Pipeline Group Factual Report

ATTACHMENT 26

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Carmichael, Mississippi
DCA 08 MP 001

Final Report No. 06-3R

FINAL REPORT

on

INVESTIGATION OF HYDROSTATIC TEST BREAKS THAT OCCURRED DURING THE 2004 HYDROSTATIC TEST OF THE DEMOPOLIS-TO-MILNER SEGMENT OF THE DIXIE PIPELINE

to

DIXIE PIPELINE L.P.

February 17, 2006

by

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INVESTIGATION OF HYDROSTATIC TEST BREAKS THAT OCCURRED DURING THE 2004 HYDROSTATIC TEST OF THE DEMOPOLIS-TO-MILNER SEGMENT OF THE DIXIE PIPELINE

by

John F. Kiefner and Thomas F. Wahjudi

INTRODUCTION

This report presents the results of our investigation of 12 hydrostatic test breaks that occurred during the 2004 hydrostatic test of the Demopolis-to-Milner segment of the Dixie Pipeline. This 226.7-mile portion of the pipeline is comprised of an 83.2-mile segment of 10.75-inch-OD, 0.219-inch-wall, API 5L Grade X52 ERW line pipe extending from Opelika to Milner and a 143.5-mile segment of 12.75-inch-OD, 0.250-inch-wall, API 5L Grade X52 ERW line pipe extending from Demopolis to Opelika. The ERW seams of both of these materials were made by means of low-frequency current. The hydrostatic test was performed to address potential seam-integrity concerns. Seam-integrity issues typically are more of a concern when a low-frequency process is used than when a high-frequency process is used.

The list of the hydrostatic test breaks is presented in the table below. All were seam splits.

Mile Post as Marked on the Sample	Our Designation	Diameter (inches)	Measured Wall Thickness (inch)	Pressure at Failure at Site	
				psig	% SMYS
685	**10A**	10.75	0.216	1,733	81.8
677	**10B**	10.75	0.219	1,812	85.5
635.32	**10C**	10.75	0.211	1,818	85.8
637.05	**10D**	10.75	0.230	1,814	85.6
579.01	**12A**	12.75	0.248	1,966	96.4
584.34	**12B**	12.75	0.249	1,932	94.7
586.43	**12C**	12.75	0.249	1,860	91.2
589.28	**12D**	12.75	0.250	1,917	94.0
611.88	**12E**	12.75	0.245	1,848	90.6
625.3	**12F**	12.75	0.244	1,825	89.5
526.28	**12G**	12.75	0.253	1,832	89.8
528.05	**12H**	12.75	0.239	1,891	92.8

SUMMARY

All 12 breaks initiated at original seam-manufacturing defects. None exhibited any evidence of having been extended by pressure-cycle-induced fatigue crack growth. None occurred within the immediate vicinity of a pump station. Two of the breaks in 10-inch pipe occurred within 10 miles downstream from a pump station. All others occurred at distances exceeding 18 miles from a pump station. All breaks except one occurred at pressure levels exceeding 85 percent of SMYS, the standard level of hydrostatic test stress applied by the manufacturers for these sizes and grades of materials at the time of their manufacture. The one 10-inch sample, which failed at a stress level below 85 percent of SMYS, failed at 81.8 percent of SMYS. No evidence of time-dependent defect growth was found to be associated with any of these samples.

DESCRIPTION OF THE 2004 HYDROSTATIC TEST

The following information was obtained from the hydrostatic test contractor's written documentation. The 2004 hydrostatic test was conducted in two parts for each of 12 test sections. The procedure involved a 4-hour strength test to the target test pressure (85 to 90 percent of SMYS range for the 10-inch pipe; 90 to 95 percent of SMYS range for the 12-inch pipe), followed by a 4-hour leak test at a somewhat lower pressure (usually about 100 psig below the target test pressure).

TECHNICAL INVESTIGATION

The fracture origin in each test break was identified. On some samples it was very difficult to locate the origin because the fracture surfaces had been stored outdoors for several months before being shipped to Kiefner and Associates, Inc. The fracture surfaces at the presumed origins were examined before and after being cleaned to determine the fracture modes and relevant features that may have contributed to the test breaks.

In the following descriptions, the test breaks in the 10-inch pipe are discussed first, followed by the discussions of the test breaks in the 12-inch pipe. Where appropriate an analysis is provided based on the log-secant equation for failure pressure versus defect size*.

Sample 10A

This test break occurred at MP 685. The break occurred at a pressure level of 1,733 psig corresponding to a hoop stress level of 81.8 percent of SMYS. The seam of this sample was split for a distance of more than 40 feet (in a joint of pipe about 60 feet in length). The long split is an indication of the relatively low toughness of the bondline region of the seam weld in this material.

The fracture surfaces at the origin are shown in Figure 1. The fracture surfaces are shown with OD pipe surfaces back-to-back. The origin was assumed to be the dark gray-colored smooth band visible at the OD surfaces. This is a hook crack, a type of manufacturing defect. A 5-inch-long portion of the hook crack is visible in Figure 1. The precursor of a hook crack is a lamination or layer of non-metallic inclusions. Neither a lamination nor an inclusion layer are necessarily injurious to the pipe where they occur away from the seam. Both result from the hot rolling of the plate or skelp used to make the pipe. They arise from voids or non-metallic particles in an ingot or slab of steel. Upon rolling these features become flat layers of no particular consequence because they lie in planes parallel to the surfaces of the plate and do not affect its thickness or strength. When one or both of these features extends to the edge of the plate or skelp that becomes part of the seam, however, they become re-oriented into a characteristic J-shaped layer as the edges are upset during the welding of the seam. In that orientation they can and often do reduce the hoop stress carrying capacity of the pipe.

A metallographic section across the probable origin of the test break was cut between the 1.6-inch and 2.0-inch marks on the scale shown in Figure 1. This section is shown at two different magnifications in Figure 2 and Figure 3. As seen in these figures, the hook crack extends from the OD surface to a depth of about 12 percent of the actual thickness including the ID flash. The bondline of the weld is distorted. At the OD surface it is just to the left of the

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*Kiefner, J. F., Maxey, W. A., Eiber, R. J., and Duffy, A. R., "Failure Stress Levels of Flaws in Pressurized Cylinders", *Progress in Flaw Growth and Fracture Toughness Testing*, ASTM STP 536, American Society for Testing and Materials, pp. 461-481 (1973).

hook crack. Below the hook crack it has shifted to the right where it coincides with what appears to be intermittent areas where the two fracture surfaces do not match. These non-matching surfaces indicate that there may have been voids/inclusions occupying 50 percent of the wall thickness or more in the bondline of the seam. The axial length of this region lies between the 1.0-inch mark and the 4.3-inch mark on Figure 1.

The grain coarsening visible in Figure 3 in the vicinity of the bondline is a characteristic of a low-frequency-welded ERW seam. The larger grain size in this region contributes to relative brittleness of fracture in the bondline region of a low-frequency-welded ERW seam.

Another section was cut at the 5-inch mark in Figure 1 across a large hook crack that appears to be a continuation of the hook crack at the origin. This section is shown in Figure 4 and Figure 5. This hook crack is deeper than the one shown in Figures 2 and 3. It extends to a depth of about 40 percent of the wall thickness. While this hook crack is deeper than the one shown in Figures 2 and 3, it likely is not the origin because the nearly 45-degree angle of the fracture suggests that the fracture was propagating rather than initiating at this point.

The likely reason that the shorter, shallower hook crack is the origin instead of the deeper, longer hook crack (5 inches long and 40 percent through the wall at the deepest point) is that the smaller of the two is accompanied by other apparent defects (i.e., voids or inclusions on the bondline) and because it resides in the coarse-grained region surrounding the bondline, a material that can be expected to have lower toughness than the parent metal.

The parent metal exhibited a yield strength of 66,500 psi and a Charpy V-notch upper-shelf energy of 57 ft-lb (full-size specimen equivalent). The wall thicknesses measured on both sides of the seam in the parent metal were 0.226 inch and 0.227 inch. The cause of the break is a manufacturing defect that consisted of a hook crack and an area of voids or inclusions along the bondline of the ERW seam. No evidence of in-service crack growth was found.

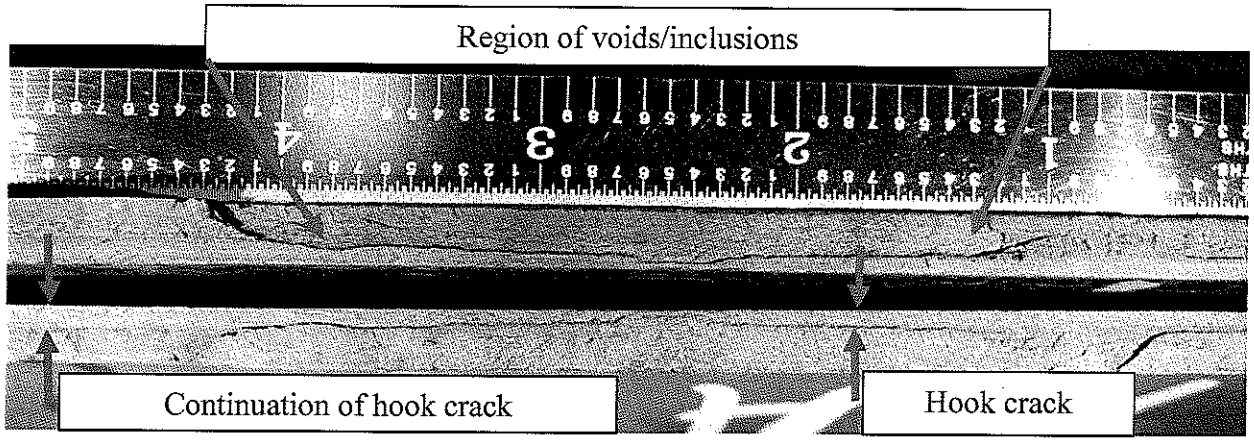


Figure 1. Initiating defects, Sample 10A (OD surfaces of pipe back-to-back).

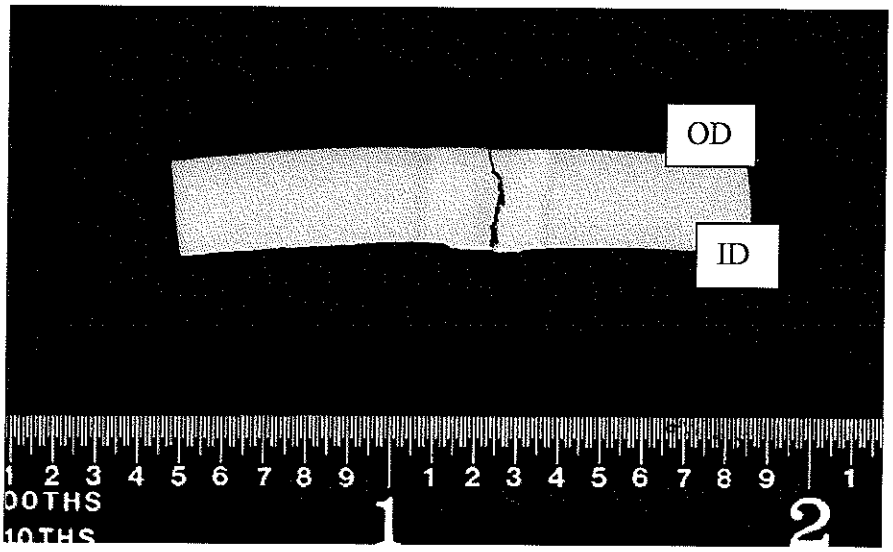


Figure 2. Metallographic section at apparent origin region, Sample 10A (2X).

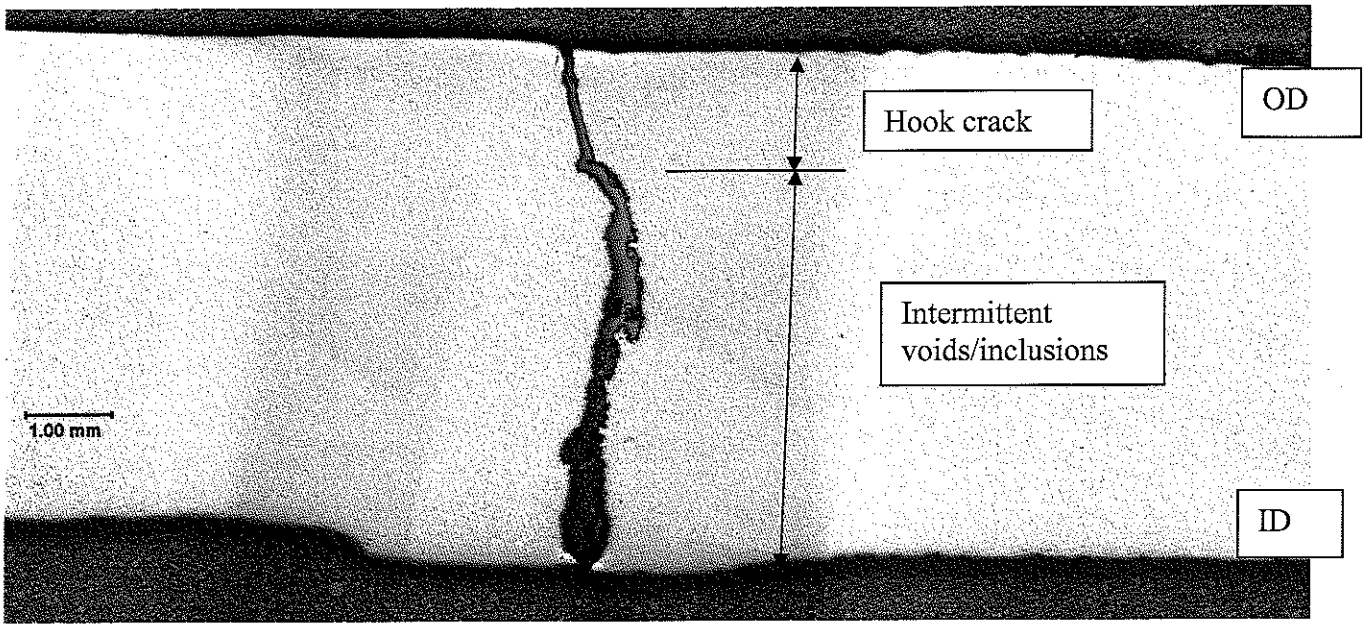


Figure 3. Metallographic section at apparent origin region, Sample 10A (10X).

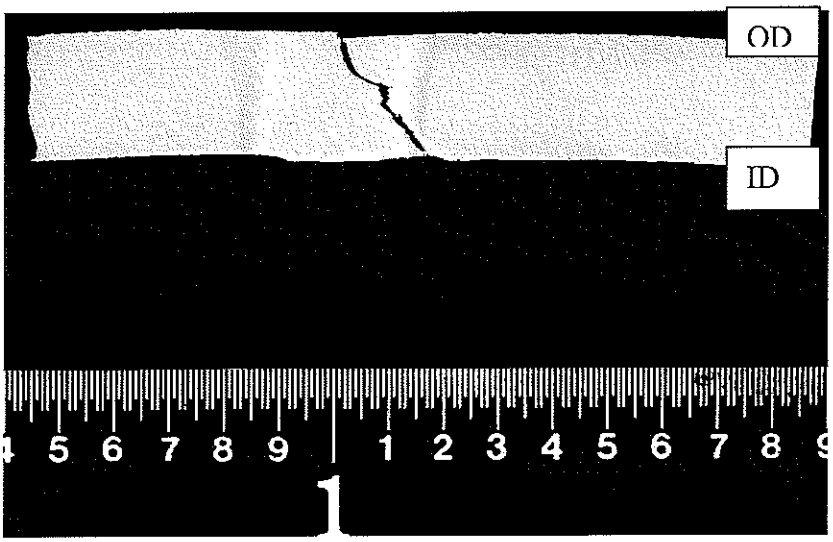


Figure 4. Section located away from apparent origin, Sample 10A (2X).

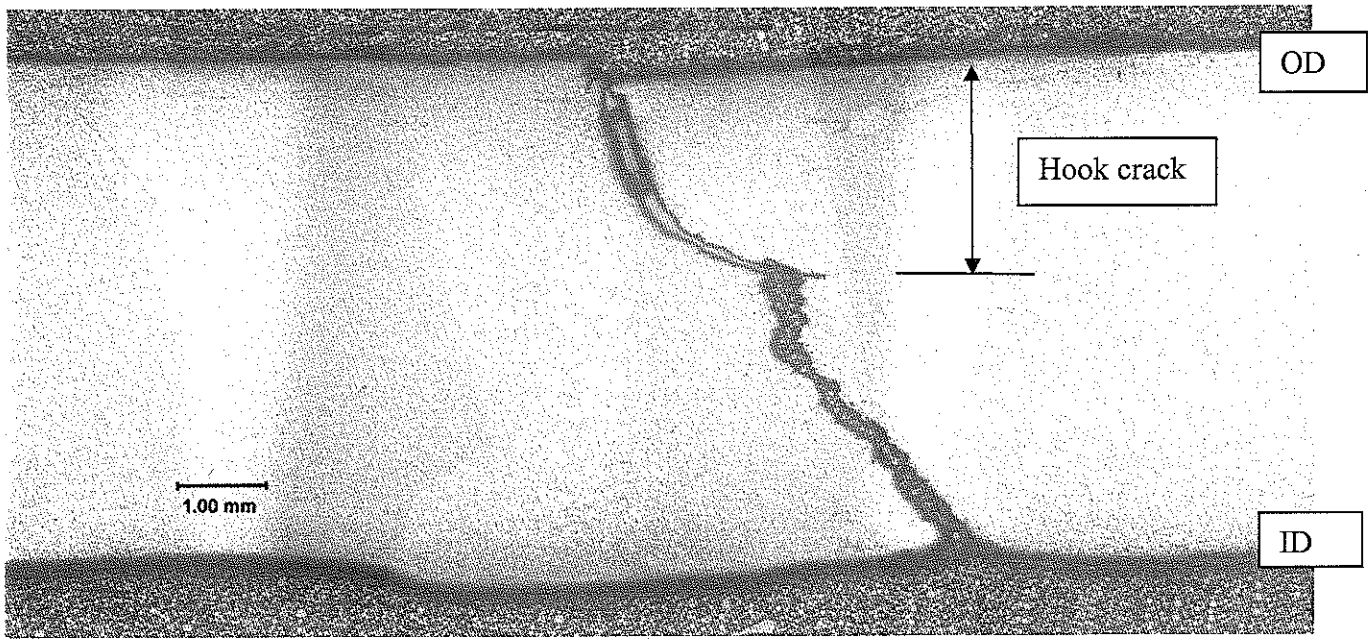


Figure 5 . Section located away from apparent origin, Sample 10A (12X).

Two analyses of the apparent initiating defect based on the log-secant equation and the assumption that the anomaly has a uniform depth are presented in Figure 6 and Figure 7. The analysis presented in Figure 6 is used to infer an inherent toughness level for the bondline region based on the assumption that the initiating defect consisted solely of the hook crack shown in Figure 3. The dimensions used are a length of 4 inches and a depth of 12 percent of the wall thickness. The failure pressure of 1,733 psig is represented by the red horizontal line. A Charpy energy level of 5.1 ft-lb generates d/t versus length curves that result in the coincidence of a defect length of 4 inches, a d/t curve of 0.12, and the 1,733-psig level. Because a Charpy energy of 5.1 ft-lb is not unreasonably low for the material in the vicinity of the ERW bondline, it is possible that the hook crack alone would have been of sufficient size to cause the failure. However, if the toughness is actually greater than the level corresponding to a Charpy energy level of 5.1 ft-lb, the presumed voids or inclusions likely did contribute to the occurrence of the break.

The analysis presented in Figure 7 is used to infer a defect size needed to cause the break at a pressure of 1,733 psig if the effective toughness level for the region at the bottom of the hook crack in Figure 5 is 57 ft-lb, the same as that of the parent material. The inferred defect length based on a depth of 48 percent of the wall thickness is 10 inches. Coupled with the fact

that the rupture appeared to be propagating at the location of the metallographic section shown in Figure 5, this information reinforces our conclusion that the initiating defect was the combination of defects shown in Figure 3 (i.e., shallow hook crack plus voids or inclusions). It is also interesting to note that a 10-inch-long defect with depth of only 46 percent of the wall thickness would have been expected to survive the mill test pressure of 1,810 psig. It may be that the defect was on the verge of failure in the mill test and was extended during the test so that its subsequent failure pressure was only 1,733 psig. This phenomenon is termed a "pressure reversal", and it is not all that uncommon in the testing of older ERW pipe.

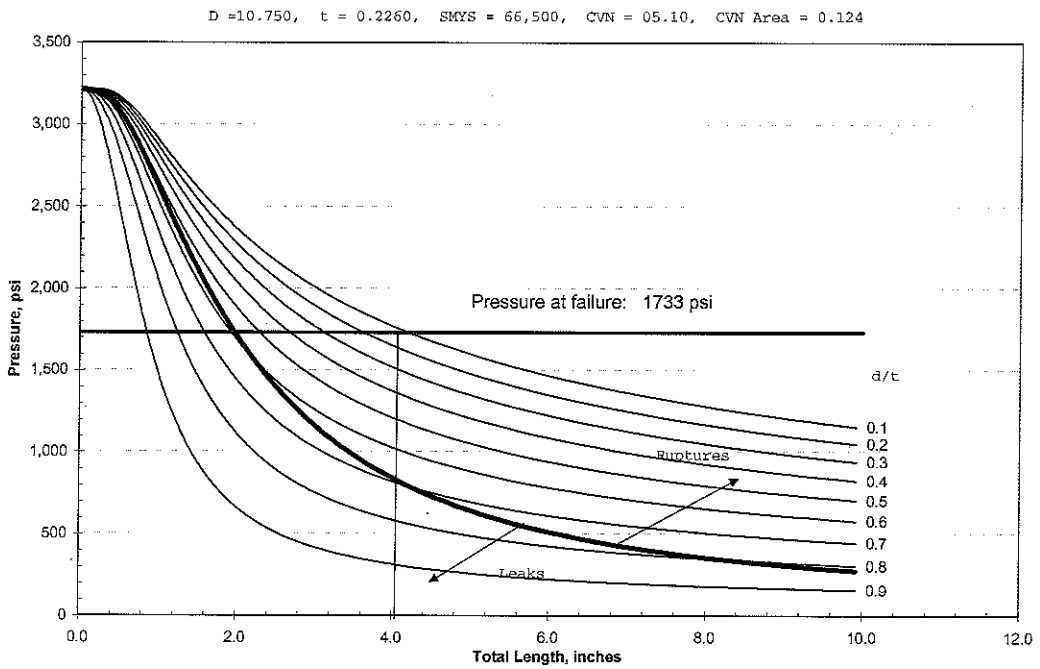


Figure 6. Charpy energy for Sample 10A inferred from shallow hook crack.

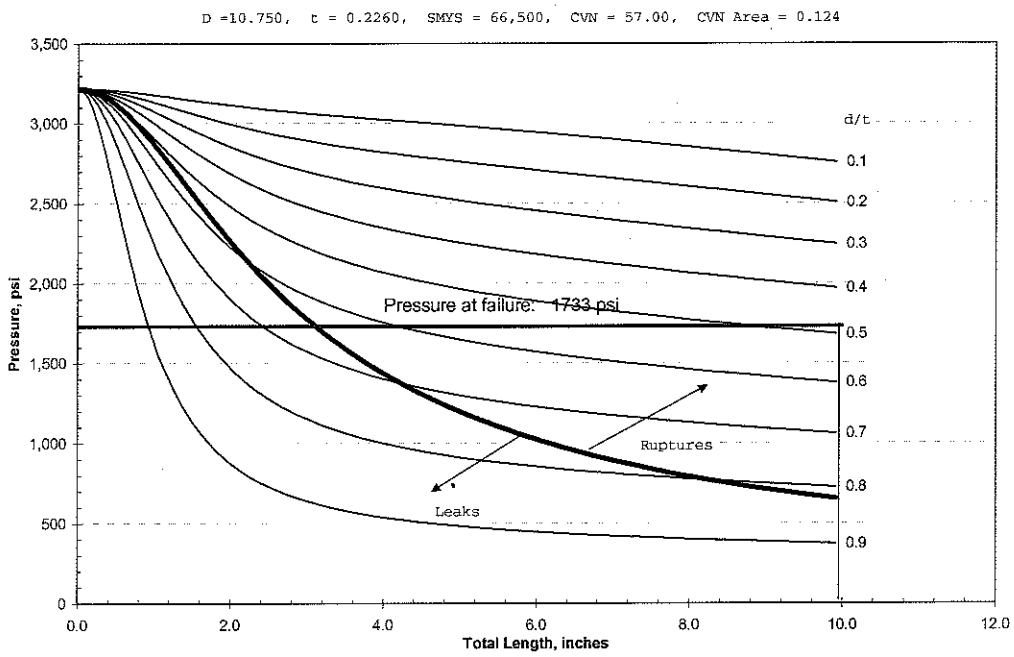


Figure 7. Inferred defect size based on Sample 10A; Charpy energy of 57 ft-lb.

Sample 10B

This test break occurred at MP 677. The break occurred at a pressure level of 1,812 psig corresponding to a hoop stress level of 85.5 percent of SMYS. The seam of this sample was split for a distance of more than 54 feet (in a joint of pipe about 57 feet in length). The long split is an indication of the relatively low toughness of the bondline region of the seam weld in this material.

The fracture surfaces at the origin are shown in Figure 8. The fracture surfaces are shown with OD pipe surfaces back-to-back. The initiating defect was assumed to be comprised of two bands of different colors, the dark gray-colored irregular band visible in Figure 6 at the OD surfaces and the lighter gray band extending nearly to the mid-thickness of the plate edges. This defect appeared to extend about 6.5 inches in the axial direction. It is apparently some type of manufacturing defect.

A metallographic section across this probable origin was cut at the 2-inch mark on the scale shown in Figure 8. This section is shown at two different magnifications in Figure 9 and Figure 10. As seen in these figures, the defect extends from the OD surface in two stages at two distinct angles to a total depth of about 50 percent of the actual thickness including the ID flash.

The bondline of the weld is located to the left of the angled anomaly, and it is distorted in a way that suggests that it was formed with this angular anomaly already present. The angular anomaly appears to consist of voids/inclusions that were created during some stage of manufacturing prior to the formation of the seam. A reasonable explanation is that one edge of the skelp was either damaged or improperly trimmed so that the two edges did not come together squarely. The grain coarsening in the vicinity of the bondline is a characteristic of a low-frequency- welded ERW seam. The larger grain size in this region contributes to relative brittleness of fracture in the bondline region of a low-frequency-welded ERW seam.

The parent metal exhibited a yield strength of 65,500 psi and a Charpy V-notch upper-shelf energy of 38 ft-lb (full-size specimen equivalent). The wall thicknesses measured on both sides of the seam in the parent metal were 0.227 inch and 0.227 inch. The cause of the break is a manufacturing defect that consisted of layers of voids or inclusions near one edge of the skelp. Apparently these were reoriented to the angles shown in Figure 10 during the seam-welding process. No evidence of in-service crack growth was found.

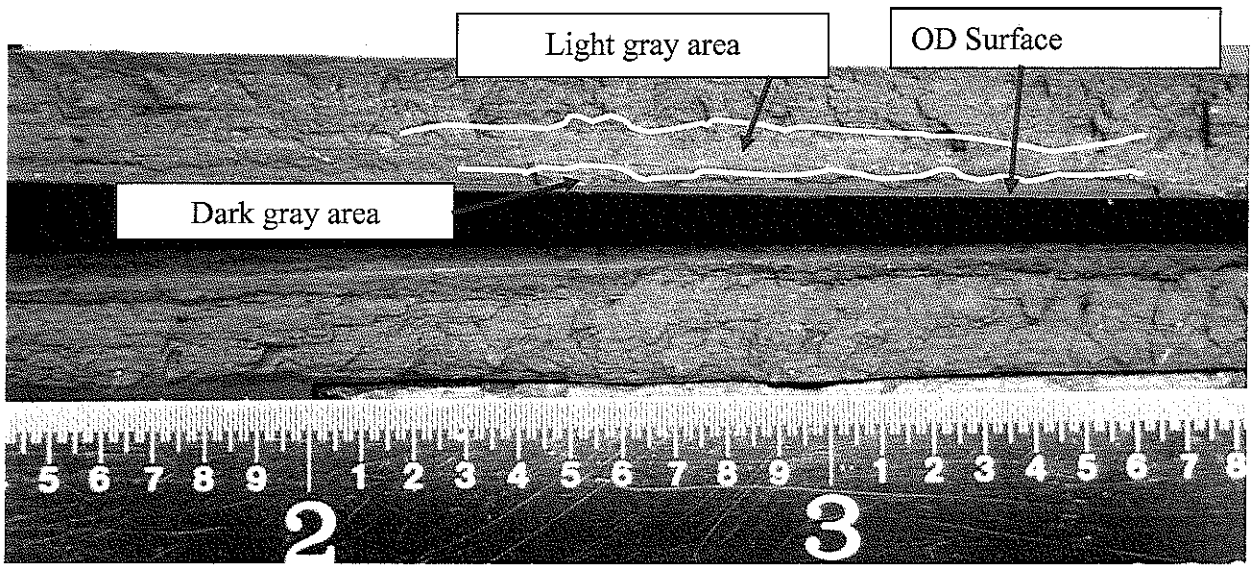


Figure 8. Initiating defects, Sample 10B (OD surfaces of pipe back-to-back).

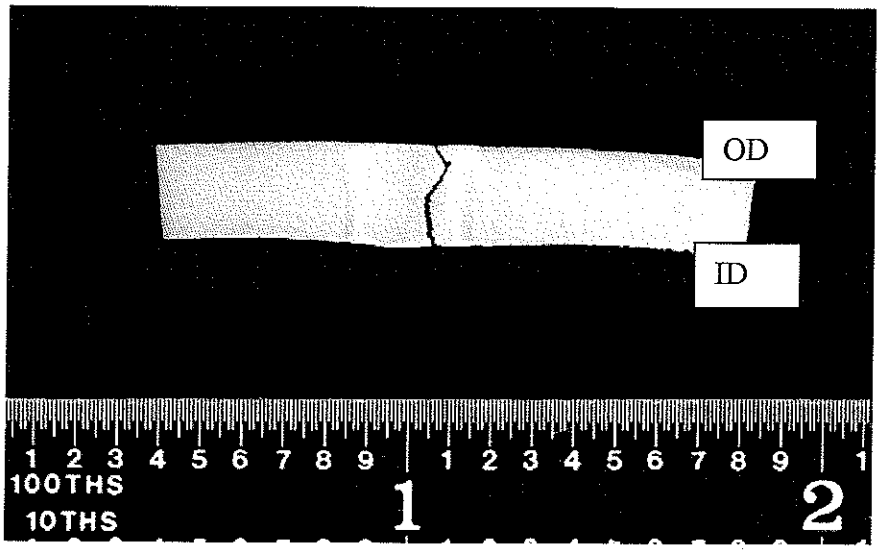


Figure 9. Metallographic section at apparent origin region, Sample 10B (2X).

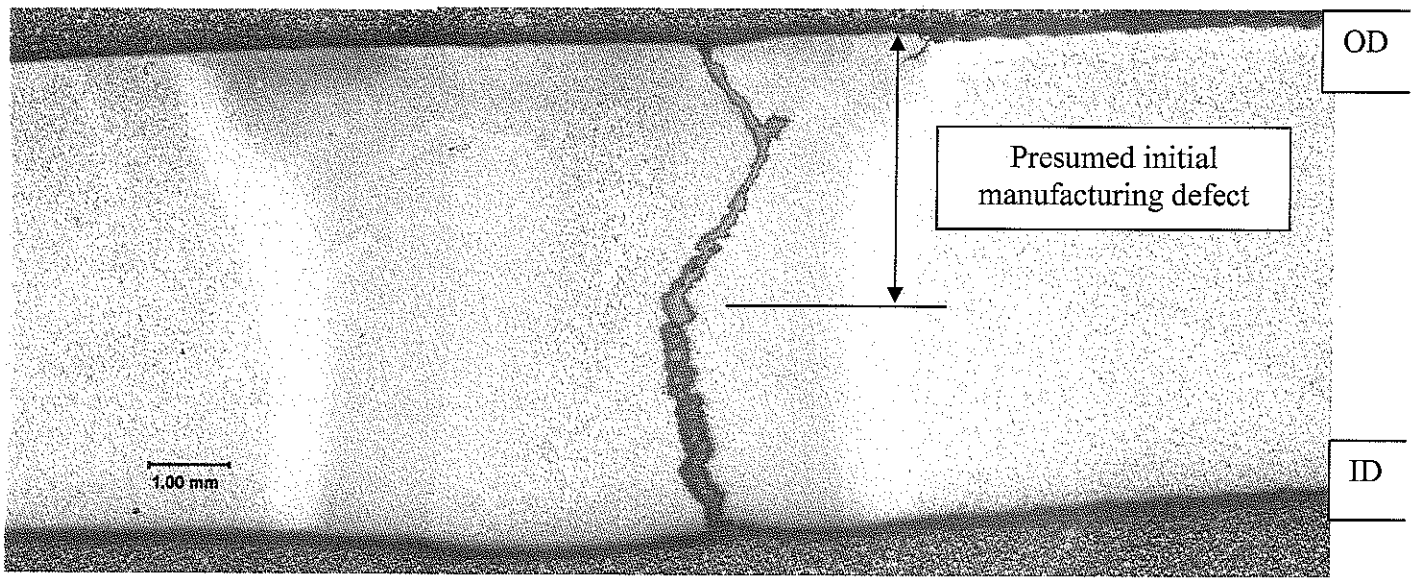


Figure 10. Metallographic section at apparent origin region, Sample 10B (12X).

As seen in Figure 11 below, the inferred defect length for a 50-percent through-the-wall defect that would fail at a pressure of 1,812 psig is 6 inches for a material with a Charpy energy of 38 ft-lb. This is reasonably close to the actual length of the defect, 6.5 inches.

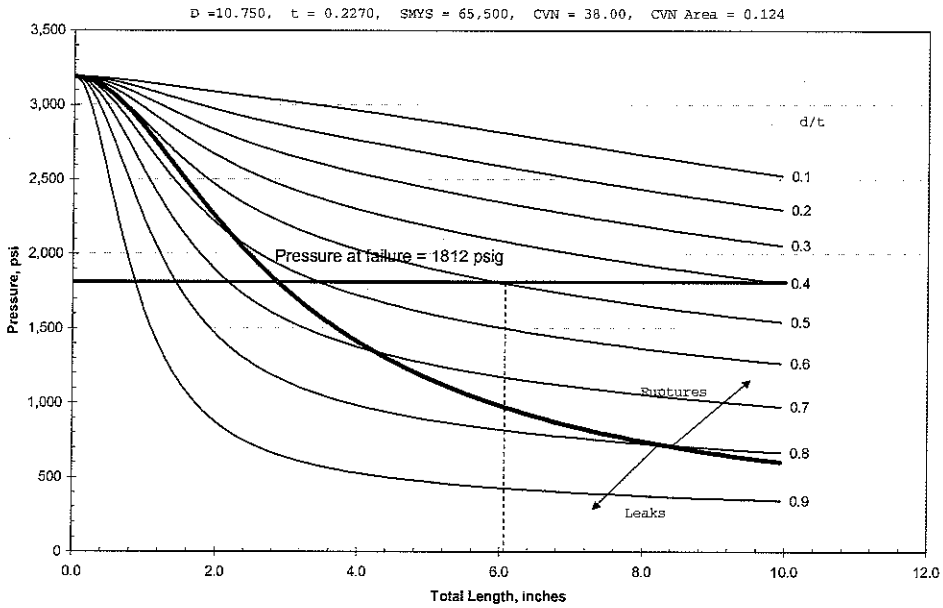


Figure 11. Inferred defect size based on Sample 10B Charpy energy of 38 ft-lb.

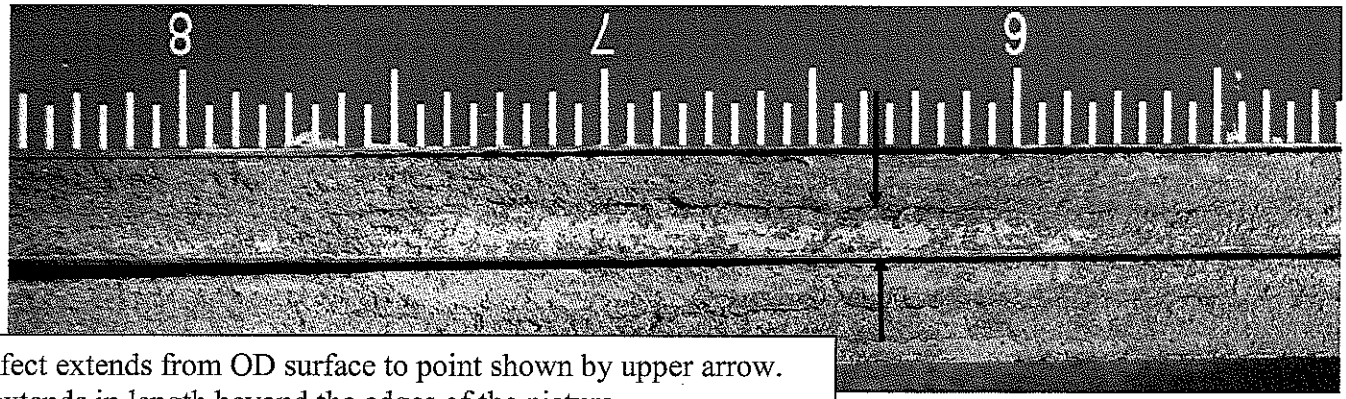
Sample 10C

This test break occurred at MP 635.32. The break occurred at a pressure level of 1,818 psig corresponding to a hoop stress level of 85.8 percent of SMYS. The split in the seam of this sample was about 8 feet in length.

The fracture surfaces at the origin are shown in Figure 12. The fracture surfaces are shown with OD pipe surfaces back-to-back. Initially it was thought to be a cold weld (defined later in the report), however, there are no stitch marks and the large size of the defect indicates much more toughness than one usually associates with the bondline region. The defect is probably a hook crack that is very close to the bondline. In Figure 12, the defect corresponds to the long, smooth region that has penetrated from the OD surfaces to depths ranging from 30 to 50 percent of the wall thickness. This defect appeared to extend about 12 inches in the axial direction. It is clearly a manufacturing defect, and there is no evidence of any in-service crack growth associated with it.

A metallographic section across the probable origin of the test break was cut at the 6.75-inch mark on the scale shown in Figure 12. This section is shown at two different magnifications in Figure 13 and Figure 14. As seen in these figures, the defect extends from the OD surface to a depth of about 45 percent of the actual thickness including the ID flash.

The parent metal exhibited a yield strength of 64,500 psi and a Charpy V-notch upper-shelf energy of 58 ft-lb (full-size specimen equivalent). The wall thicknesses measured on both sides of the seam in the parent metal were 0.222 inch and 0.223 inch.



Defect extends from OD surface to point shown by upper arrow.
It extends in length beyond the edges of the picture.

Figure 12. Initiating defect, Sample 10C (OD surfaces of pipe back-to-back).

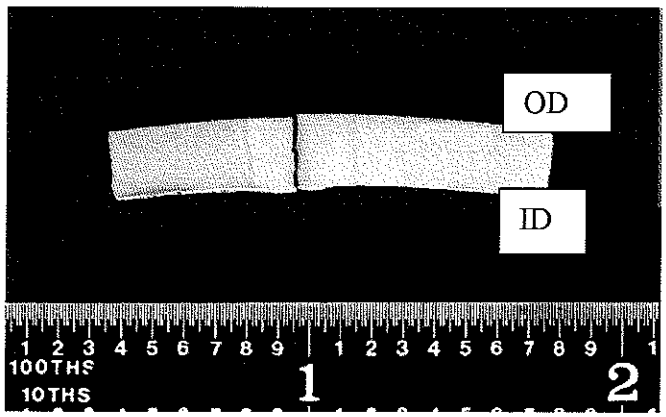


Figure 13. Metallographic section at origin region, Sample 10C (1.5X)

As seen in Figure 15 below, the inferred defect length for a 45-percent through-the-wall defect that would fail at a pressure of 1,818 psig is 10.5 inches for a material with a Charpy energy of 58 ft-lb. This is reasonably close to the actual length of the defect, 12 inches. The existence of such a large defect with a failure stress level of 85.8 percent of SMYS this close to the bondline is unusual. For some reason the effective toughness was more than one would normally expect for the grain-coarsened bondline region. The fact that the rupture in this sample was only 8 feet as opposed to 40 and 54 feet for Samples 10A and 10B suggests that this piece possessed more toughness along the bondline than did the other two samples.

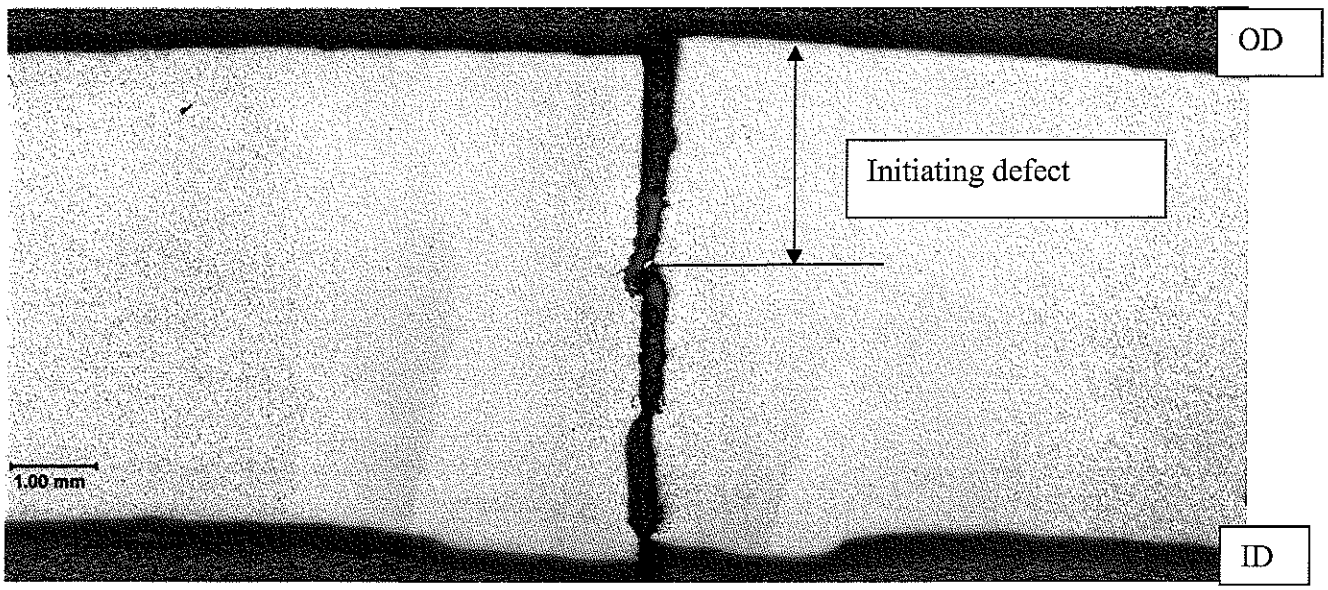


Figure 14. Metallographic section at origin region, Sample 10C (12X).

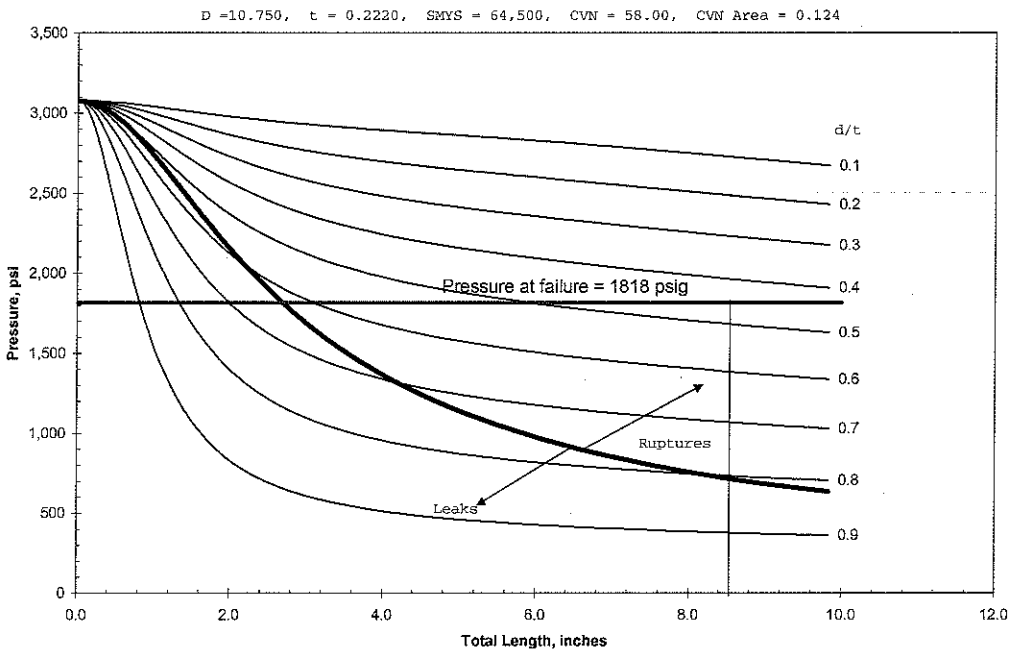


Figure 15. Inferred defect size based on Sample 10C Charpy energy of 58 ft-lb.

Sample 10D

This test break occurred at MP 637.05. The break occurred at a pressure level of 1,814 psig corresponding to a hoop stress level of 85.6 percent of SMYS. The split in the seam of this sample was about 12 feet in length.

The fracture surfaces at the origin are shown in Figure 16. The fracture surfaces are shown with OD pipe surfaces back-to-back. Initially it was thought to be a cold weld (defined later in the report), however, there are no stitch marks and the large size of the defect indicates much more toughness than one usually associates with the bondline region. The defect is probably a hook crack that is very close to the bondline. In Figure 16, the defect corresponds to the long, smooth region that has penetrated from the OD surfaces to a depth of about 30 percent of the wall thickness. This defect appeared to extend about 6.25 inches in the axial direction. It is clearly a manufacturing defect, and there is no evidence of any in-service crack growth associated with it.

A metallographic section across the origin of the test break was cut at the 3-inch mark on scale shown in Figure 16. This section is shown at two different magnifications in Figure 17 and Figure 18. As seen in these figures the defect extends from OD surface to a depth of about 30 percent of the actual thickness including the ID flash. This defect appears to coincide with the bondline.

The parent metal exhibited a yield strength of 61,000 psi and a Charpy V-notch upper-shelf energy of 52 ft-lb (full-size specimen equivalent). The wall thicknesses measured on both sides of the seam in the parent metal were 0.235 inch and 0.234 inch.

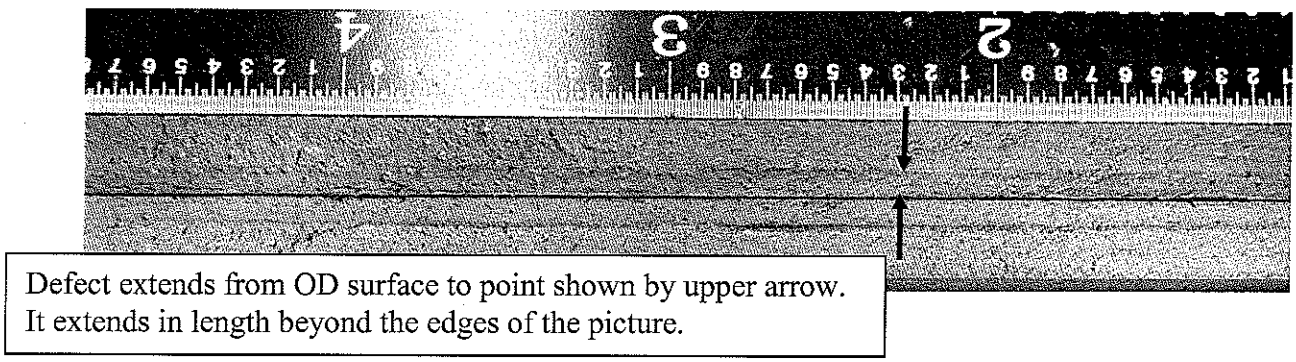


Figure 16. Initiating defect, Sample 10D (OD surfaces of pipe back-to-back).

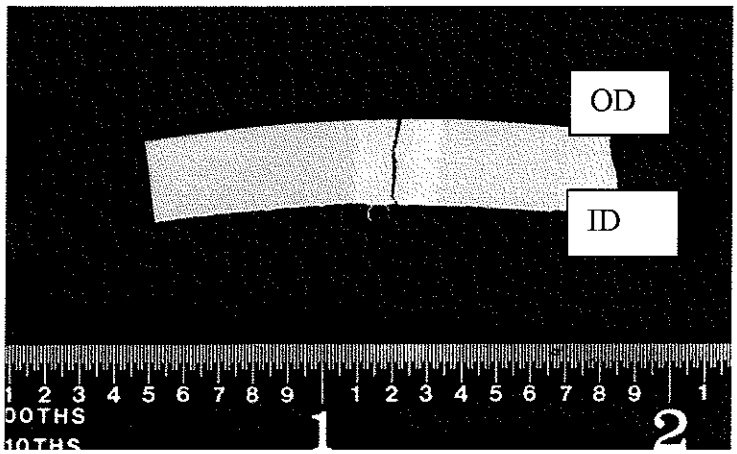


Figure 17. Metallographic section at origin region, Sample 10D (2X).

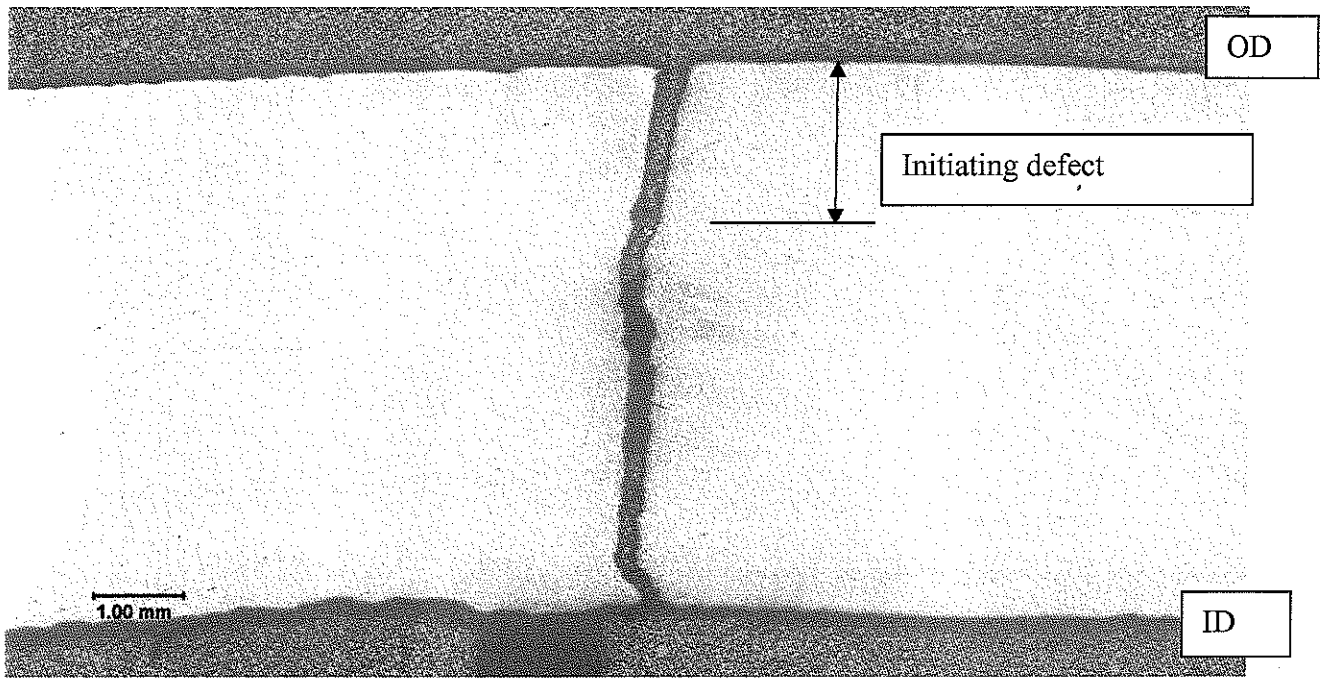


Figure 18. Metallographic section at origin region, Sample 10D (12X).

As seen in Figure 19 below, the inferred Charpy energy that is consistent with the failure of the 6.25-inch-long, 30-percent-through defect at a pressure of 1,814 psig is 14 ft-lb. This indicates that the toughness of the material adjacent to the bondline where the defect exists is less than that of the parent material (52 ft-lb). This is not surprising for the bondline region for a low-frequency-welded ERW seam.

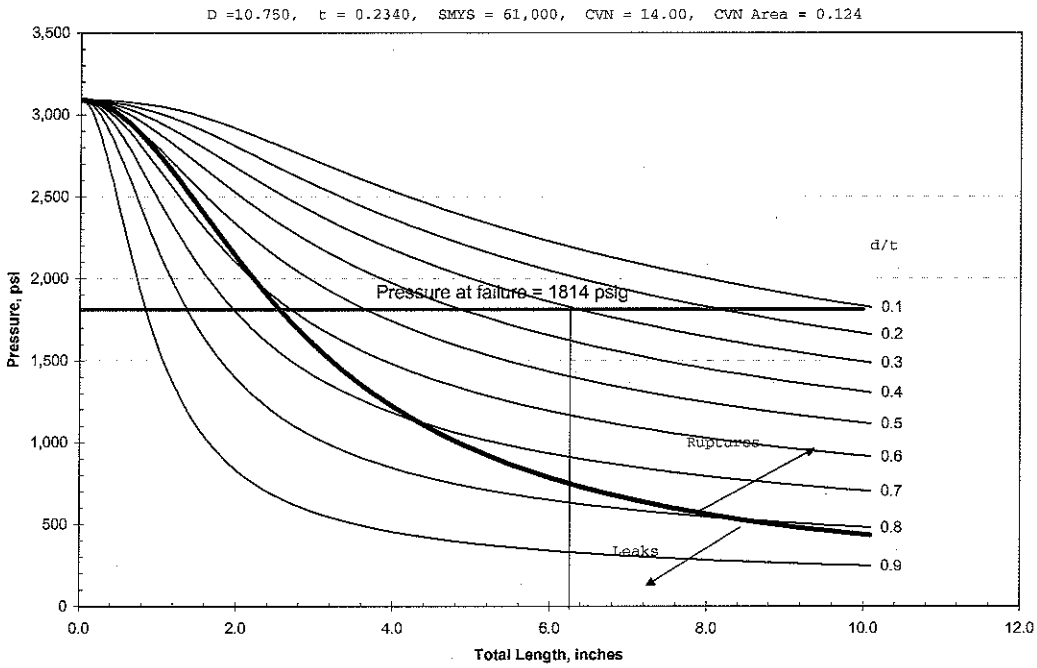


Figure 19. Charpy energy for Sample 10D inferred from the actual defect.

Sample 12A

This test break occurred at MP 579.01. The break occurred at a pressure level of 1,966 psig corresponding to a hoop stress level of 96.4 percent of SMYS. The split in the seam of this sample was about 6 feet in length.

The fracture surfaces at the origin are shown in Figure 20. The fracture surfaces are shown with OD pipe surfaces back-to-back. The initiating defect was a "cold weld", a lack of bonding of the edges of the skelp resulting from unclean bonding surfaces, inadequate mechanical force being applied, inadequate heating of the edges, or some combination of these circumstances during welding. Sometimes a split along the bondline of a low-frequency-welded ERW seam will exhibit a repetitive pattern called "stitching" on the fracture surface where bonding actually occurred (i.e., where there is no cold weld). For whatever reason no stitch marks were visible on the fracture surface of this break. Nevertheless, the fracture started at an intermittent cold-weld defect of indistinct dimensions (i.e., fragments of fractured and corroded surfaces are interspersed with the non-bonded regions). Because of the uncertainty of the boundaries of the initiating defect, no attempt was made to analyze the effective toughness. The

total area of cold weld is relatively small, however, so it is safe to assume that the bondline material is not nearly as tough as the parent metal. In any case the defect is clearly a manufacturing defect, and there is no evidence of any in-service crack growth associated with it.

A metallographic section across the probable origin of the test break was cut at the 5.4-inch mark on scale shown in Figure 20. This section is shown at two different magnifications in Figure 21 and Figure 22. As seen in these figures the cold weld corresponds to the smooth areas along the bondline.

The parent metal exhibited a yield strength of 63,000 psi and a Charpy V-notch upper-shelf energy of 54 ft-lb (full-size specimen equivalent). The wall thicknesses measured on both sides of the seam in the parent metal were 0.255 inch and 0.255 inch.

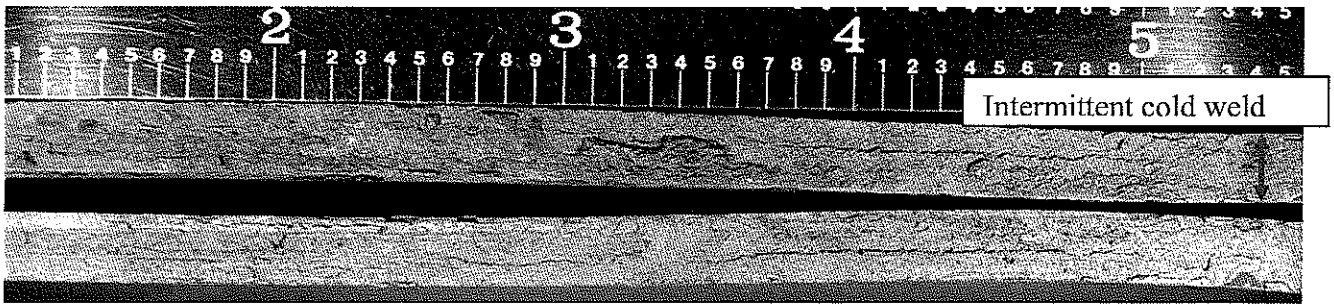


Figure 20. Initiating defect, Sample 12A (OD surfaces of pipe back-to-back).

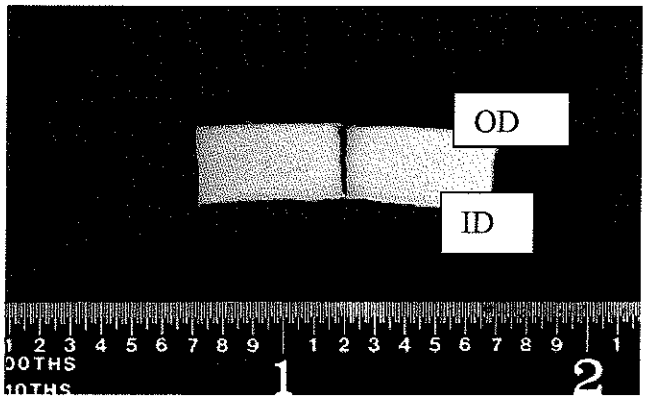


Figure 21. Metallographic section at probable origin, Sample 12A (1.5X).

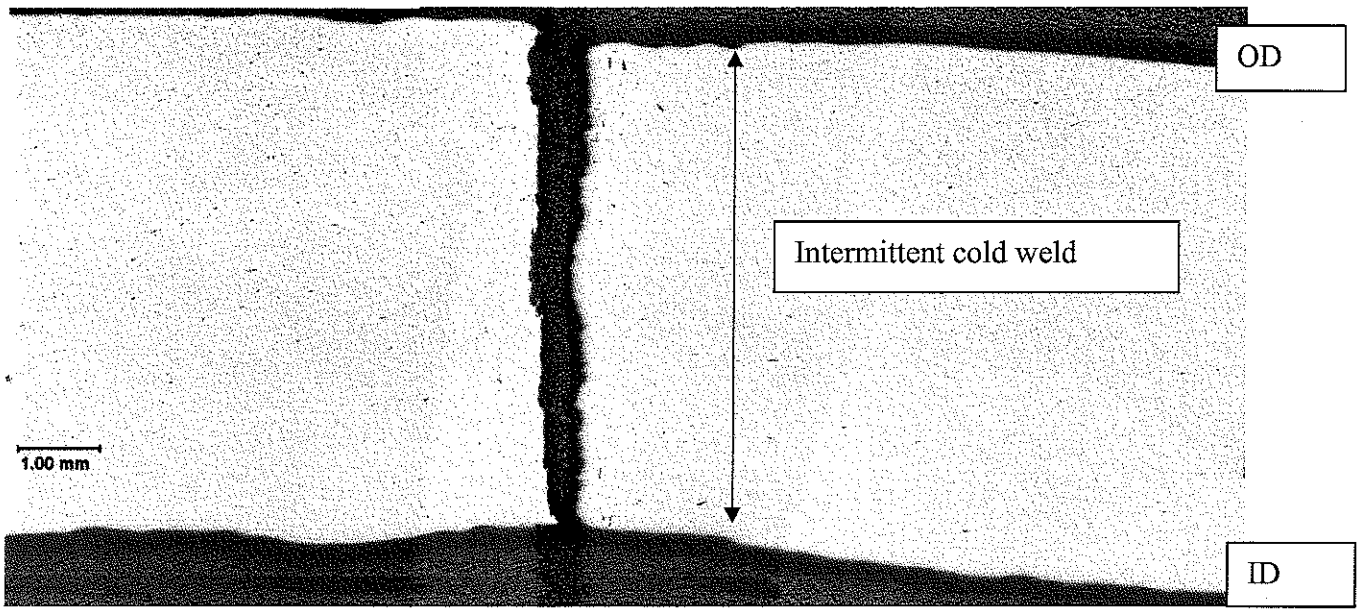


Figure 22. Metallographic section at probable origin, Sample 12A (10X).

Sample 12B

This test break occurred at MP 584.34. The break occurred at a pressure level of 1,932 psig corresponding to a hoop stress level of 94.7 percent of SMYS. The split in the seam of this sample was just over 5 feet in length. That turned out to be helpful since the initiating defect was not readily apparent.

The fracture surfaces at the probable origin are shown in Figure 23. The fracture surfaces are shown with OD pipe surfaces back-to-back. The "woody" appearance of the surface is characteristic of an ERW heat-affected zone where numerous non-metallic inclusions are present. This appearance suggests that the fracture jumped from one band of inclusions to another. As is often the case when the fracture has this appearance, there is no obvious "origin" defect. A location for a metallographic section was arbitrarily selected at the 3.5-inch mark on Figure 23 because similar conditions prevail over a length of more than 6 inches.

The chosen metallographic section is shown at two different magnifications in Figure 24 and Figure 25. This section reveals mismatched skelp edges. The edge on the right was higher than the edge on the left at the point where they came together. As is usually the case when the situation exists, the high-side edge tends to get forced up and over the low-side edge at the instant of bonding. The resulting bondline is oriented, as seen in Figure 25, at an appreciable angle to the surfaces of the pipe. The mismatch reduced the effective thickness by around 10

percent. The reduced section in conjunction with the numerous inclusions adjacent to the bondline appears to have resulted in a plane of relative weakness along the slanting bondline, which it is where it failed. The cause of the break is a manufacturing defect. No evidence of in-service crack growth was found. Because of the uncertainty of the boundaries of the initiating defect, no attempt was made to analyze the effective toughness.

The parent metal exhibited a yield strength of 63,500 psi and a Charpy V-notch upper-shelf energy of 55 ft-lb (full-size specimen equivalent). The wall thicknesses measured in the parent metal was 0.252 inch, but because of the mismatch, the net thickness immediately adjacent to the seam on one side ranged from 0.223 inch to 0.230 inch, about 9 to 11 percent less than the parent metal thickness.

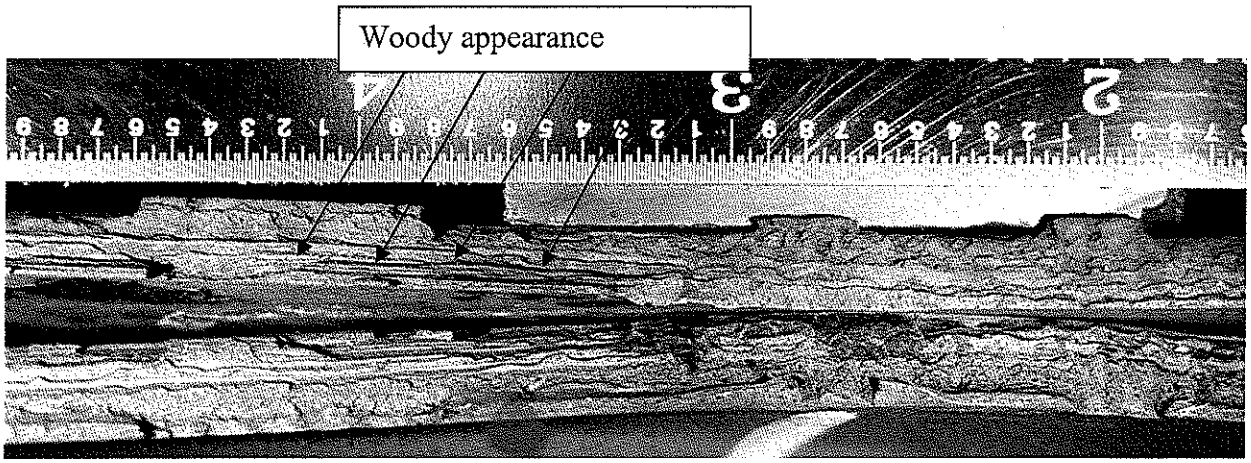


Figure 23. Region where fracture initiated in Sample 12B (OD surfaces of pipe back-to-back).

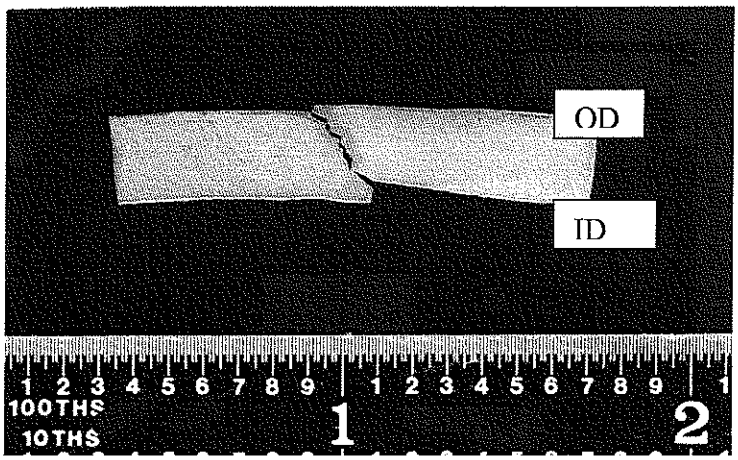


Figure 24. Metallographic section at probable origin, Sample 12B (2X).

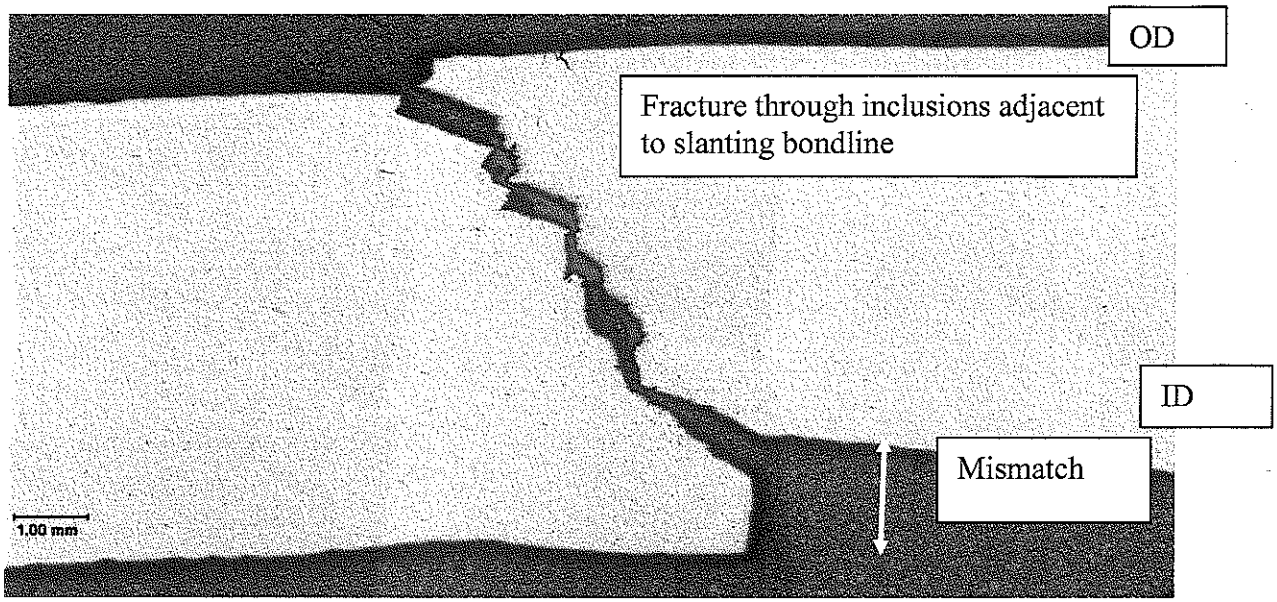


Figure 25. Metallographic section at probable origin, Sample 12B (10X).

Sample 12C

This test break occurred at MP 586.43. The break occurred at a pressure level of 1,860 psig corresponding to a hoop stress level of 91.2 percent of SMYS. The split in the seam of this sample was just over 9 feet in length.

The fracture surfaces at the probable origin are shown in Figure 26. The fracture surfaces are shown with OD pipe surfaces back-to-back. The "stitch" pattern is often a visual characteristic of fracture along the bondline of a low-frequency-welded ERW seam. The periodic variation in fracture surface appearance reflects probable variations in bondline quality and toughness. The variations arise from the fluctuations of welding heat corresponding to the sine-wave electric-power-versus-time function associated with commercial ac power. Such a condition suggests that the welding was taking place at a too-high travel speed. The stitched appearance suggests that the fracture resulted from low ductility of the bondline material. As is often the case when the fracture has this appearance, there is no obvious "origin" defect. A location for a metallographic section was arbitrarily selected at the 3-inch mark on Figure 26 because similar conditions prevail over the whole length of the fracture.

The chosen metallographic section is shown at two different magnifications in Figure 27 and Figure 28. This section reveals that the fracture lies almost entirely along the bondline. The

cause of the break is low bondline ductility associated with a stitched weld, a manufacturing defect. No evidence of in-service crack growth was found. Because of the uncertainty of the boundaries of the initiating defect, no attempt was made to analyze the effective toughness.

The parent metal exhibited a yield strength of 63,500 psi and a Charpy V-notch upper-shelf energy of 44 ft-lb (full-size specimen equivalent). The wall thicknesses measured on both sides of the seam in the parent metal were 0.250 inch and 0.254 inch.

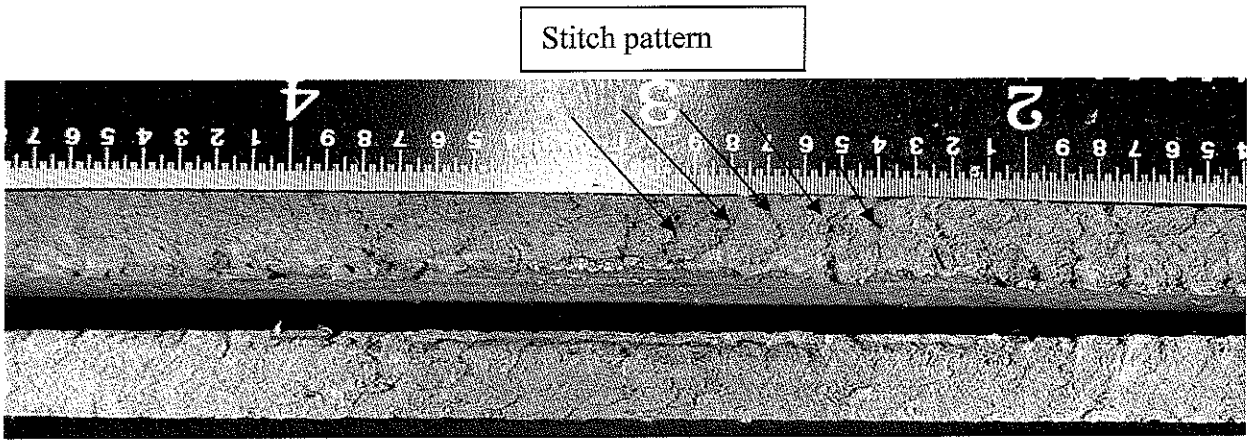


Figure 26. Region where fracture initiated in Sample 12C (OD surfaces of pipe back-to-back).

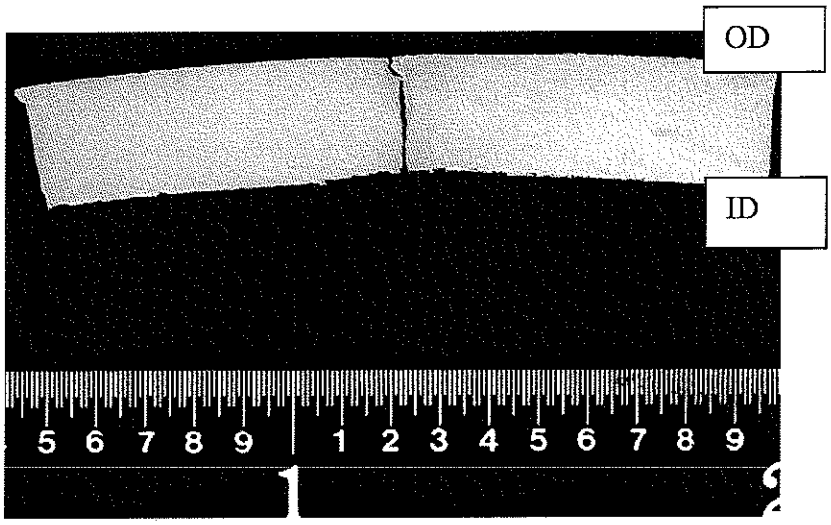


Figure 27. Metallographic section at probable origin, Sample 12C (2.5X).

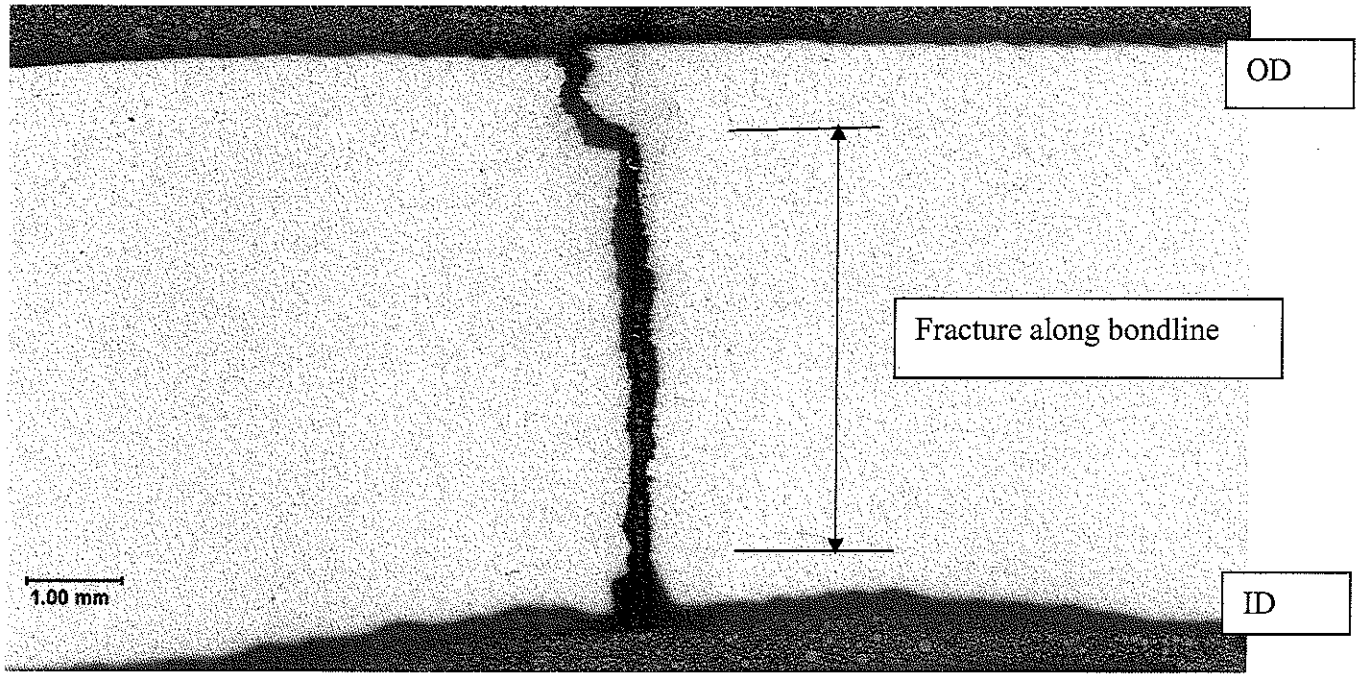


Figure 28. Metallographic section at probable origin, Sample 12C (12X).

Sample 12D

This test break occurred at MP 589.28. The break occurred at a pressure level of 1,917 psig corresponding to a hoop stress level of 94.0 percent of SMYS. The split in the seam of this sample was just over 5 feet in length.

The fracture surfaces at the probable origin are shown in Figure 29. The fracture surfaces are shown with OD pipe surfaces back-to-back. The initiating defect is a hook crack. A location for a metallographic section was arbitrarily selected at the 3.3-inch mark on Figure 29.

The chosen metallographic section is shown at two different magnifications in Figure 30 and Figure 31. This section reveals the smooth surface of the initiating hook crack that lies adjacent to the bondline. The hook crack is a manufacturing defect. No evidence of in-service crack growth was found.

The parent metal exhibited a yield strength of 64,000 psi and a Charpy V-notch upper-shelf energy of 44 ft-lb (full-size specimen equivalent). The wall thicknesses measured on both sides of the seam in the parent metal were 0.248 inch and 0.254 inch.

Because of the varying depth of the hook crack, an analysis of this test break was carried out based on the assumption that the defect had a semi-elliptical profile. As seen in Figure 32 below, the inferred Charpy energy that is consistent with the failure of the 7-inch-long, 30-

percent-through maximum-depth defect at a pressure of 1,917 psig is 15 ft-lb. This indicates that the toughness of the material adjacent to the bondline where the defect exists is less than that of the parent material (44 ft-lb). This is not surprising for the bondline region for a low-frequency-welded ERW seam.

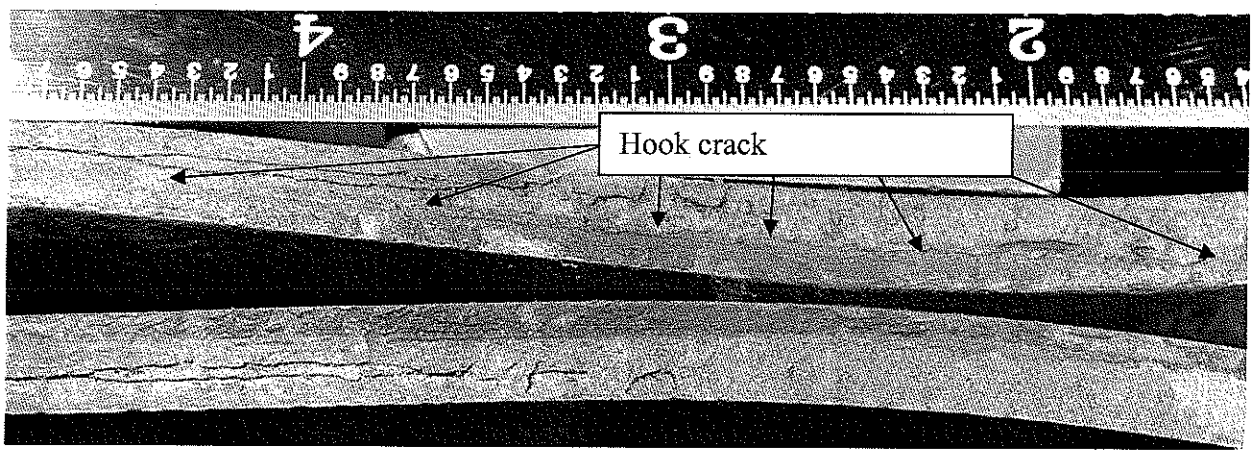


Figure 29. Initiating defect, Sample 12D (OD surfaces of pipe back-to-back).

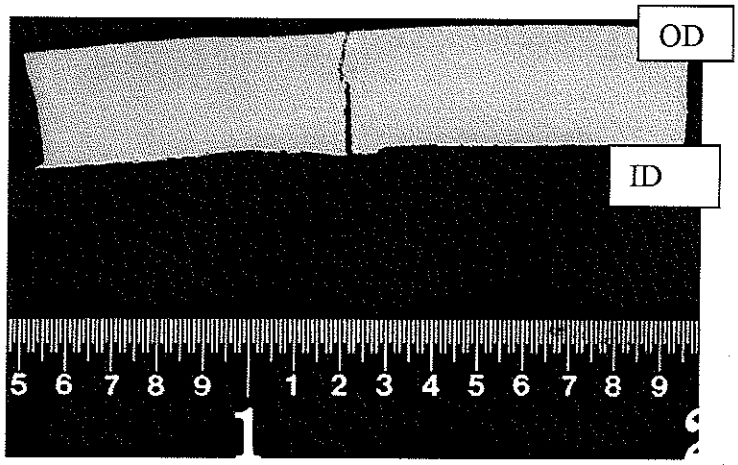


Figure 30. Metallographic section at origin region, Sample 12D (2X).

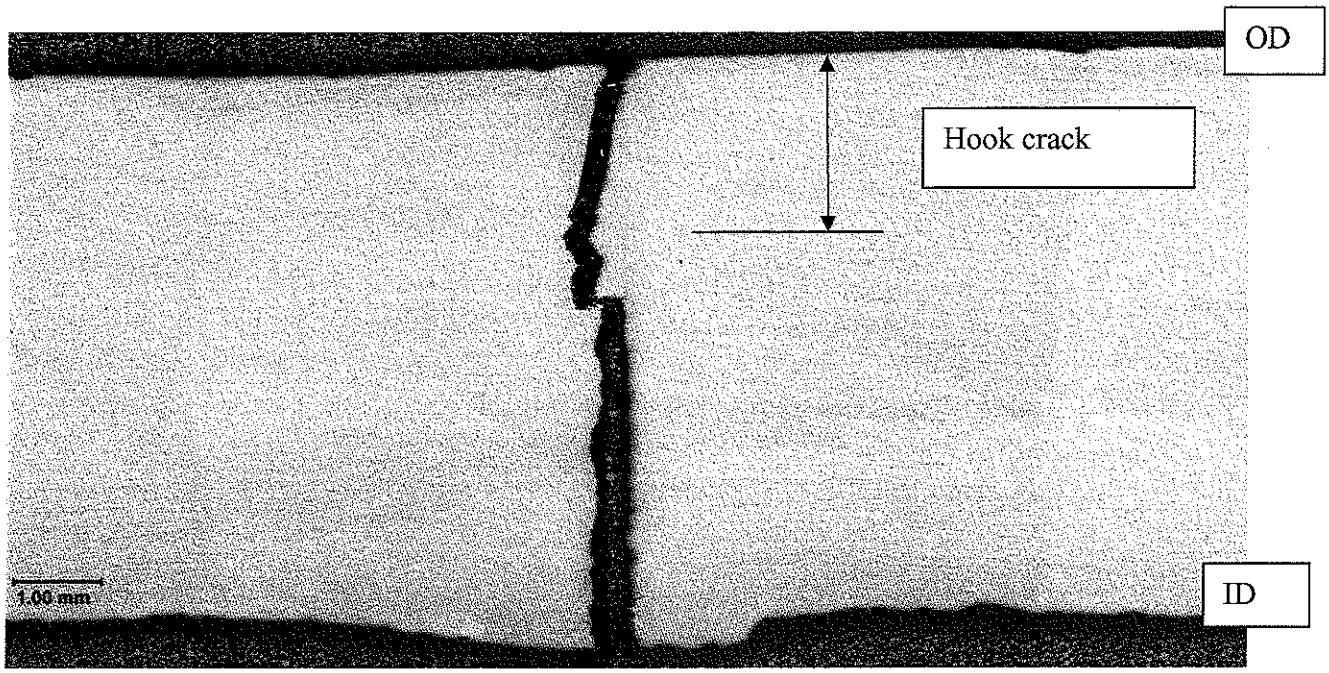


Figure 31. Metallographic section at origin region, Sample 12D (12X).

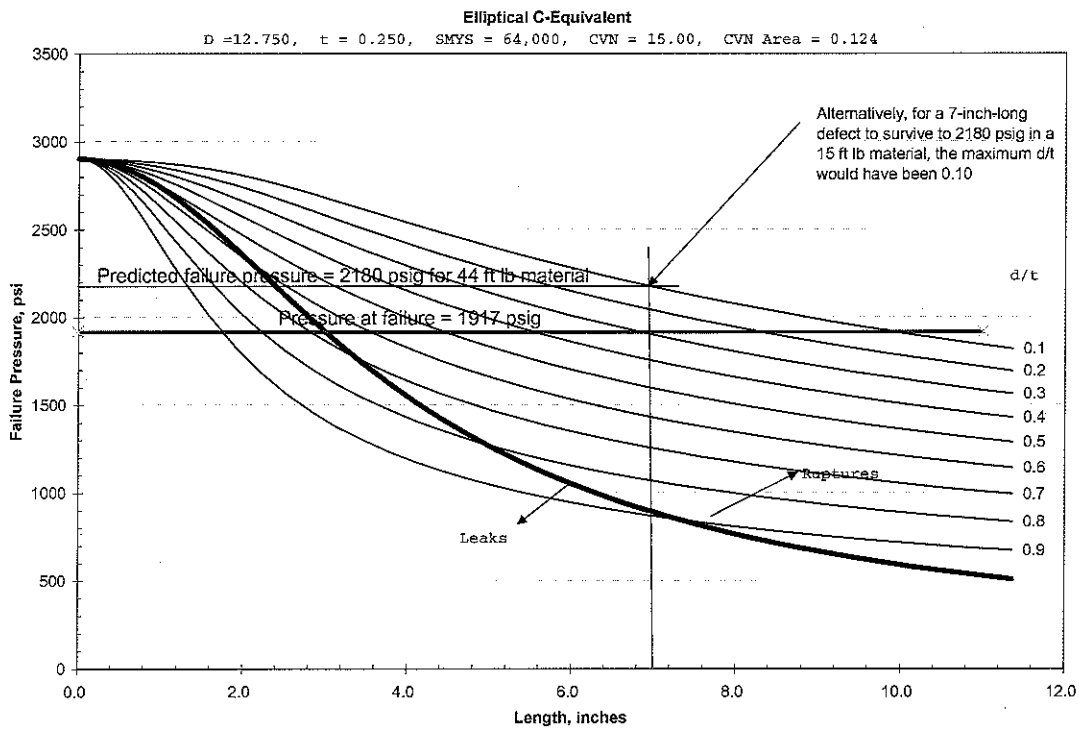


Figure 32. Charpy energy for Sample 12D inferred from the actual defect.

Sample 12E

This test break occurred at MP 611.88. The break occurred at a pressure level of 1,848 psig corresponding to a hoop stress level of 90.6 percent of SMYS. The split in the seam of this sample was just over 4 feet in length.

The fracture surfaces in the region of the origin are shown in Figure 33. The fracture surfaces are shown with OD pipe surfaces back-to-back. The actual initiating defect could be either low-ductility region denoted by the stitch pattern or the region of short OD and ID hook cracks, or a combination of both. To assess both of these features, two metallographic sections were removed, one at the 1.5-inch mark and one at the 5.1-inch mark on the scale. The metallographic section through the stitched area is shown at two different magnifications in Figure 34 and Figure 35. This section reveals that the fracture lies almost entirely along the bondline, an area low ductility. The metallographic section through the hook cracks is shown at two magnifications in Figure 36 and Figure 37. This section reveals an OD hook crack with a depth of less than 10 percent of the wall thickness and an ID hook crack with a depth of less than 25 percent of the wall thickness. Regardless of whether the stitching, the hook cracks, or a combination of the two caused the failure, the failure was the result of manufacturing defects. No evidence of in-service crack growth was found. Because of the uncertainty of the boundaries of the initiating defect, no attempt was made to analyze the effective toughness.

The parent metal exhibited a yield strength of 61,000 psi and a Charpy V-notch upper-shelf energy of 52 ft-lb (full-size specimen equivalent). The wall thicknesses measured on both sides of the seam in the parent metal were 0.249 inch and 0.251 inch.

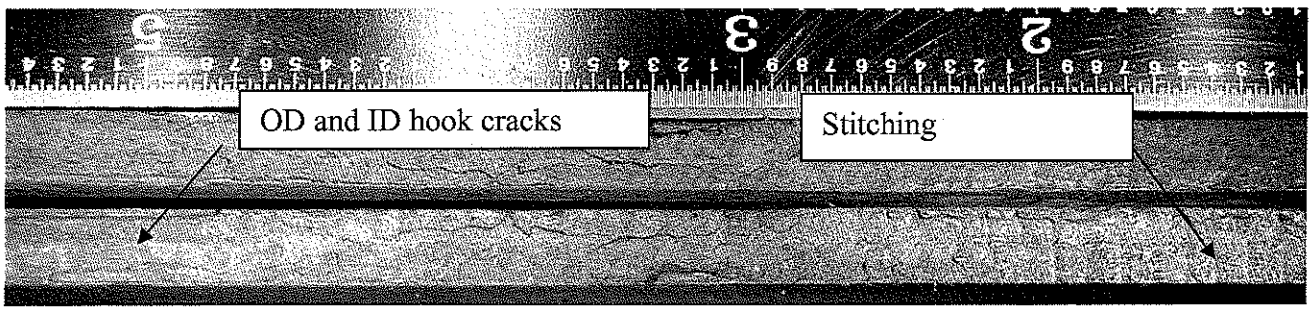


Figure 33. Region where fracture initiated in Sample 12E (OD surfaces of pipe back-to-back).

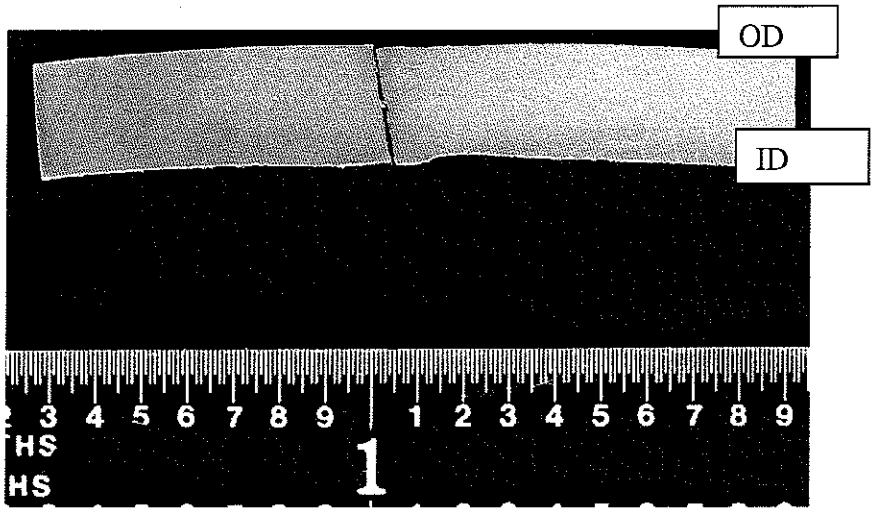


Figure 34. Metallographic section at possible origin, Sample 12E (2.5X).

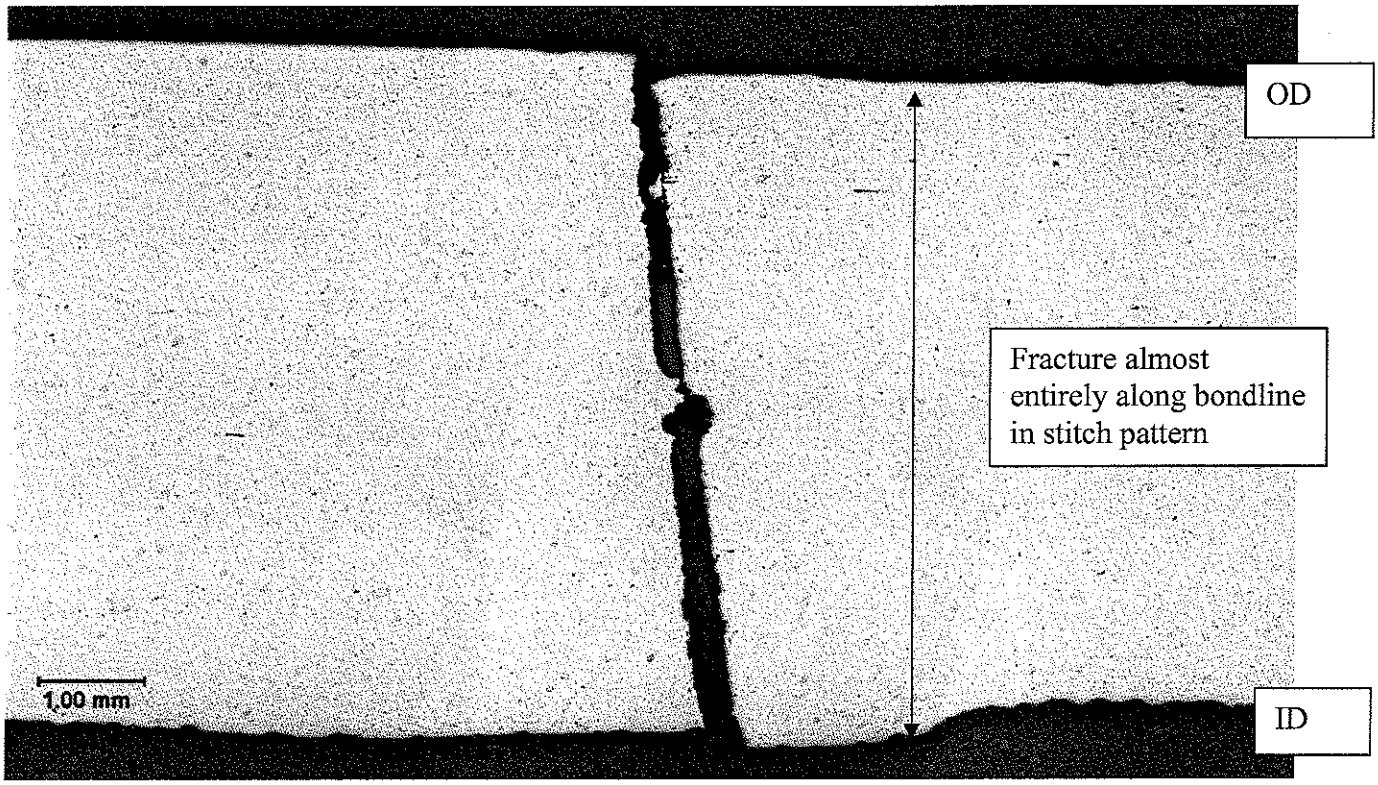


Figure 35. Metallographic section at probable origin, Sample 12E (15X).

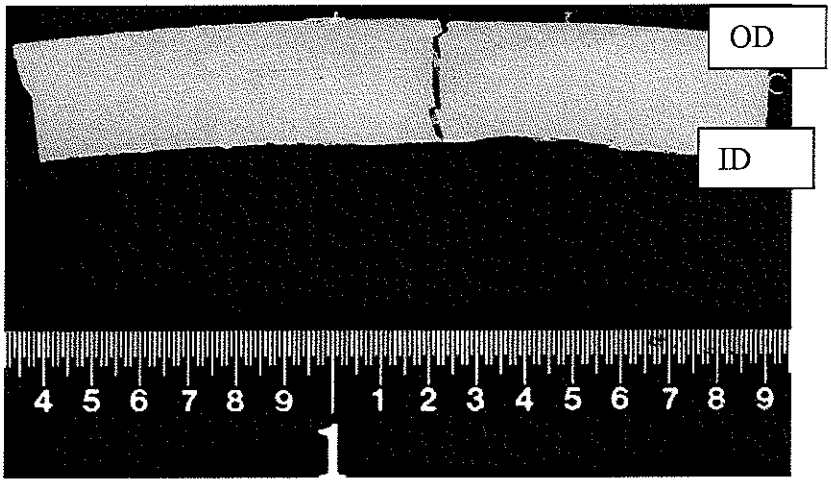


Figure 36. Metallographic section at possible origin, Sample 12E (2.5X).

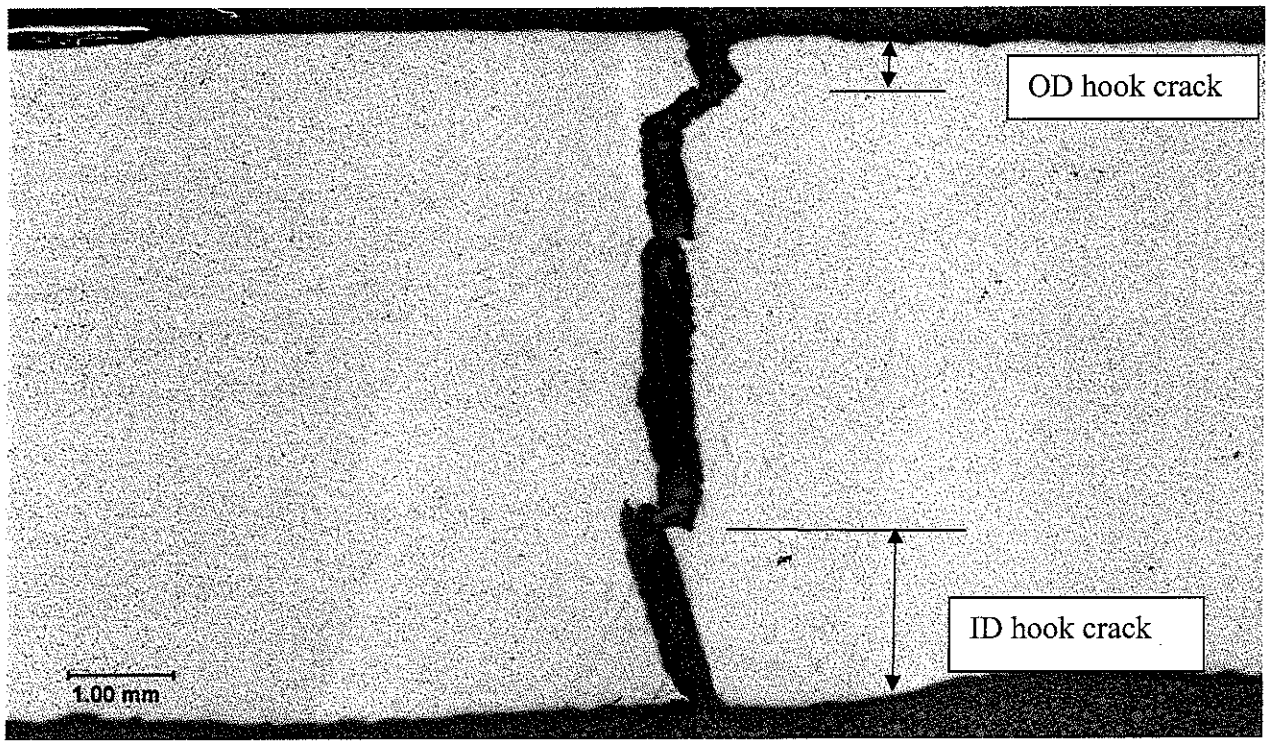


Figure 37. Metallographic section at possible origin, Sample 12E (15X).

Sample 12F

This test break occurred at MP 625.3. The break occurred at a pressure level of 1,825 psig corresponding to a hoop stress level of 89.5 percent of SMYS. The split in the seam of this sample was just over 12 feet in length.

The fracture surfaces at the probable origin are shown in Figure 38. The fracture surfaces are shown with OD pipe surfaces back-to-back. In the absence of an obvious defect and the presence of a stitch pattern, one can reasonably assume that this test break was the result of the low ductility of the bondline region of the material. As is often the case when the fracture has this appearance, there is no obvious "origin" defect. A location for a metallographic section was arbitrarily selected at the 4-inch mark on Figure 38 because the configuration of the fracture edges suggests that this is probably about the point of initiation.

The chosen metallographic section is shown at two different magnifications in Figure 39 and Figure 40. This section reveals that the fracture lies entirely along the bondline. The cause of the break is low bondline ductility associated with a stitched weld, a manufacturing defect. No evidence of in-service crack growth was found. Because of the uncertainty of the boundaries of the initiating defect, no attempt was made to analyze the effective toughness.

The parent metal exhibited a yield strength of 66,500 psi and a Charpy V-notch upper-shelf energy of 46 ft-lb (full-size specimen equivalent). The wall thicknesses measured on both sides of the seam in the parent metal were 0.253 inch and 0.253 inch.

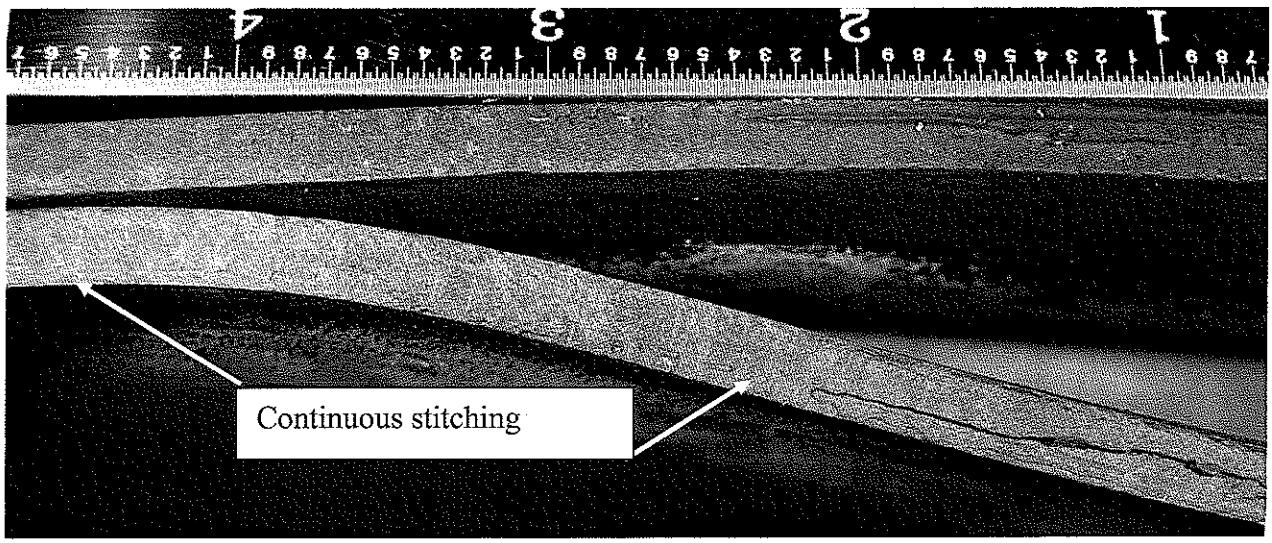


Figure 38. Region where fracture initiated in Sample 12F (OD surfaces of pipe back-to-back).

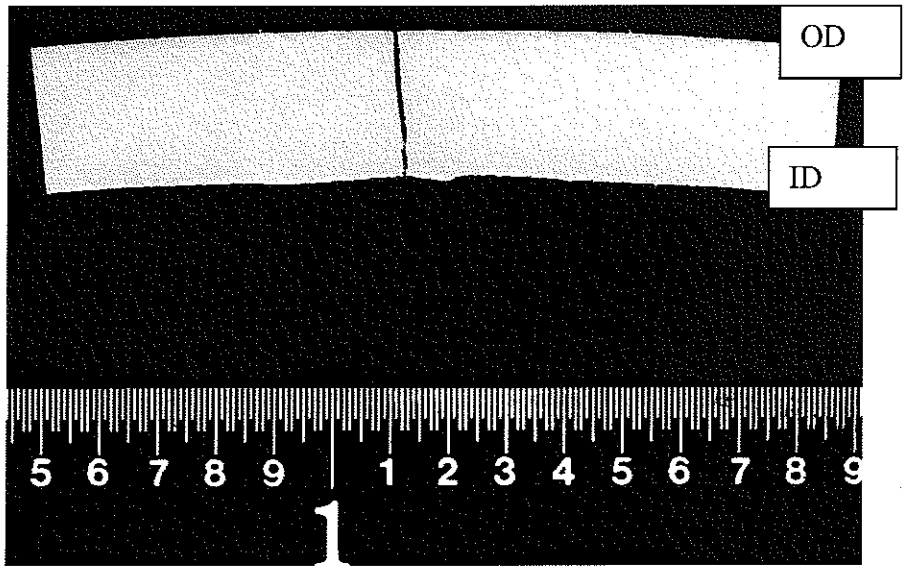


Figure 39. Metallographic section at probable origin, Sample 12F (3X).

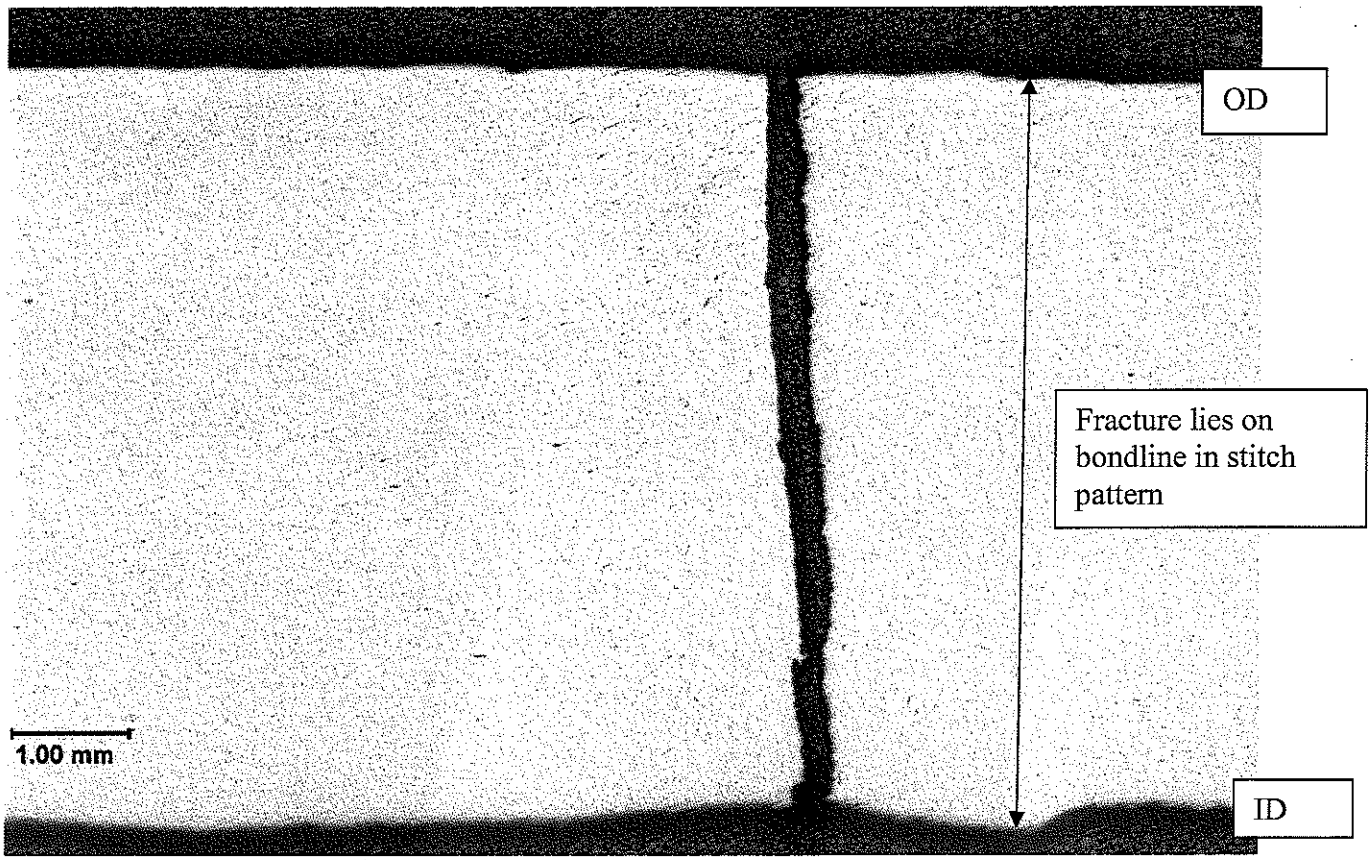


Figure 40. Metallographic section at probable origin, Sample 12F (17X).

Sample 12G

This test break occurred at MP 526.28. The break occurred at a pressure level of 1,832 psig corresponding to a hoop stress level of 89.8 percent of SMYS. The split in the seam of this sample was about 4 feet in length.

The fracture surfaces at the probable origin are shown in Figure 41. The fracture surfaces are shown with OD pipe surfaces back-to-back. The initiating defect corresponds to the smooth flat surface denoted by arrows in Figure 41. This defect was initially thought to be an ID hook crack. It extends over an axial distance of 10 inches, and its depth varies between 30 and 42 percent of the wall thickness. A location for a metallographic section was arbitrarily selected at the 3.3-inch mark on Figure 41.

The metallographic section is shown at two different magnifications in Figure 42 and Figure 43. As seen in these figures, the defect extends from the ID surface to a depth of about 42 percent of the actual thickness including the ID flash. It has a length of 10 inches. This defect does not lie on a J-shaped curved plane as one would expect in the case of a hook crack. It does not lie on the bondline either. It is a large defect, however, and that means that the material in which it was embedded exhibited relatively high resistance to fracturing. The defect appears to be an unbonded seam in the material. How it got there is not clear, but it is believed to be some type of a manufacturing defect. There is no evidence of any in-service crack growth associated with it.

The parent metal exhibited a yield strength of 64,500 psi and a Charpy V-notch upper-shelf energy of 54 ft-lb (full-size specimen equivalent). The wall thicknesses measured on both sides of the seam in the parent metal were 0.250 inch and 0.252 inch.

An analysis was carried out to see what defect depth would be predicted for a 10-inch-long defect that would fail at a pressure of 1,832 psig in a material with a Charpy energy of 54 ft-lb. As seen in Figure 44 below, a depth-to-thickness ratio of 0.39 is predicted. The actual length of the defect is 12 inches, and the actual maximum depth-to-thickness ratio was 0.42, so the material appeared to exhibit a toughness at least as high as that of the parent metal even though the location of the material is practically on the bondline of the seam. This is unusual for a low-frequency-welded ERW line pipe material, but clearly a large defect existed, and it had a high failure pressure. This could only happen if the effective toughness of the material was relatively high.

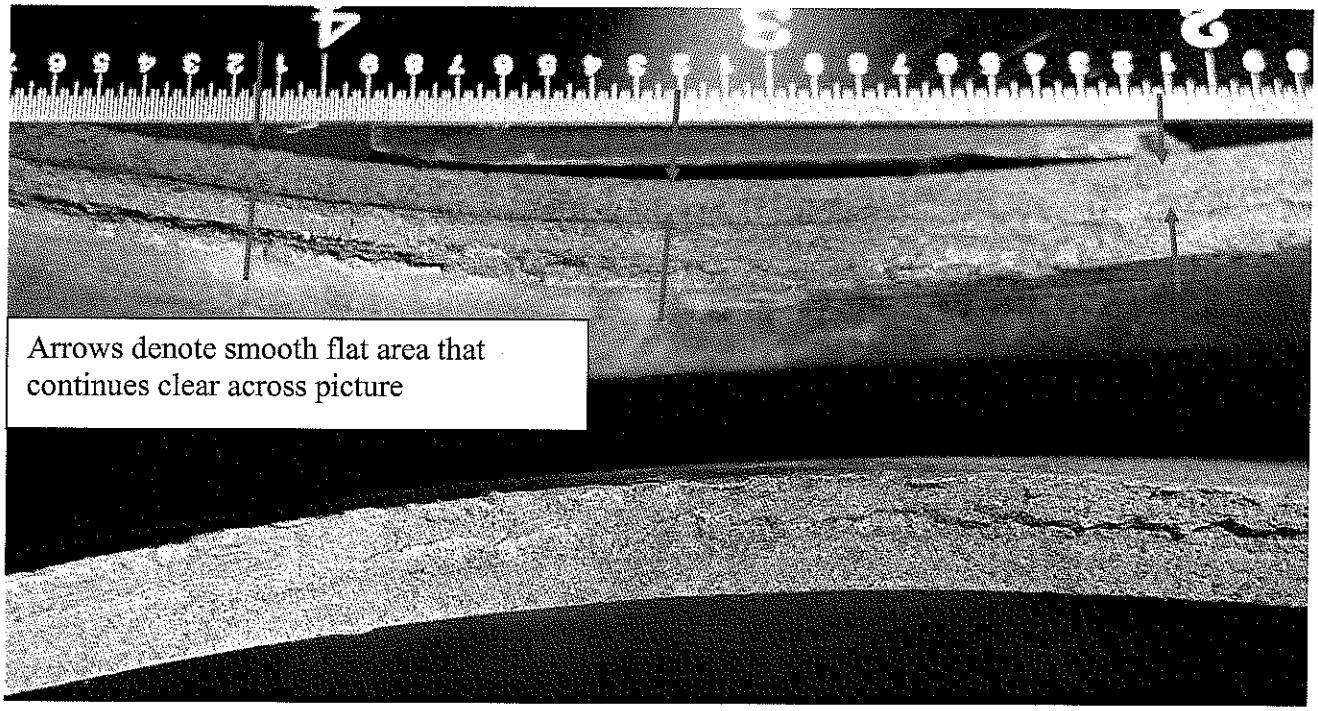


Figure 41. Initiating defect, Sample 12G (OD surfaces of pipe back-to-back).

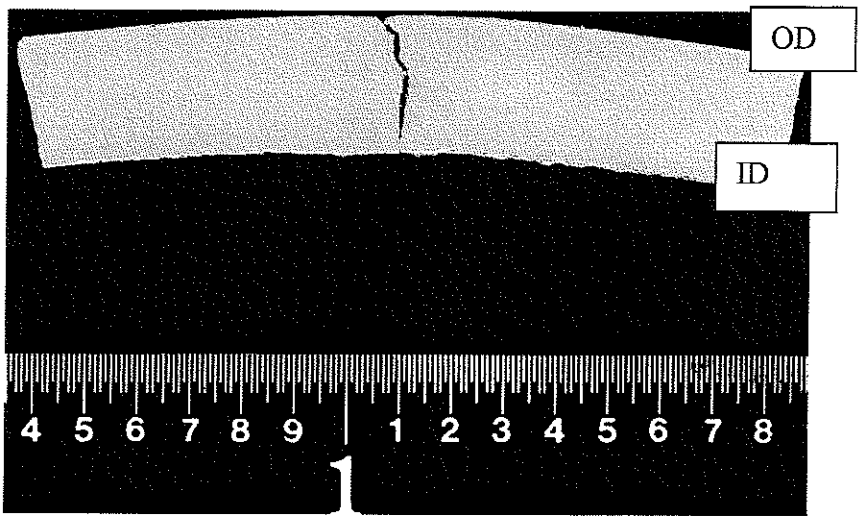


Figure 42. Metallographic section at origin region, Sample 12G (2.7X).

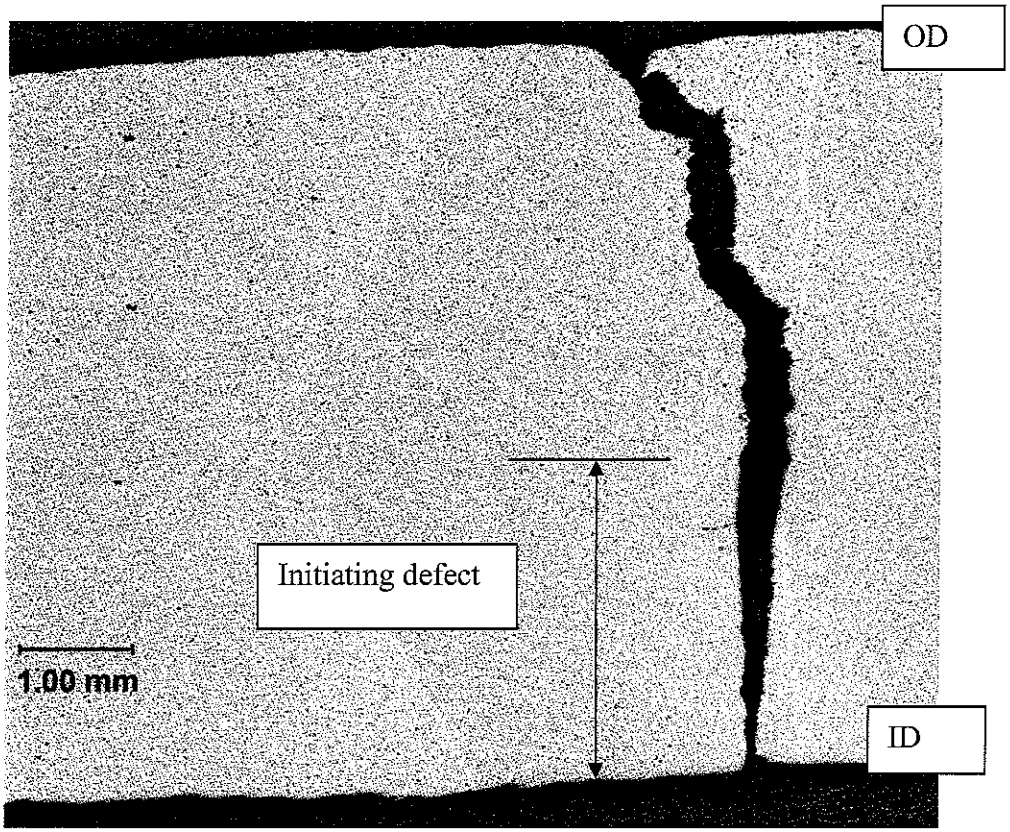


Figure 43. Metallographic section at origin region, Sample 12G (15X).

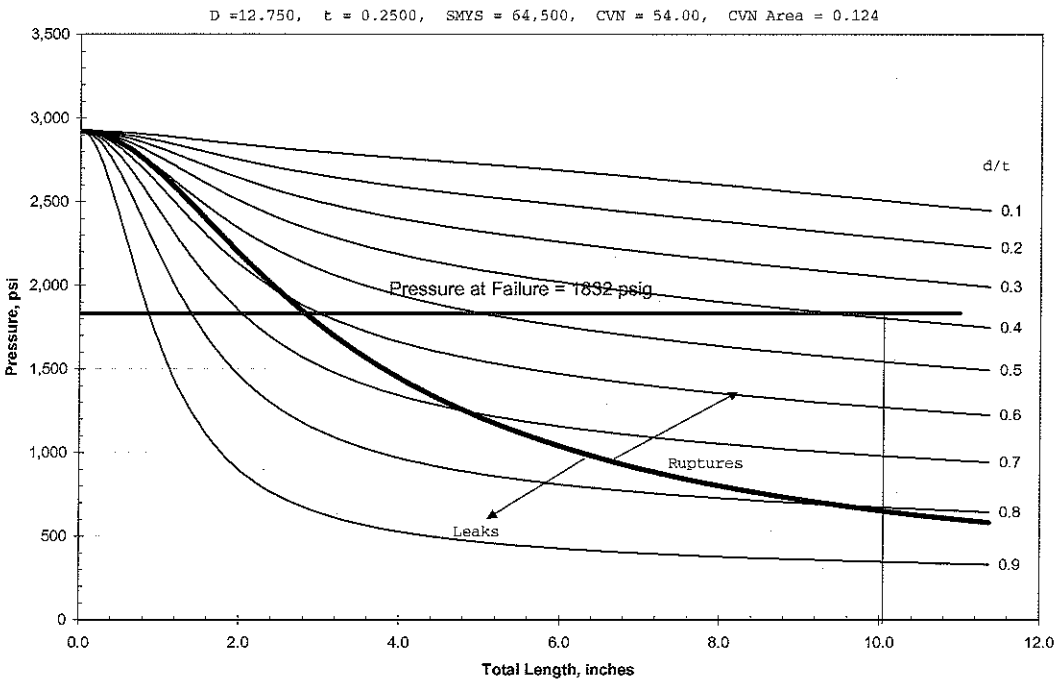


Figure 44. Inferred defect size based on Sample 12G, Charpy energy of 54 ft-lb.

Sample 12H

This test break occurred at MP 528.05. The break occurred at a pressure level of 1,891 psig corresponding to a hoop stress level of 92.8 percent of SMYS. The split in the seam of this sample was about 6 feet in length.

The fracture surfaces at the probable origin are shown in Figure 45. The fracture surfaces are shown with OD pipe surfaces back-to-back. The initiating defect corresponds to the dark-colored surface denoted by arrows in Figure 45. This defect was confirmed to consist of three cascading hook cracks. The defect extends over an axial distance of 3 inches, and its maximum depth is 45 percent of the wall thickness. A location for a metallographic section was arbitrarily selected at the 2.6-inch mark on Figure 45.

The metallographic section is shown at two different magnifications in Figure 46 and Figure 47. As seen in these figures, the defect extends in three steps from the OD surface to a depth of about 45 percent of the actual thickness including the ID flash. It is a cascade of three hook cracks on different planes. Clearly, this is a manufacturing defect. There is no evidence of any in-service crack growth associated with it.

The parent metal exhibited a yield strength of 64,500 psi and a Charpy V-notch upper-shelf energy of 48 ft-lb (full-size specimen equivalent). The wall thicknesses measured on both sides of the seam in the parent metal were 0.250 inch and 0.249 inch.

Because of the varying depth of the defect, an analysis of this test break was carried based on the assumption that the defect has a semi-elliptical profile. As seen in Figure 48 below, the inferred Charpy energy that is consistent with the failure of the 3-inch-long, 45-percent-through maximum-depth defect at a pressure of 1,891 psig is 6 ft-lb. This indicates that the toughness of the material adjacent to the bondline where the defect exists is less than that of the parent material (48 ft-lb). This is not surprising for the bondline region for a low-frequency-welded ERW seam.

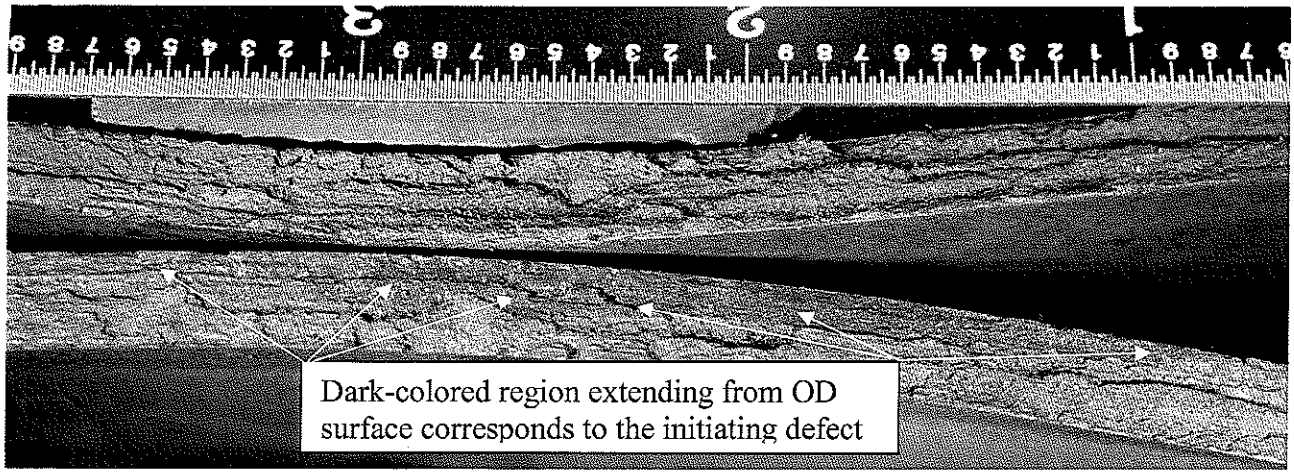


Figure 45. Initiating defect, Sample 12H (OD surfaces of pipe back-to-back).

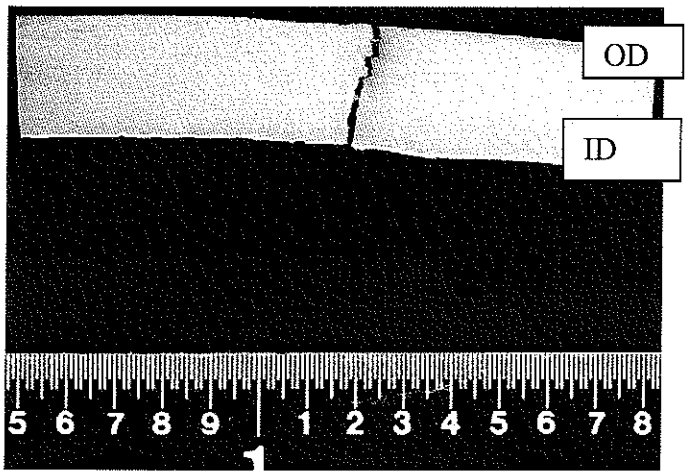


Figure 46. Metallographic section at origin region, Sample 12H (2.5X).

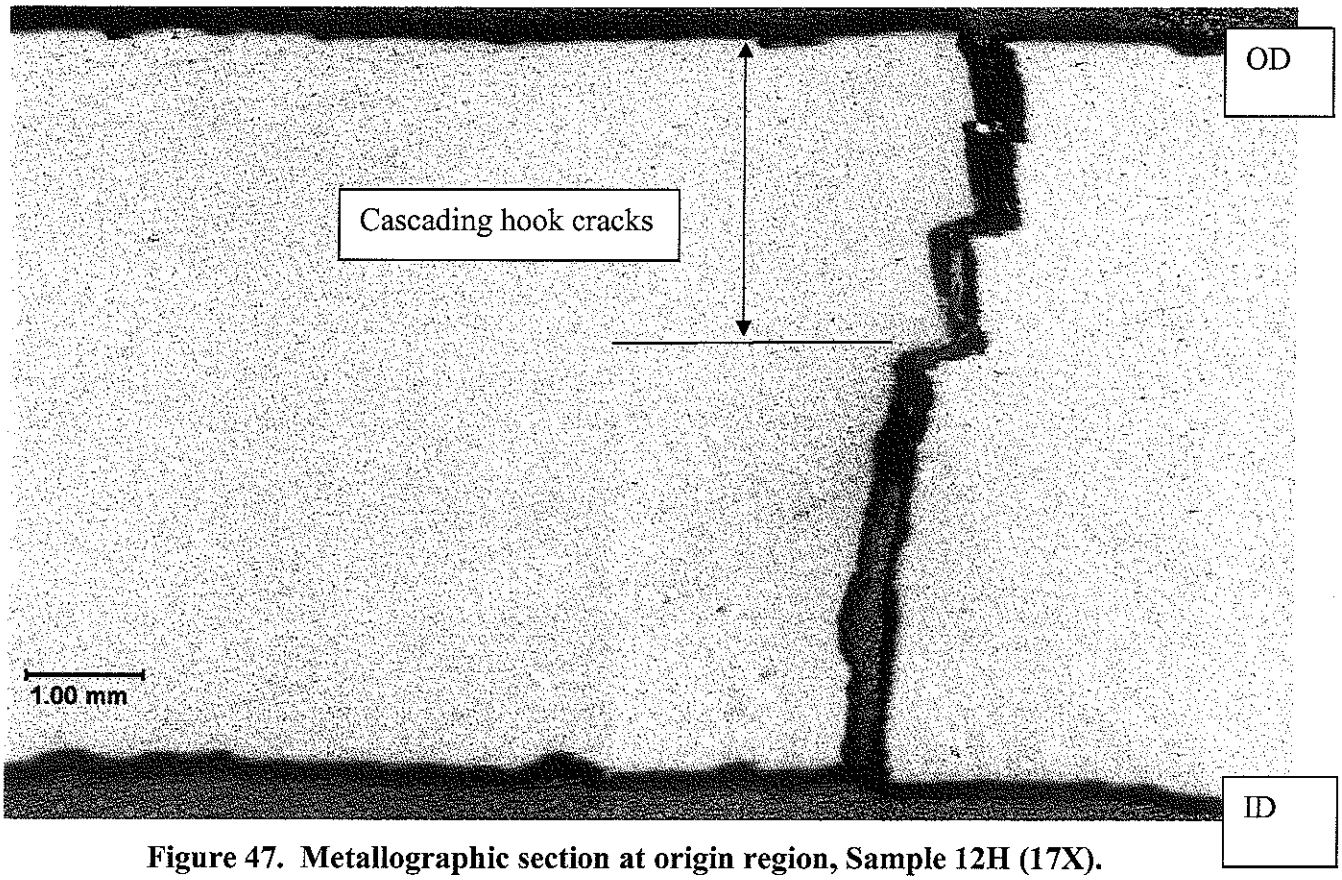


Figure 47. Metallographic section at origin region, Sample 12H (17X).

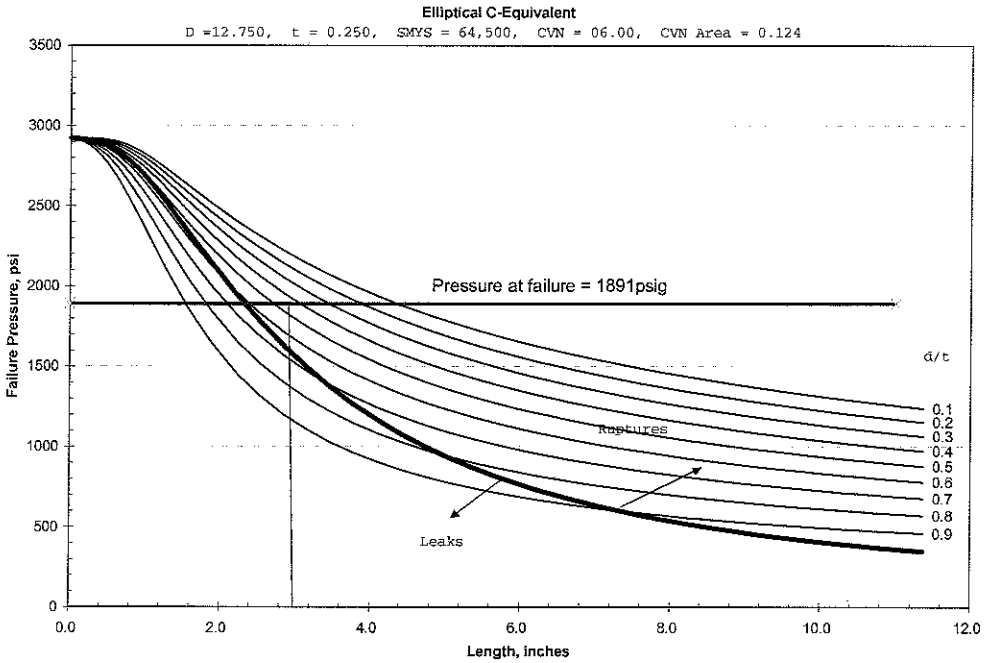


Figure 48. Inferred Charpy energy for Sample 12H.

MATERIAL PROPERTIES OF THE PIPE

Material-property coupons from the pipe segments were used to machine samples to measure longitudinal tensile properties, to measure transverse base metal Charpy V-notch impact toughness properties, and to conduct a chemical analysis of the pipes material. The tensile and chemical data for the pipes are tabulated in Tables 1 and 2 for 10-inch and 12-inch nominal diameter pipes, respectively. All materials met the requirements of the edition of API 5L that was in effect at the time the pipeline was installed, API Specification 5LX, 9th Edition, February 1960 for ERW, Electric Furnace Grade X52 Line Pipe.

The weldability of the pipe material is governed by its chemical composition as expressed by its carbon equivalent (CE). The CE of low carbon steel is currently estimated using the International Institute for Welding (IIW) equation for steel with carbon content greater than 0.12 percent

$$CE(IIW) = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Cu + Ni}{15}$$

where the symbols are abbreviations for the elements and the quantities are expressed in percent by weight listed in Tables 1 and 2 for 10-inch and 12-inch nominal diameter pipes, respectively.

Transverse Charpy V-notch impact tests were performed using specimens machined from flattened coupons to obtain specimens as thick as possible. The transverse impact data, which are summarized in Tables 3 and 4 for 10-inch and 12-inch nominal diameter pipes, respectively. In Tables 3 and 4 for 10-inch and 12-inch nominal diameter pipes, respectively, the reported upper-shelf energy is the impact energy at which the fracture behaviors are fully ductile. The full-size equivalent value in Row 3 is the upper-shelf energy in Row 2 multiplied by the ratio of the thickness of a standard full-size Charpy specimen, 0.394 inch, to the Charpy specimen size in Row 1. The CVN transition temperature, Row 4a, was established from the shear-area curve at 85-percent shear area. The full pipe wall thickness transition temperature was determined* by

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*Rosenfeld, M. J., "A Simple Procedure for Synthesizing Charpy Impact Energy Transition Curves from Limited Test Data", *ASME International Pipeline Conference*, Volume I, pp 215-221 (1996).

correcting for the difference in pipe wall thickness, 0.219 inch for 10-inch nominal diameter and 0.250 inch for 12-inch nominal diameter, relative to the thickness of the CVN specimen in Row 1 as follows

$$T_p = T_C + 66\frac{t_w^{0.55}}{t_c^{0.7}} - 100$$

where

T_p	=	Full-scale pipe transition temperature, Row 4b
T_C	=	The Charpy transition temperature at 85-percent shear area, Row 4a
t_w	=	Pipe nominal wall thickness, in this case 0.219 inch for 10-inch nominal diameter and 0.250 inch for 12-inch nominal diameter
t_c	=	Charpy specimen thickness, Row 1.

Within the samples of 10-inch pipe, it is seen that Sample 10B exhibits a shelf energy and a transition temperature that are both low relative to those of the other three samples. One reason for this may be that Sample 10B had a considerably higher sulfur content than the other samples of 10-inch pipe. Sulfur tends to have an adverse effect on shelf energy because it contributes to the formation of non-metallic inclusions. Sometimes this results in a lower transition temperature for the material (a beneficial effect) if the inclusions contribute to splits along planes parallel to the plate surfaces.

Within the samples of 12-inch pipe, it is seen that Sample 12D exhibits a transition temperature that is well below those of the other seven samples. Yet, it has about the same shelf energy as the others. In this case one explanation could be the fact that Sample 12D had a considerably higher manganese content than the other samples of 12-inch pipe. The increased manganese content of Sample 12D could have had a beneficial effect on the transition temperature of the material.

Table 1. Tensile and Chemical Properties for 10-Inch Nominal Diameter Pipe

Pipe Designation	10A	10B	10C	10D	Requirements by API Specification 5LX, 9th Edition, February 1960, for ERW, Electric Furnace Grade X52 Line Pipe
Tensile Tests					
Yield Strength, psi (at 0.5 percent total strain)	66,500	65,500	64,500	61,000	52,000
Ultimate Strength, psi	93,500	95,000	96,500	93,500	66,000
Elongation, percent (in a 2-inch gage length)	19.0	22.0	25.0	26.0	16.0 (for 10-inch nominal diameter pipe)
Chemical Analysis (percent by weight)					
Carbon	0.287	0.283	0.321	0.324	0.35max
Manganese	1.160	1.050	1.080	1.060	1.40 max
Phosphorus	0.011	0.010	0.008	0.008	0.05 max
Sulfur	0.013	0.023	0.015	0.012	0.06 max
Silicon	0.017	0.008	0.012	0.014	-
Copper	0.012	0.015	0.017	0.015	-
Tin	0.001	0.001	0.001	0.001	-
Nickel	0.008	0.008	0.008	0.008	-
Chromium	0.013	0.015	0.010	0.015	-
Molybdenum	0.011	0.006	0.007	0.007	-
Aluminum	0.005	0.010	0.009	0.005	-
Vanadium	0.002	0.002	0.002	0.003	-
Niobium	0.001	0.002	0.001	0.001	-
Titanium	0.002	0.002	0.002	0.002	-
Cobalt	0.006	0.007	0.006	0.007	-
Carbon Equivalent	0.487	0.464	0.506	0.507	-

Table 2. Tensile and Chemical Properties for 12-Inch Nominal Diameter Pipe

Pipe Designation	12A	12B	12C	12D	12E	12F	12G	12H	Requirements by API Specification 5LX, 9th Edition, February 1960, for ERW, Electric Furnace Grade X52 Line Pipe
Tensile Tests									
Yield Strength, psi (at 0.5 percent total strain)	63,000	63,500	63,500	64,000	61,000	66,500	64,500	64,500	52,000
Ultimate Strength, psi	85,000	90,500	87,500	88,500	84,000	95,500	89,500	89,000	66,000
Elongation, percent (in a 2-inch gage length)	29.0	27.0	27.0	26.0	28.0	25.0	28.0	27.0	18.0 (for 12-inch nominal diameter pipe)
Chemical Analysis (percent by weight)									
Carbon	0.271	0.275	0.269	0.301	0.270	0.278	0.304	0.270	0.35max
Manganese	1.140	1.150	1.150	1.380	1.190	1.150	1.210	1.130	1.40 max
Phosphorus	0.025	0.024	0.031	0.039	0.030	0.029	0.031	0.031	0.05 max
Sulfur	0.016	0.015	0.024	0.019	0.023	0.015	0.021	0.027	0.06 max
Silicon	0.033	0.039	0.039	0.030	0.048	0.037	0.038	0.050	-
Copper	0.370	0.397	0.507	0.400	0.402	0.407	0.418	0.432	-
Tin	0.010	0.011	0.020	0.014	0.022	0.012	0.017	0.018	-
Nickel	0.050	0.061	0.105	0.068	0.076	0.062	0.124	0.078	-
Chromium	0.020	0.028	0.038	0.030	0.028	0.028	0.036	0.035	-
Molybdenum	0.011	0.012	0.015	0.015	0.013	0.013	0.016	0.014	-
Aluminum	0.001	0.002	0.001	0.002	0.001	0.000	0.001	0.001	-
Vanadium	0.002	0.003	0.003	0.003	0.003	0.002	0.003	0.002	-
Niobium	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	-
Titanium	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	-
Cobalt	0.011	0.010	0.010	0.010	0.010	0.011	0.011	0.010	-
Carbon Equivalent	0.496	0.506	0.513	0.572	0.509	0.510	0.553	0.503	-

Table 3. Charpy V-Notch/Transition Temperature Data for 10-Inch Nominal Diameter Pipe

Pipe Segment	10A	10B	10C	10D
1. Charpy Specimen Thickness, inch	0.18	0.171	0.17	0.188
2. Upper-Shelf Energy, ft-lb	26	16.5	25	25
3. Full-Size Equivalent, ft-lb	56.9	38.0	57.9	52.4
4. Transition Temperature, °F				
a. CVN Specimen	128	23	95	85
b. Full Pipe Wall Thickness*	123	22	94	77

* Based on a wall thickness of 0.219 inch.

Table 4. Charpy V-Notch/Transition Temperature Data for 12-Inch Nominal Diameter Pipe

Pipe Segment	12A	12B	12C	12D	12E	12F	12G	12H
1. Charpy Specimen Thickness, inch	0.205	0.179	0.221	0.191	0.197	0.218	0.174	0.194
2. Upper-Shelf Energy, ft-lb	28	25	24.9	21.5	26	25.5	24	23.5
3. Full-Size Equivalent, ft-lb	53.8	55.0	44.4	44.4	52.0	46.1	54.3	47.7
4. Transition Temperature, °F								
a. CVN Specimen	78	130	67	-8	60	118	65	66
b. Full Pipe Wall Thickness*	71	133	56	-10	56	107	70	63

* Based on a wall thickness of 0.250 inch.