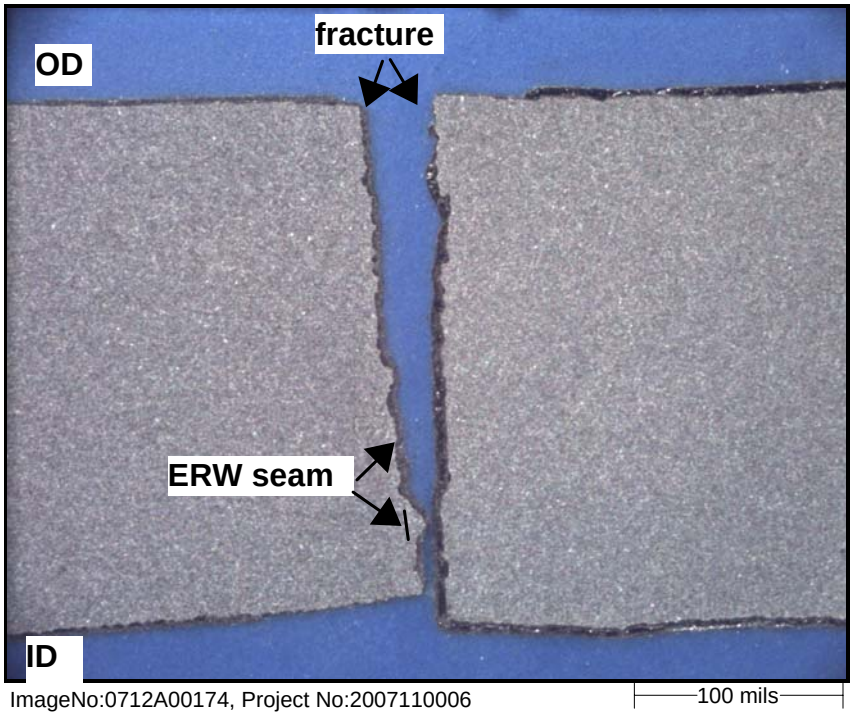


Figure 39. Photograph of a portion of metallurgical section "1-1" showing the near mating longitudinal fracture faces. The inside diameter is located at the bottom. Etched with 2% Nital reagent. The black line indicates the approximate position of the ERW seam. The fracture was mostly through the ERW seam.

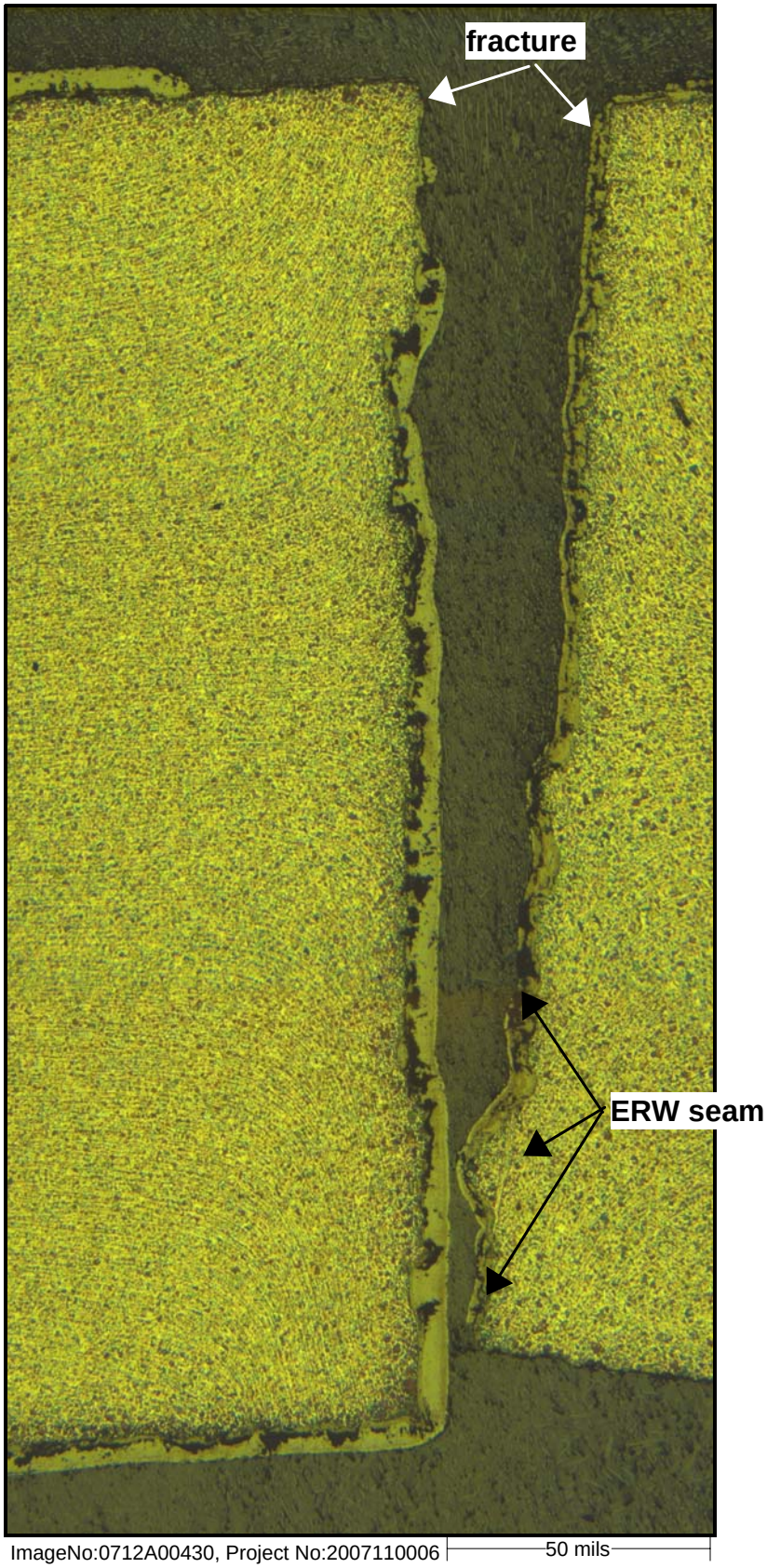


Figure 40. Composite photograph of a portion of secton "1-1". Etched with Nital reagent.

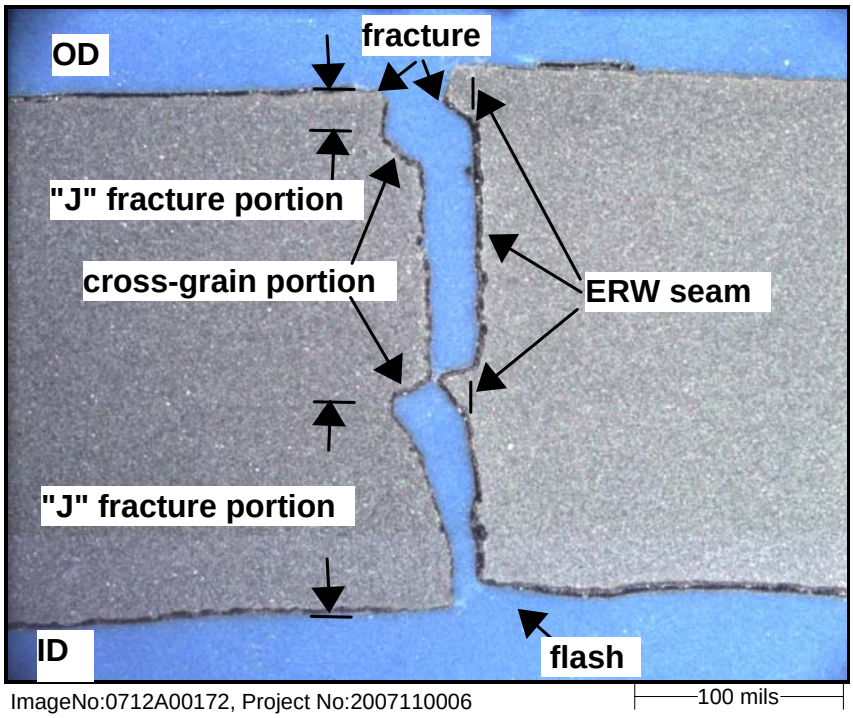


Figure 41. Photograph of a portion of metallurgical section "2-2" showing the near mating longitudinal fracture faces. The inside diameter is located at the bottom. The depth of the "J" fracture on the outer surface was about 10% of the wall thickness and on the inner surface was about 42% of the wall thickness. Etched with 2% Nital reagent.

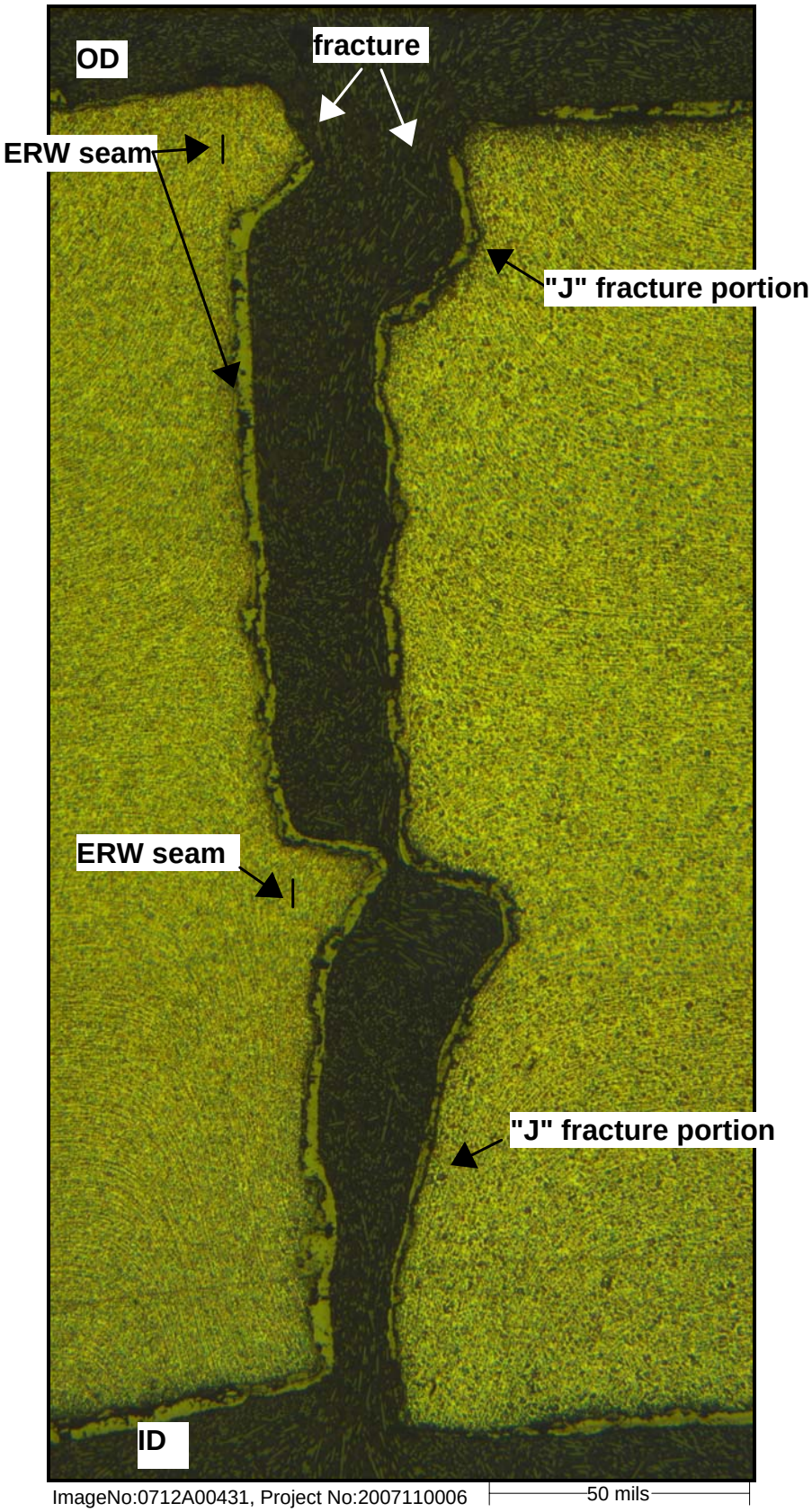


Figure 42. Composite photograph of a portion of section "2-2". Etched with Nital reagent.

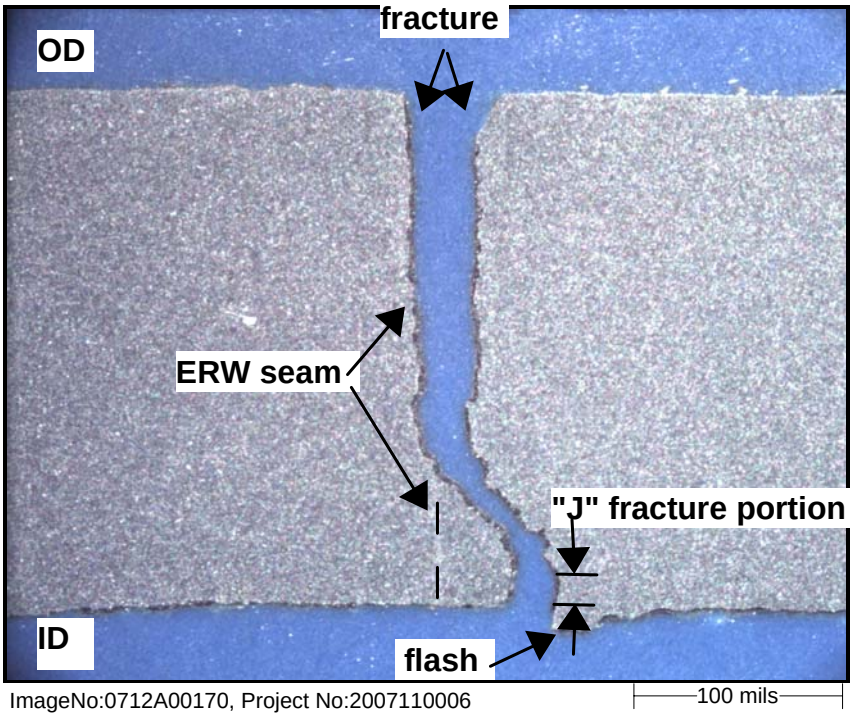


Figure 43. Photograph of a portion of metallurgical section "3-3" showing the near mating longitudinal fracture faces. The inside diameter is located at the bottom. The depth of the "J" fracture was about 7% of the wall thickness. Etched with 2% Nital reagent.

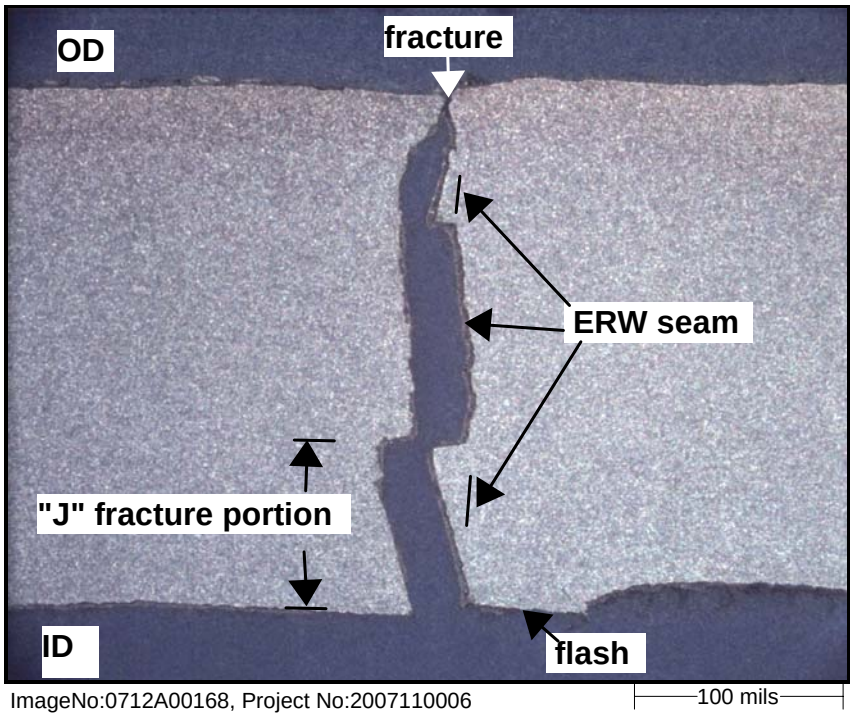
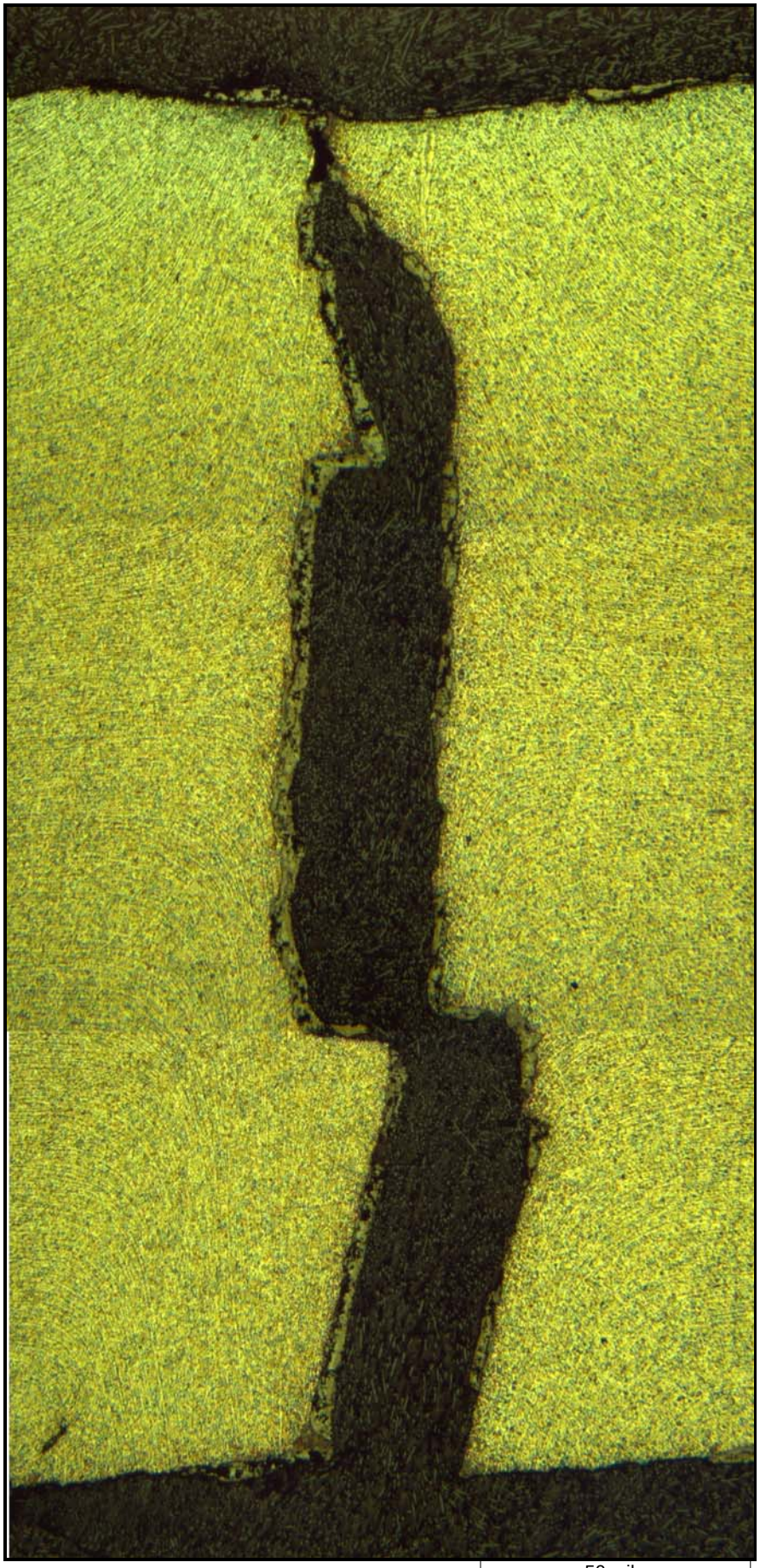


Figure 44. Photograph of a portion of metallurgical section "4-4" showing the near mating longitudinal fracture faces. The inside diameter is located at the bottom. The depth of the "J" fracture portion was about 27% of the wall thickness. Etched with 2% Nital reagent.



ImageNo: 0805A00107, Project No:2007110006

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Figure 45. Composite photograph of a portion of section "4-4". Etched with Nital reagent.

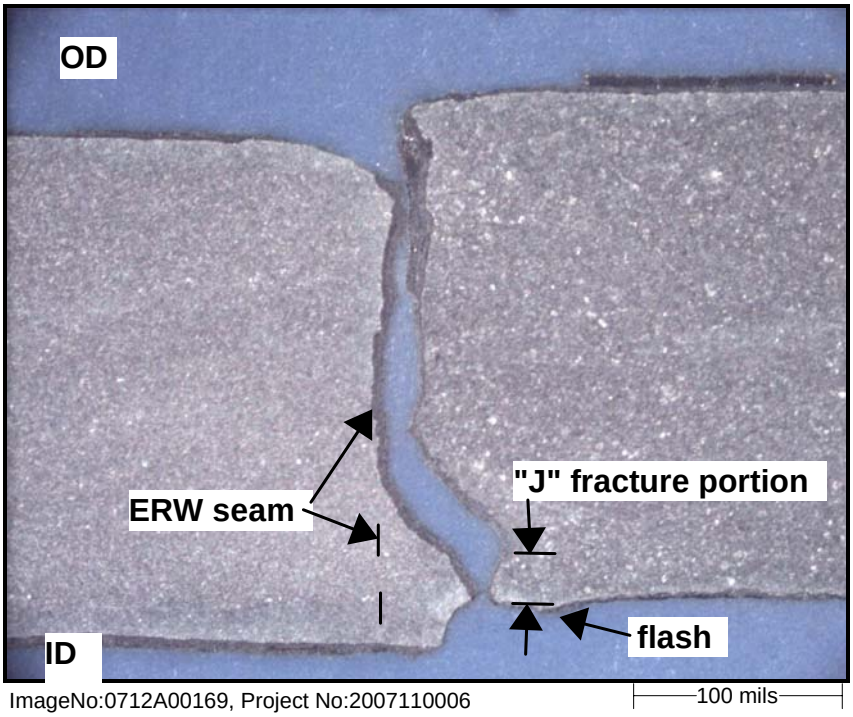
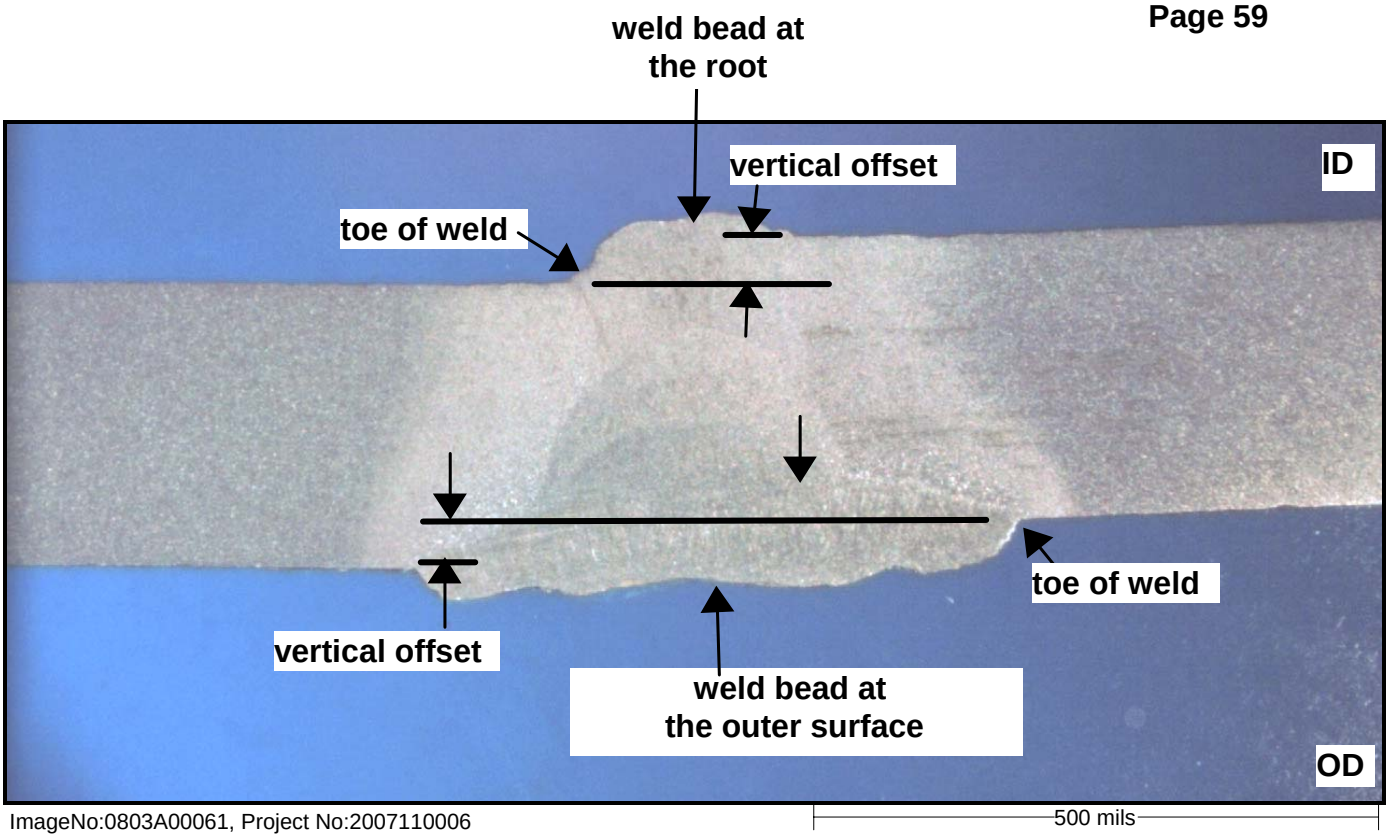


Figure 46. Photograph of a portion of metallurgical section "5-5" showing the near mating longitudinal fracture faces. The inside diameter is at the bottom. The depth of the "J" fracture portion was about 10% of the wall thickness. Etched with 2% Nital reagent.



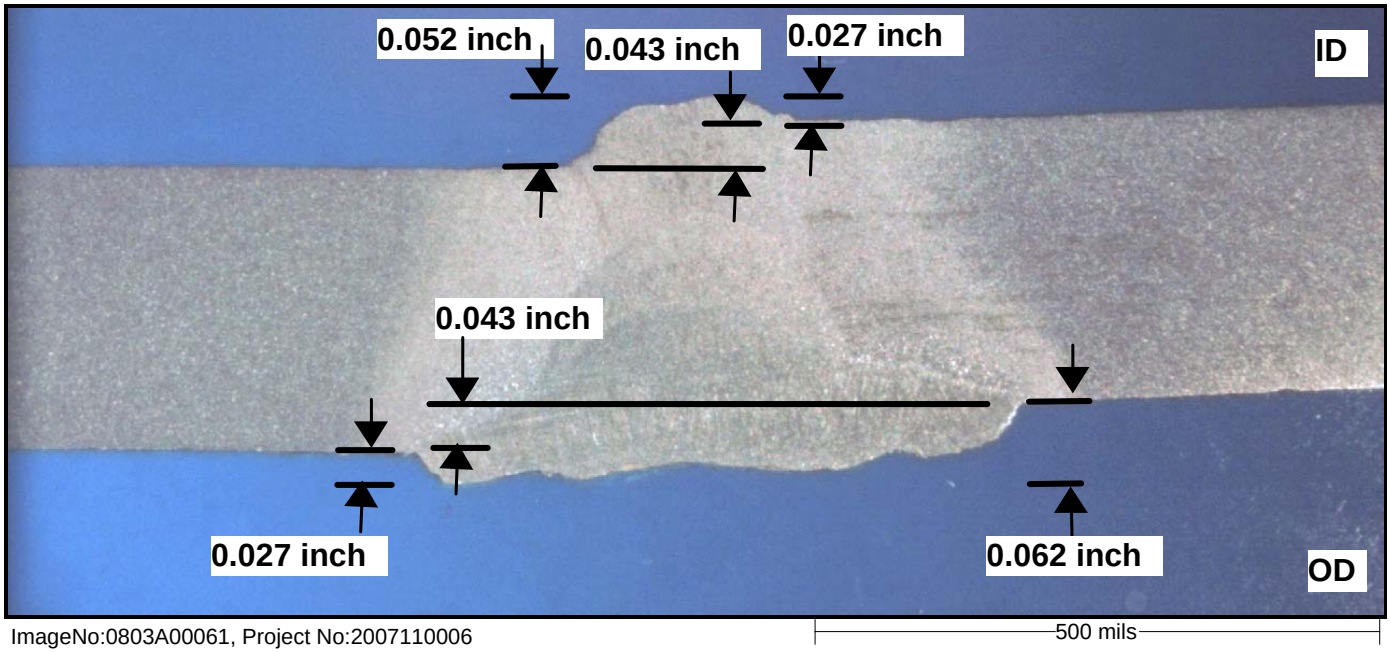


Figure 47. Photographs of section "7-7" showing the intact upstream girth weld that was located at the bottom portion of the pipe. The upper photograph shows a description of the different areas of the weld and the lower photograph shows the measured distances between areas of interest on the same girth weld. The girth weld is a single "V" butt weld joint. This section showed no evidence of a crack. Etched with Nital reagent.

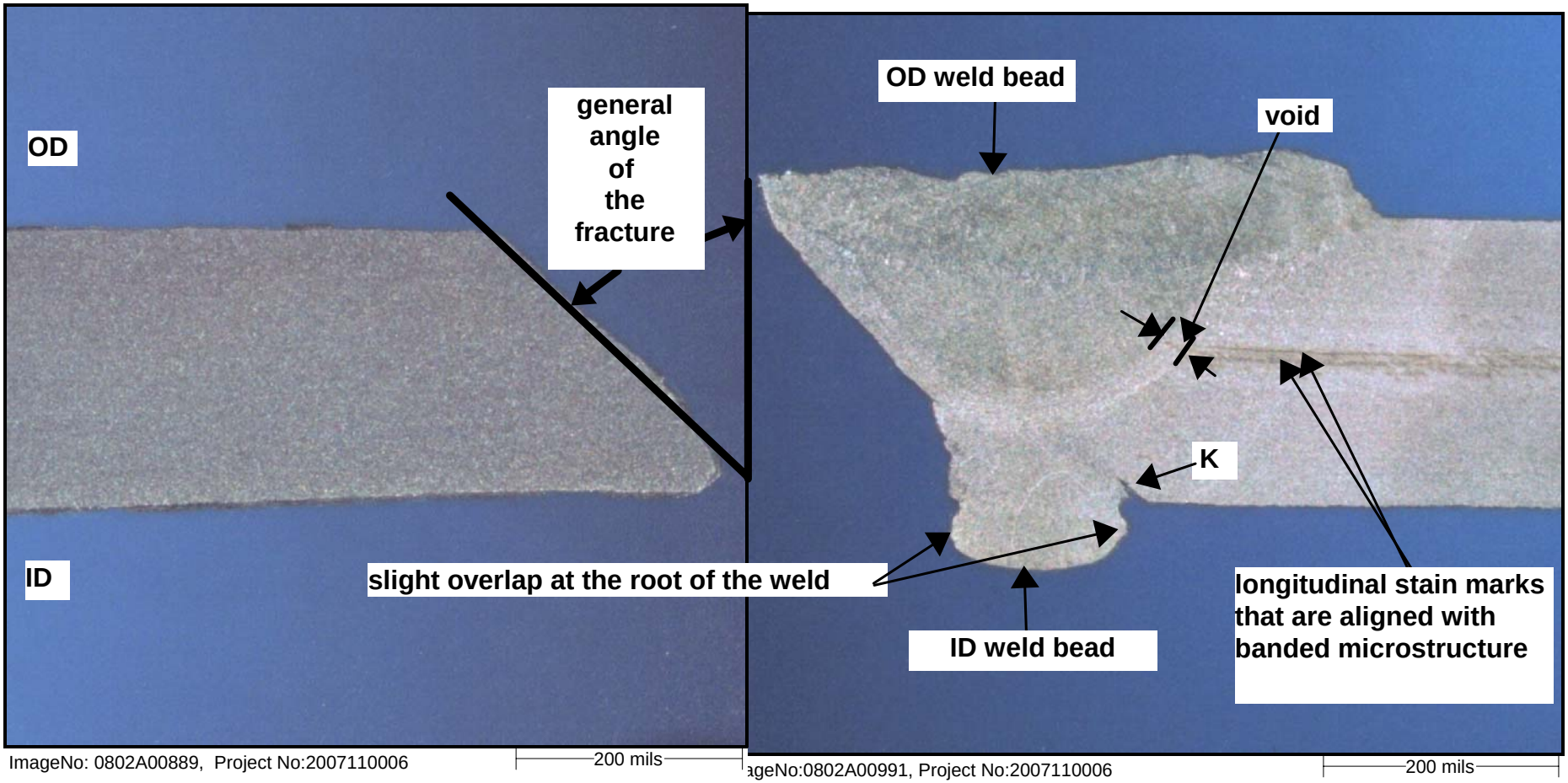


Figure 48. Composite photograph of section "6-6" showing the fractured upstream girth weld that was located at the top portion of the pipe (near the top dead center). Fracture at the outer half portion of the pipe wall for the most part extended through the base metal and the fracture at the inner half portion of the wall extended through the outer boundary of the weld. Arrow "K" indicates a crack that extended from the nearly-longitudinal girth weld fracture arrowed "W" in figure 18. The general angle of the fracture face was measured in the orientation indicated in the photograph. The bevel angle of at the edge of a plate prior to welding is measured in the same manner. Etched with Nital reagent. After etching, residual brown stain marks were found on the surface that corresponded to location of banded microstructure. No evidence of cracks or delamination was found in these stained areas.

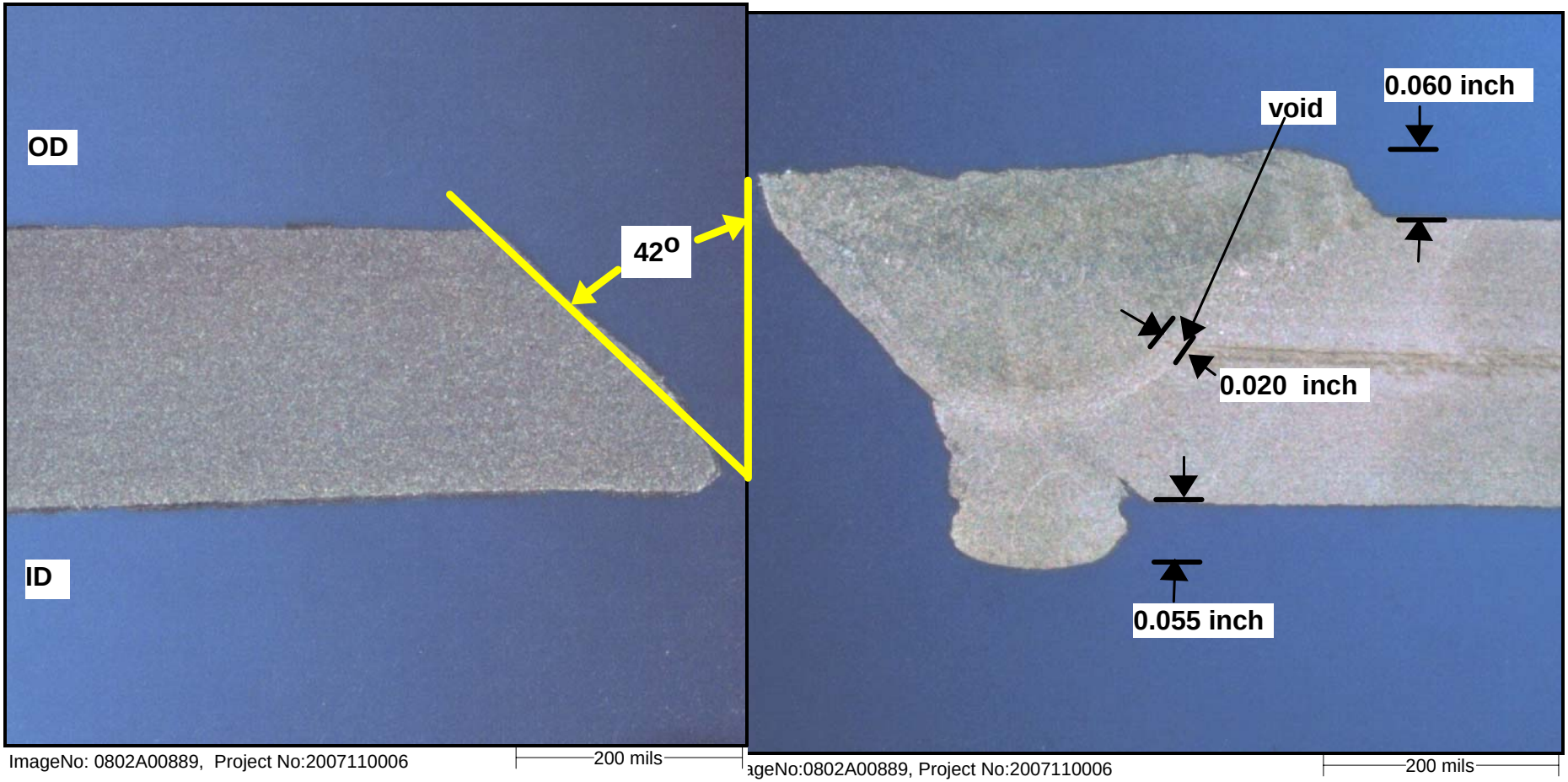


Figure 49. Composite photograph of section "6-6" in the area of the fractured upstream girth weld showing the measured distances between areas of interest. Etched with Nital reagent.