NBSIR 73-299

Examination of Failed Eight Inch Welded Steel Pipe Natural Gas Main, UGI Corp., Coopersburg, Pennsylvania

M. L. Picklesimer and T. R. Shives

Mechanical Properties Section
Metallurgy Division
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National Bureau of Standards
Washington, D. C. 20234

November, 1973

Failure Analysis Report

Prepared for
Office of Pipeline Safety
Department of Transportation
Washington, D. C. 20590

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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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FIGURES (Continued)

SUMMARY

The Office of Pipeline Safety, Department of Transportation, submitted a four foot length of eight inch diameter welded steel pipe natural gas main containing a crack in the weld to the NBS Mechanical Properties Section for examination. The apparent crack origin was located at about the 4:30 o'clock position, assuming the top of the pipe to be at twelve o'clock and the outside of the bend of the pipe as installed was at three o'clock. The crack had propagated about two-thirds of the way around the pipe circumference. Optical and scanning electron microscopy revealed the fracture to have been predominantly brittle in nature. There was lack of weld penetration around a large part of the weld circumference and the weld metal exhibited some porosity. These features are normal for steel pipe welded by the oxy-acetylene practice used at the time the weld was made. While these features of the weld helped to define the path of the fracture, they probably did not contribute to it. Examination of the fracture and comparison of its features with those of fractures produced in the laboratory indicated that failure was probably brought about as a result of a single event, impact loading from an external source.

Examination of Failed Eight Inch Welded Steel Pipe
Natural Gas Main, UGI Corp., Coopersburg, Pennsylvania

1. INTRODUCTION

1.1 Reference

Office of Pipeline Safety, Department of Transportation, Washington, D. C. This investigation was conducted at the request of Mr. Lance F. Heverly of OPS under order number DOT-AS-10041. The request was made on March 1, 1973.

1.2 Background Information

The information in this section was furnished by Mr. Lance F. Heverly of the Office of Pipeline Safety, Mr. John Flaherty of the Pennsylvania Public Utility Commission, and Tpr. George F. Umberger, Fire Marshall, Pennsylvania State Police, at a meeting at the National Bureau of Standards with M. L. Picklesimer of NBS on March 1, 1973.

On February 21, 1973 at 11:52 A.M., there was a natural gas explosion involving two duplex apartment buildings at 41-43 and 45-47 North Main Street in Coopersburg, Pennsylvania. The explosion resulted in the loss of life, personal injuries, and property damage. After the explosion, pressure testing of the eight inch diameter welded steel pipe natural gas main in North Main Street with air caused water to squirt from the ground, indicating the location of a leak which was found to be at a cracked weld. This crack is shown in figure 1 with the pipe still in place in the ditch after that part of the pipe containing the cracked weld had been uncovered. The photograph shown in figure 1 was reported to have been taken looking straight down on the pipe. (Photograph furnished by and used with permission of the Pennsylvania State Police.)

The pipeline had been installed in 1924 and was under 30 inches of soil consisting primarily of shale, on top of which was an eight inch layer of concrete. The welds in the line were assumed to have been made by the oxy-acetylene torch process, since arc welding was not used in the construction of gas distribution lines in Pennsylvania prior to 1929. Gas pressure in this area of the Coopersburg gas distribution system was maintained at 45 psig.

During the process of removing the cover material from the cracked part of the pipe, a water main was broken and the cracked weld in the gas pipe was submerged for more than three hours. After the water was removed from the ditch, the gas pipe was clamped around the crack with a rubber gasket. When pressure tested with air, water came out at the break. With the clamp left in place, a length of pipe containing the crack was cut by torch from the pipeline and removed for examination.

Prior to the explosion, blasting holes had been drilled in the vicinity of the gas main and blasting charges had been set off. The nearest blasting hole was 4 feet 10 inches from the gas main. The dynamite sticks used in the blasting charges were 2 inches by 16 inches and were inserted to a depth of 7 1/2 inches into the holes. A 2 1/2 pound charge was used in each hole. The last six charges were set off at 11:15 A.M. on February 21, 1973, which was 37 minutes before the explosion.

1.3 Part Submitted

A four foot length (approximately) of the eight inch diameter pipe which had been cut from the gas pipeline was submitted to the NBS Mechanical Properties Section for examination. The cracked weld was in the approximate center of the submitted length. The clamp and gasket were still in place (figure 2) when the pipe length was delivered to the Mechanical Properties Section on March 1, 1973 by Tpr. George F. Umberger.

2. PURPOSE

The Office of Pipeline Safety requested that NBS determine the following:

1) Whether there was a pre-existing crack.

2) Whether the crack initiated and propagated over a period of time or formed in a single event.

3) Whether the crack formed from shock or vibration loading.

4) The quality of the weld.

5) The probable properties of the welded joint.

3. EXAMINATIONS AND TESTS PERFORMED

3.1 Plan of the Examination

At a meeting at NBS on June 11, 1973 attended by Mr. Lance Heverly of OPS, Dr. Amos J. Shaler representing the UGI Corporation, and Dr. M. L. Picklesimer of NBS, the plan of the examination of the failed gas pipe discussed in this section was agreed upon.

The pipe would be cut transversely by band saw on one side of the weld and about two inches from it. The piece containing the weld was then to be cut longitudinally on a diameter starting at the transverse saw cut face to allow a portion of the pipe to be removed so that part of the fracture surface would be exposed for examination. It was proposed to cut the uncracked welded part of the pipe longitudinally into several pieces, one of which was to be used for two strips welded back to back for tensile testing by Dr. Shaler. (This material was given to Dr. Shaler at NBS on June 15, 1973.) A second piece was to contain partly cracked weld and partly uncracked weld and was to be fractured through the weld in tension at liquid nitrogen temperature. A third piece was to be used for a strip tensile specimen with the reduced section being weld metal. This specimen was to be tested at room temperature (70° F).

After photographing the fracture surface, the cutoff piece which contained the fracture surface was to be cleaned ultrasonically with detergent and water and then, if necessary, would be cleaned with sodium citrate to remove the remaining corrosion product. The specimen was to be examined after every step in the cleaning process.

The direction of further work would depend upon the results up to that time.

3.2 Other Examinations and Tests Performed

In addition to the planned examinations discussed in Section 3.1, a visual examination of the pipe wall surfaces was made, particularly in the area of the weld. The fracture surface was examined visually, macroscopically, and with the scanning electron microscope (SEM).

A specimen was broken through weld material in impact at 38° F (to approximate the soil temperature at the time of the explosion). A specimen containing some cracked weld and some uncracked weld metal was fractured through the weld in tension at 35° F (again to approximate the soil temperature at the time of the explosion). The fracture surfaces produced from these tests and the two other tests performed at NBS (discussed in Section 3.1) were examined visually and with the SEM.

The relative amounts of quasi-cleavage (brittle fracture) and dimpled rupture (ductile fracture) were determined on the SEM for selected areas of various fracture surfaces by point counting with a ten point grid. At least twenty fields were used for each determination.

Hardness measurements were made on longitudinal sections through the pipe and the weld, and metallographic examinations were performed in selected areas.

3.3 Summary of Mechanical Tests Performed at NBS

A summary of the mechanical tests (except hardness tests) that were performed at NBS and discussed in Sections 3.1 and 3.2 is presented below. The specimen locations referred to are shown in figure 3.

A. Weld metal pulled to fracture in tension near liquid nitrogen temperature. Specimen had been located between 6 and the end of the tail of the chalk arrow (piece second from the right in figure 3b).

B. Tensile specimen with reduced section being all weld metal, tested at 70° F. Specimen had been located between 3 and 4 (piece second from the left in figure 3b).

C. Specimen broken through weld metal in impact at 38° F. Specimen had been located between 2 and 3 (right part of the piece at the far left in figure 3b).

D. Weld metal pulled to fracture in tension at 35° F. Specimen had been located left of 2 (piece to the far left in figure 3b with the impact specimen removed).

The two pieces given to Dr. Shaler were located between 4 and 6.

4. RESULTS OF EXAMINATIONS AND TESTS

4.1 Visual and Macroscopic Examinations

4.1.1 Surfaces of pipe and weld

The crack in the weld traversed about two-thirds of the circumference of the pipe. One end of the crack was near the top of the pipe. The length of the crack is indicated in figure 4. This figure shows four views of the pipe in the weld area as seen from the top, both sides, and the bottom with the pipe in the as received condition except for the clamp having been removed. The weld bead around the outside of the pipe appeared to have been made in a single continuous pass while the pipe was rotated. The surface topography of the weld bead appears to be typical of welds made with an oxy-acetylene torch used manually.

The outside wall surface of the pipe length was covered with a heavy scale (corrosion product). There were areas that were also covered with what appeared to be tightly adhering soil. The top of the pipe appeared to have less scale and fewer soil deposits than the rest of the pipe. According to OPS, the bolts holding the clamp on the pipe were at the top of the pipe. The clamp is shown in place in figure 2. The letter "T" in figure 4a indicates this position, which is somewhat at variance with the top of the pipe as indicated in figure 1.

The inside wall surfaces of the pipe had patches of light scale, but in general were relatively clean. There appeared to be somewhat more corrosion product in the region near the weld (probably due to welding flux) than in other areas as can be seen in figure 5. The area shown in this figure contains both cracked and uncracked weld. There is evidence of lack of weld penetration, since over much of the pipe circumference, the weld material does not come through to the inside pipe wall.

4.1.2 Service failure fracture surface

Part of the fracture surface, after being cut from the pipe length, is shown in figure 6. Several specimens had been removed before this photograph was taken. General areas of incomplete weld penetration are indicated by arrows 1. The fracture surface was covered with corrosion product which masked most of the fracture features. There were some spheres of slag on top of the rust which were probably from the oxy-acetylene torch cutting of the pipe section to allow removal from the ditch.

The fracture surface was cleaned ultrasonically with water and detergent, which removed most of the rust. When examined with a low-power optical microscope, the fracture surface appeared to exhibit quasi-cleavage. A photomacrograph of part of the fracture surface is shown in figure 7 at higher magnification than in figure 6. Careful examination of the cleaned fracture surface indicated that the features were flat and finer in the region about midway in the length of the crack (measured circumferentially) than closer to the crack arrest regions. Based on this observation, it is probable that the crack origin was about midway between the crack arrest regions or at about the 4:30 o'clock position assuming the top of the pipe to be at 12 o'clock as shown in figure 1 and the outside of the bend of the pipe as installed to be at three o'clock.

4.2 Fractographic Examination

4.2.1 Service fracture

The service fracture was examined in several areas with the SEM. These included regions near both crack arrest sites, an area near the apparent crack origin, and an area about halfway between the apparent crack origin and one of the crack arrest sites. Each of these areas exhibited quasi-cleavage as the primary fracture feature, indicating that the fracture was basically brittle in nature. There was, however, some dimpled rupture exhibited by each of the areas, indicating some degree of ductility. In order to determine quantitatively the relative amounts of dimpled rupture and quasi-cleavage, a point counting method referred to in Section 3.2 was employed with the following results:

1. Near one crack arrest site: 9% dimpled rupture, remainder quasi-cleavage.

2. Near the other crack arrest site: 15% dimpled rupture, remainder quasi-cleavage.

3. Apparent crack origin: 3.5% dimpled rupture in one area, 4% dimpled rupture in another area, remainder quasi-cleavage.

4. About half way between the apparent crack origin and one of the crack arrest sites: 9 1/2% dimpled rupture, remainder quasi-cleavage.

Thus, the fracture appeared to be less ductile near the apparent crack origin than away from the origin. Representative SEM photomicrographs of the service fracture are shown in figures 8 and 9. Quasi-cleavage is the primary fracture feature exhibited, but some dimpled rupture can be seen in both figures.

4.2.2 Fracture through weld metal pulled in tension after cooling in liquid nitrogen

The fracture surface produced by extending the service crack through weld metal under a tensile load at near liquid nitrogen temperature exhibited quasi-cleavage as essentially the only fracture feature, indicating a completely brittle fracture. An SEM photomicrograph representative of this fracture surface is shown in figure 10.

4.2.3 Tensile fracture through weld metal at 70° F

The fracture surface of the tensile specimen with an all weld metal reduced cross section exhibited essentially all dimpled rupture indicating a ductile fracture. The specimen had an ultimate tensile strength of about 50,800 psi and an apparent elongation in 2 inches of 5 percent. Since one face of the specimen had been curved to a radius of 3.5 inches to eliminate voids in the root of the weld and to assure fracture through the weld, the true elongation was somewhat greater than 5 percent. This amount of elongation indicates that the weld metal was ductile, which agrees with the results of the fractographic examination. An SEM photomicrograph showing a representative area of the tensile specimen fracture surface is shown in figure 11.

4.2.4 Weld metal fractured in impact at 38° F

The fracture surface of the specimen fractured in impact through weld metal at 38° F exhibited 6 percent dimpled rupture, the remainder being quasi-cleavage. A representative area of this specimen fracture surface is shown in figure 12.

4.2.5 Fracture through weld metal pulled in tension at 35° F

The fracture surface produced by extending the service crack under tensile loading at 35° F exhibited 11 percent dimpled rupture compared to 9 percent dimpled rupture for the service crack adjacent to it. The remainder of the fracture features at each point exhibited quasi-cleavage, indicating that the fracture was primarily of a brittle nature. A representative area of this fracture surface is shown in figure 13.

4.3 Metallographic Examination

A longitudinal side of the tensile specimen tested at 70° F was prepared metallographically before the test was conducted. A low magnification view of this in the etched condition (figure 14) indicates that the weld was made in one pass. There is a small amount of mismatch between the two pieces of pipe at this point, as the planes of the wall surfaces of one piece do not quite coincide with the corresponding planes of the wall surfaces of the other piece.

Longitudinal sections through both pieces of pipe intersecting the fracture surface are shown in figure 15. The microstructure of the weld material (area A) is similar for both pieces and consists of a ferrite matrix in a Widmanstätten pattern with a little cementite and some pearlite in the grain boundaries. A representative area of the weld material is shown in figure 16. The microstructure of the pipe material adjacent to the weld (area B), again similar for both pieces, is shown in figure 17. The microstructure appears to have undergone phase transformation (austenite to ferrite) as a result of heating during welding. It consists of a ferrite matrix with some cementite and pearlite in the grain boundaries. The heat affected zones (area C, figure 15) on both sides of the weld exhibit similar microstructures. A representative area is shown in figure 18. This microstructure, consisting of small grains of ferrite and some pearlite and cementite in the grain boundaries, appears to have been heated into the lower part of the ferrite plus austenite temperature range. There were some differences between the microstructures of the two pieces of pipe in area D (fig. 15) just beyond the heat affected zones. In both cases, ferrite is the primary constituent with some pearlite and cementite in the grain boundaries, but one exhibits a Widmanstätten structure and the other does not. Examples of these microstructures are shown in figure 19.

There was some porosity in the weld material. An example of this in an unetched longitudinal section is shown in figure 20a. An area more typical of the weld material is shown in an unetched longitudinal section in figure 20b. Such porosity is normal in manual torch welding.

There were some inclusions in the pipe material as shown in figure 21. This is an area of a longitudinal section about midway between the inner and outer walls of the pipe.

4.4 Hardness Measurements

Rockwell 30T hardness measurements were made on the longitudinal sections shown in figure 15. Each value given below is an average of at least four measurements.

Area	R_{30T} Hardness — Section shown in figure 15a	R_{30T} Hardness — Section shown in figure 15b
A - Weld material	55.5	54.5
B - Heat affected zone showing results of phase transformation	59.0	61.0
C - Heat affected zone showing results of phase transformation	62.0	61.0
D - Parent pipe material	62.5	59.0

The range for any given area was never greater than three R_{30T} points.

5. DISCUSSION

The crack in this eight inch welded steel pipe natural gas main initiated and propagated in a weld and traversed about two-thirds the circumference of the pipe. Examination of the fracture surface indicated that the crack had probably initiated at the approximate midpoint between the two ends of the crack. This would be at approximately the 4:30 o'clock position, assuming the top of the pipe as shown in figure 1 to be 12 o'clock. The entire fracture appeared to be essentially brittle in nature, but there was less ductility exhibited in the area of the crack origin than away from the origin. The fracture surface appeared to be flatter in the area of the origin.

The weld appeared to have been made in a single pass by manual oxy-acetylene torch welding. There was lack of weld penetration over a large part of the pipe circumference. This could be seen at the inside wall surface of the welded joint and on the fracture surface. There was some porosity in the weld material. The Widmanstätten structure found in the microstructure of the weld material was produced by

relatively rapid cooling of the weld. While all of these features might be considered somewhat undesirable, their presence is probably consistent with welding practices employed at the time the weld was made. The weld metal exhibited adequate ductility in the 70° F tensile test. There was some mismatch between the two pieces of pipe at the weld, but this was not considered to be unacceptably large.

The microstructure of the steel pipe on each side of the joint consisted of the same phases as that of the weld material; namely, a ferrite matrix with some cementite and pearlite. In general, the cementite and the pearlite were found in the grain boundaries. The presence of a Widmanstätten structure in one of the pieces of pipe indicates that this pipe may have been cooled rapidly from the hot rolling temperature at the time of manufacture.

The scale on the outside wall surfaces of the pipe did not appear to have had a detrimental effect on the welded joint and it is not likely that it contributed significantly to the failure of the pipe.

While there were some differences in hardness among the pipe materials, the heat affected zones, and the weld material, the differences were not large and were probably insignificant.

Comparison was made of the fracture features of the service crack and the laboratory produced fractures through weld metal from the submitted pipe length in order to determine the relative amounts of ductile fracture (dimpled rupture) and brittle fracture (quasi-cleavage) present for each case. A summary of these determinations is presented below.

Fracture	% dimpled rupture	% quasi-cleavage
Service fracture		
Near origin	3.5 - 4.0	96 - 96.5
Near one crack arrest site	9	91
Near other crack arrest site	15	85
Halfway between initiation point and crack arrest site	9.5	90.5
Impact specimen (38° F)	6	94
Tensile specimen (70° F)	100	0
Tensile fracture (near liquid nitrogen temperature, ~ -320° F)	0	100
Tensile fracture (35° F)	9	91

The temperature of the soil around the pipe at the time of the accident was reported (by the Office of Pipeline Safety) to be approximately 35 to 40° F. The area of the fracture surface of the service failure near the probable crack origin exhibited less ductility than the impact specimen tested at about the temperature of the pipe environment at the time of the accident. The impact specimen fracture surface exhibited less ductility than that of the tensile fracture produced at the approximate temperature of the soil. Based on the determinations of the relative amounts of ductility and the appearance of the features of the service fracture, the pipe failure appears to have initiated as the result of impact loading by an external source. The entire crack appears to have occurred in a single event. As the crack spread from the point of initiation, the rate of propagation probably decreased, which accounts for the increased ductility exhibited by the fracture surface near the crack arrest sites.

6. CONCLUSIONS

1. The submitted length of eight inch welded steel pipe natural gas main had cracked in a weld and the crack traversed about two-thirds of the circumference of the pipe. The apparent crack origin was at about the 4:30 o'clock position, assuming the top of the pipe as shown in figure 1 to be at 12 o'clock and the outside of the bend of the pipe as installed to be at three o'clock.

2. The fracture was predominantly brittle in nature.

3. There was a heavy scale on the external pipe wall surface, but this does not appear to have contributed to the failure.

4. There was a lack of weld penetration around much of the circumference of the pipe on the inside, a feature normally produced in the welding technique used at the time.

5. Although there was some porosity in the weld, it is not considered to be excessive in light of welding techniques used at the time the weld was made.

6. The microstructures of the weld material and the pipe material appear to be compatible and normal.

7. The weld material appeared to exhibit adequate ductility in a 70° F tensile test.

8. Failure appears to have been caused by a single event, impact loading from an external source.

7. ACKNOWLEDGEMENT

Mr. L. C. Smith of the NBS Mechanical Properties Section performed most of the photographic work, made the hardness measurements, and prepared the specimens for metallographic examination.

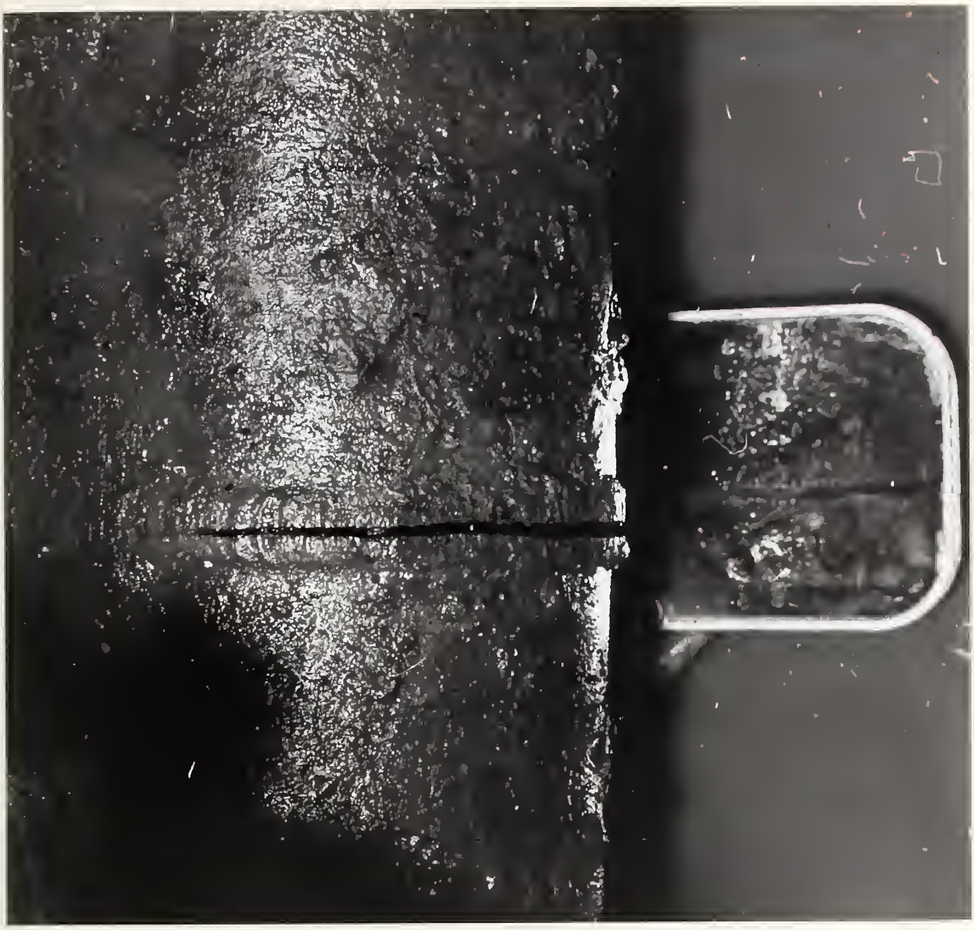


Figure 1. Part of the welded steel gas main pipe still in the ditch showing the crack in the weld. A mirror had been placed to the right and near the bottom of the pipe in order to show that part of the crack which extended to the pipe bottom. This photograph was taken looking straight down on the pipe, and was furnished by and used with permission of the Pennsylvania State Police. Approx. X 3/8

Figure 2. Length of gas pipe containing the cracked weld as received at NBS. The clamp is still in place. X 1/10

Figure 3a. Part of the pipe length with a portion of the fracture surface exposed. The numbers indicate the locations of specimens referred to in Section 3.3.

Figure 3b. Part of the pipe showing pieces cut out for mechanical test specimens. The specimen locations are discussed in Section 3.3.

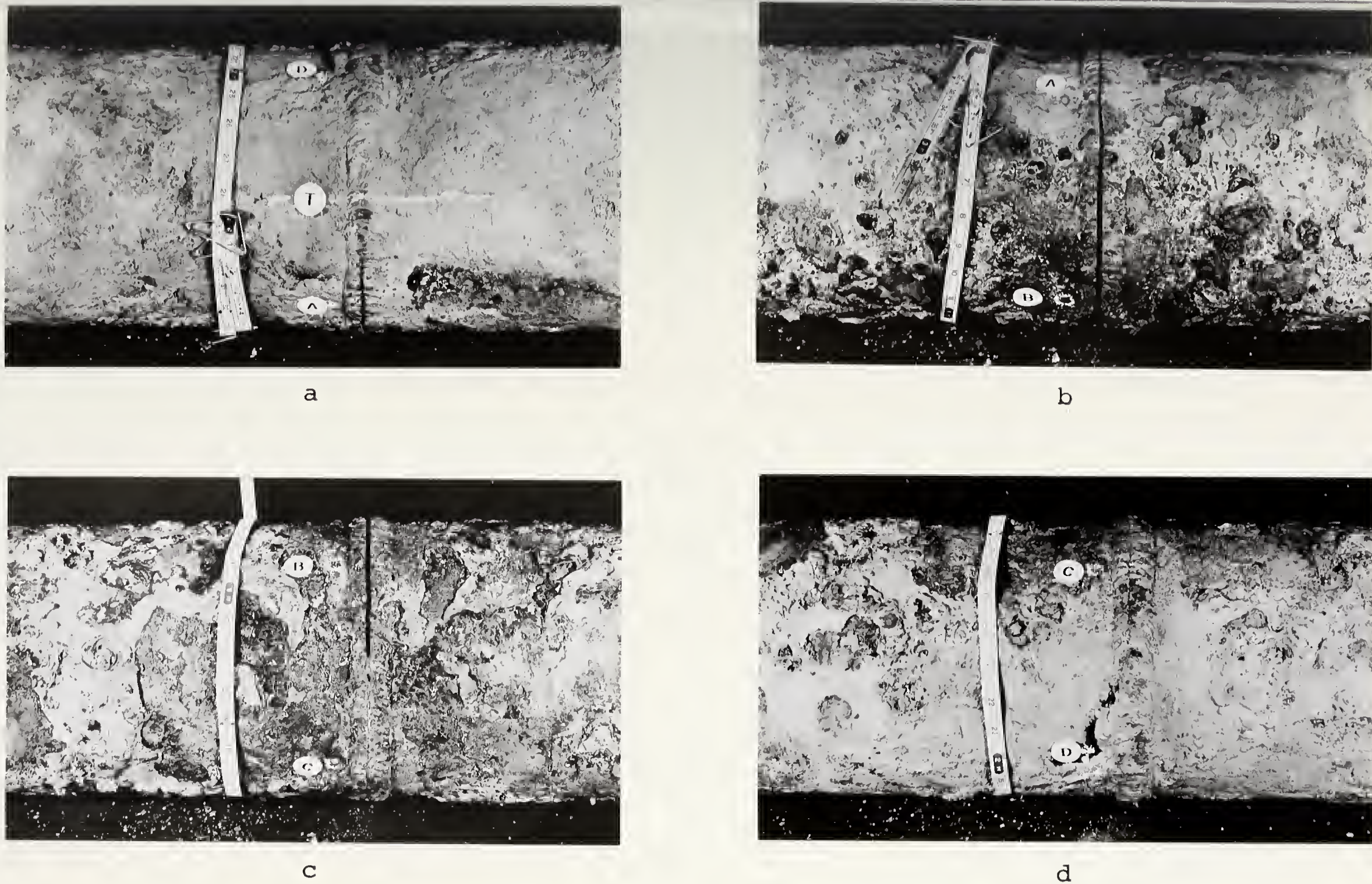


Figure 4. Four views of the outside of the pipe in the weld area.

a. Top
b. One side
c. Bottom
d. Other side

Figure 5. Part of the inside wall surface of the pipe in the area of the weld. The weld is cracked to the left of the arrow. The wall surface appears to be more heavily corroded in the area of the weld than in other areas.

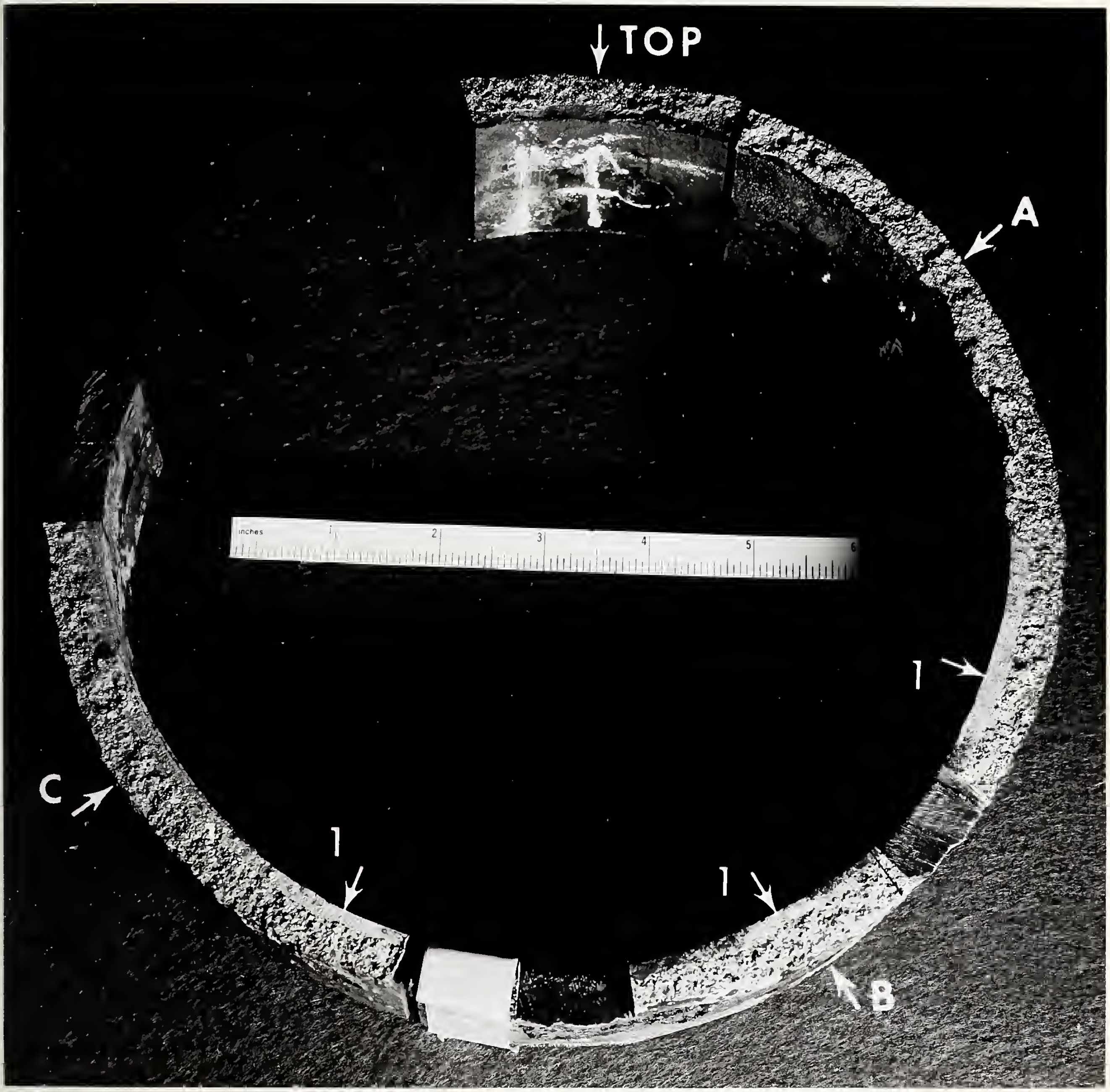


Figure 6. Part of the fracture surface of the pipe with several specimens having been removed. The lettered arrows indicate the same areas as in figure 4. Arrows 1 indicate general areas of incomplete weld penetration (flat areas on the fracture surface adjacent to the inside wall of the pipe).

Figure 7. Part of the service fracture surface near one of the crack arrest areas. X 7

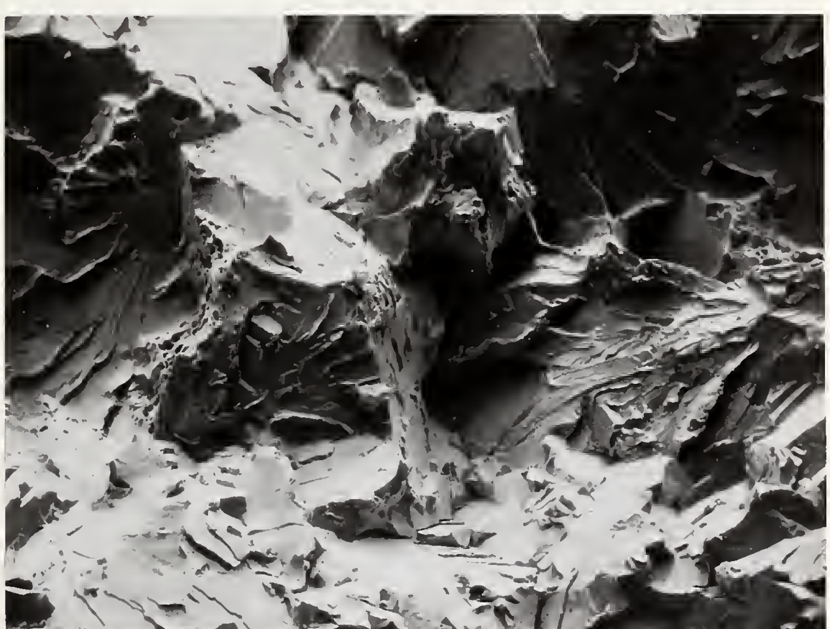


Figure 8. SEM photomicrograph of service fracture surface showing primarily quasi-cleavage and some dimpled rupture. X 105

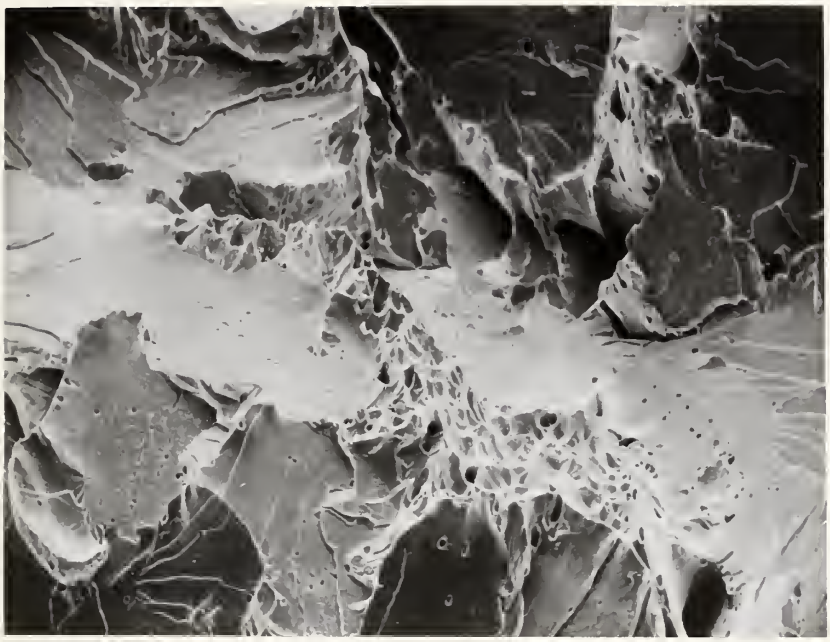


Figure 9. SEM photomicrograph of service fracture surface showing primarily quasi-cleavage and some dimpled rupture. X 250

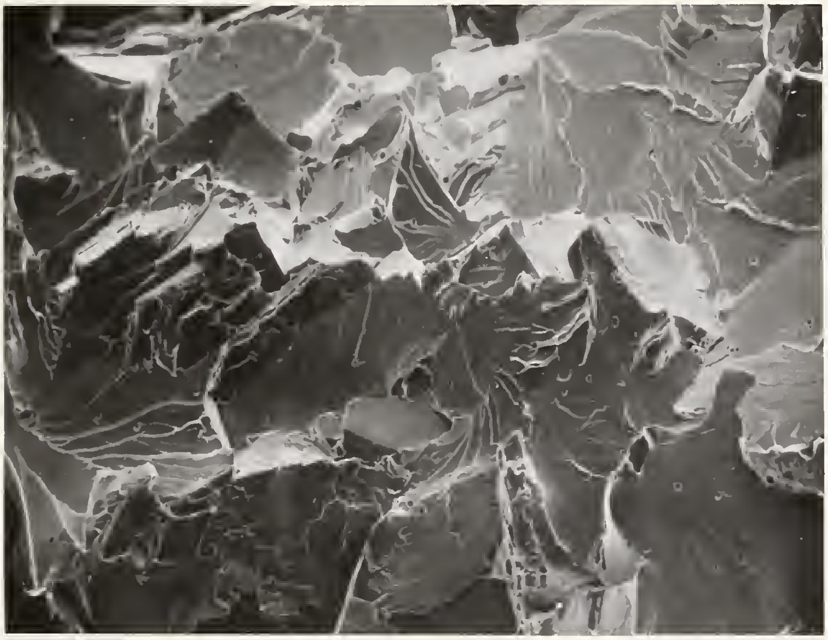


Figure 10. SEM photomicrograph of fracture surface of weld material pulled in tension after cooling in liquid nitrogen. Quasi-cleavage is essentially the only fracture feature exhibited. X 250

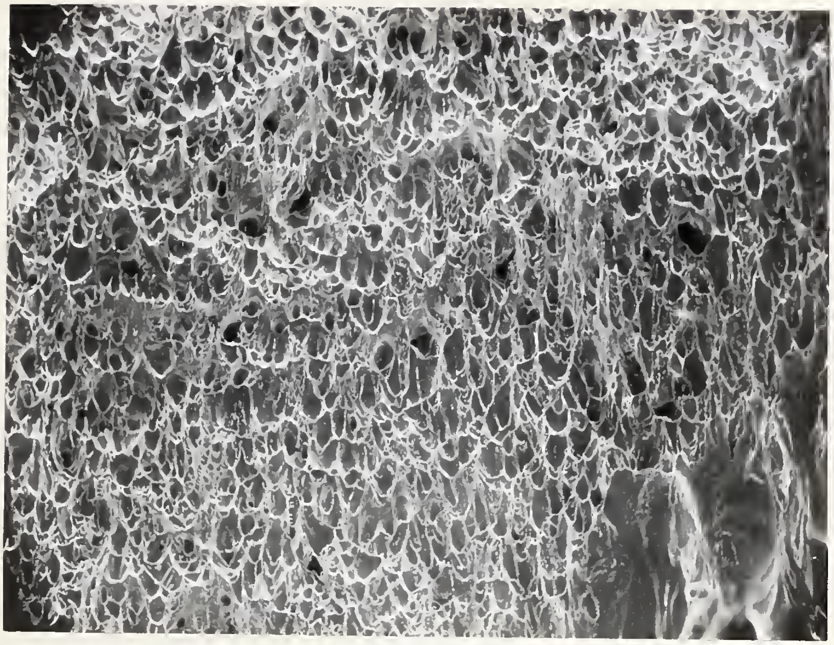


Figure 11. SEM photomicrograph of fracture surface of tensile specimen failed through weld metal at 70° F. Dimpled rupture is essentially the only fracture feature exhibited. X 140

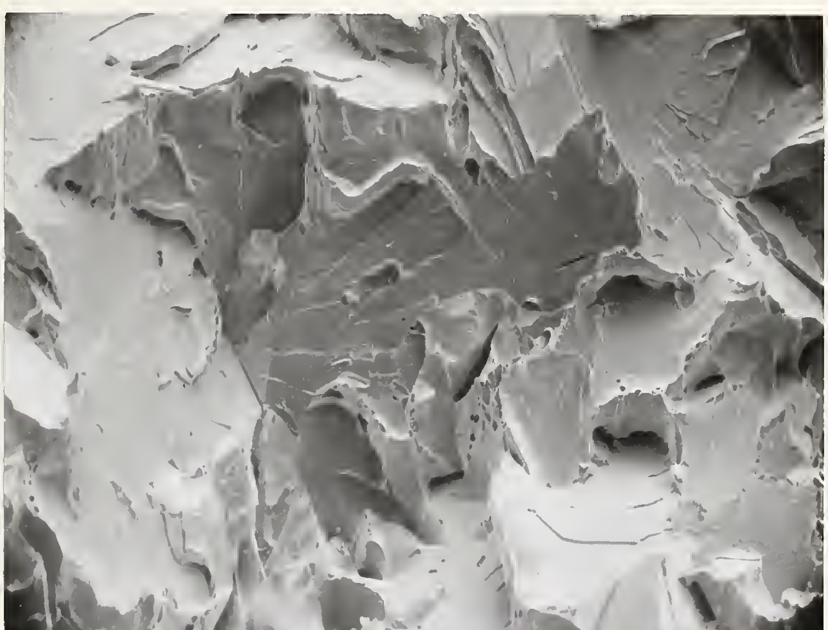


Figure 12. SEM photomicrograph of fracture surface of impact specimen tested at 38° F showing primarily quasi-cleavage and a small amount of dimpled rupture. X 135

Figure 13. SEM photomicrograph of fracture surface of weld metal pulled in tension at 35° F. Quasi-cleavage is the primary fracture feature exhibited, but there is some dimpled rupture. X 190

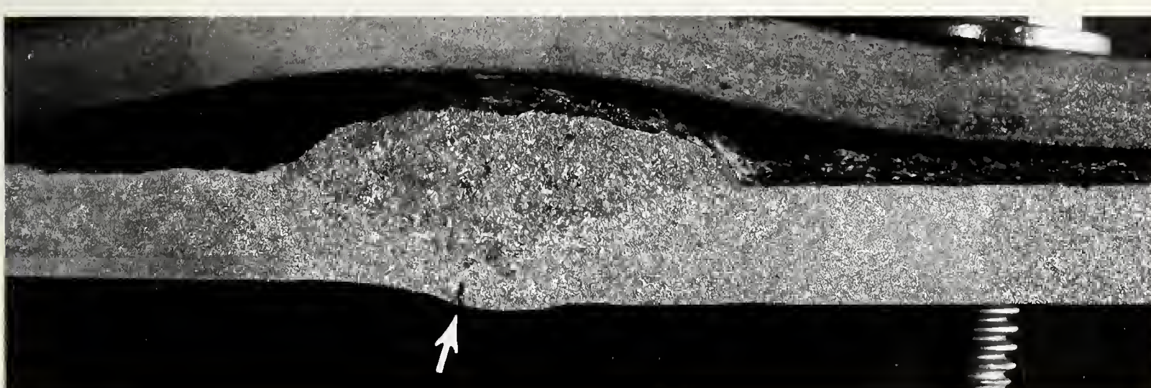


Figure 14. Etched longitudinal side of tensile specimen encompassing the weld before testing. Lack of penetration is indicated by the arrow. The weld appears to have been made in a single pass.
Etch: 20% nitric acid in water. X 2

a

b

Figure 15. Etched longitudinal sections through pieces of pipe on either side of the weld. The sections intersect the fracture. Letter designations are as follows:

A. Weld material.
B. Pipe material adjacent to the weld in the heat affected zone.
C. Heat affected zone somewhat removed from the weld.
D. Parent pipe material.

Etch: 10% nitric acid in water. X 3

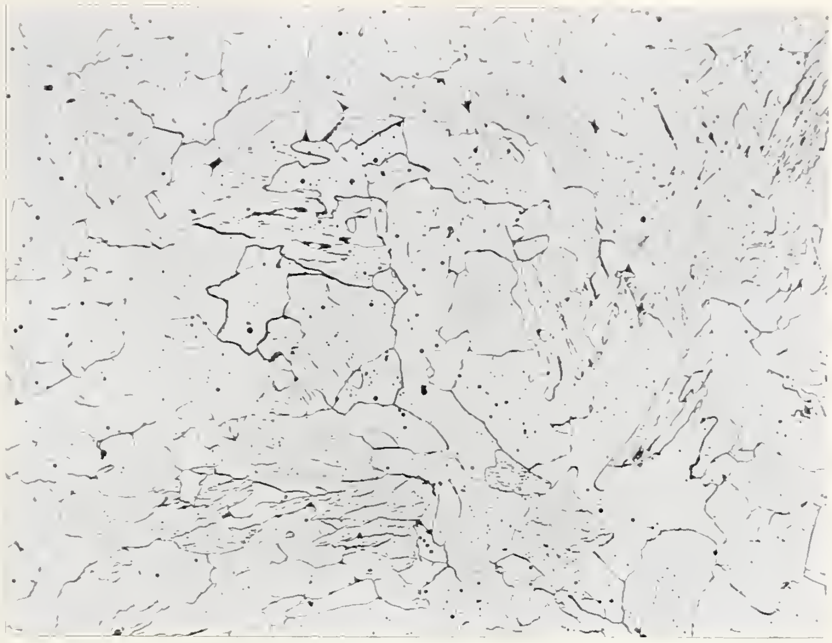


Figure 16. Etched microstructure of longitudinal section through weld. Microstructure consists primarily of ferrite, some of which is in a Widmanstätten pattern, with some cementite and pearlite in the grain boundaries.
Etch: 1% nital. X 100

Figure 17. Etched microstructure of longitudinal section through pipe material adjacent to the weld. Microstructure consists of ferrite with some cementite and pearlite in the grain boundaries. A phase transformation has taken place.
Etch: 1% nital. X 100

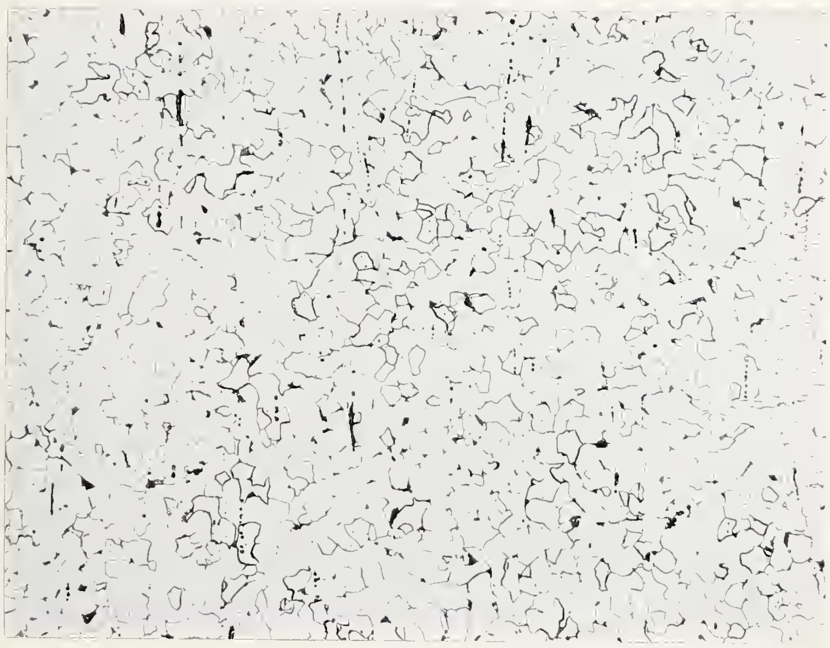


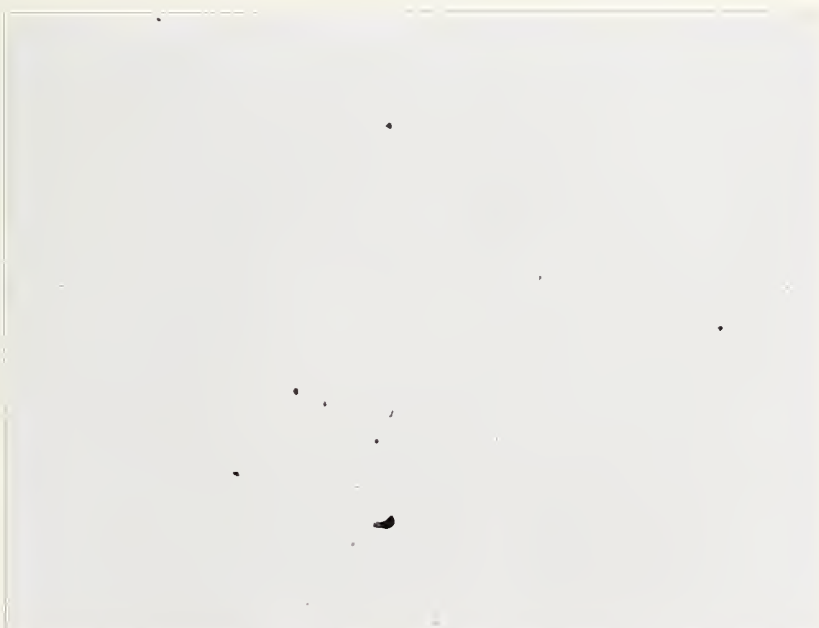
Figure 18. Representative etched area of longitudinal section through heat affected zone. Microstructure consists of ferrite and some pearlite and cementite in the grain boundaries.
Etch: 1% nital. X 100

a

b

Figure 19. Etched longitudinal sections through both pieces of pipe adjacent to the heat affected zone. In both cases, the microstructure consists primarily of ferrite with some pearlite and cementite in the grain boundaries. In figure 19a, some Widmanstätten structure can be seen.
Etch: 1% nital. X 100

a



b

Figure 20. Unetched longitudinal sections through weld material. X 100

a. Area containing more than average porosity.
b. Area representative of the weld material.

Figure 21. Unetched longitudinal section through pipe material showing the inclusion content. X 100

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Office of Pipeline Safety
Department of Transportation
Washington, D. C. 20590

13. Type of Report & Period Covered Failure Analysis Report

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

The Office of Pipeline Safety, Department of Transportation, submitted a four foot length of eight inch diameter welded steel pipe natural gas main containing a crack in the weld to the NBS Mechanical Properties Section for examination. The apparent crack origin was located at about the 4:30 o'clock position, assuming the top of the pipe to be at twelve o'clock and the outside of the bend of the pipe as installed was at three o'clock. The crack had propagated about two-thirds of the way around the pipe circumference. Optical and scanning electron microscopy revealed the fracture to have been predominantly brittle in nature. There was lack of weld penetration around a large part of the weld circumference and the weld metal exhibited some porosity. These features are normal for steel pipe welded by the oxy-acetylene practice used at the time the weld was made. While these features of the weld helped to define the path of the fracture, they probably did not contribute to it. Examination of the fracture and comparison of its features with those of fractures produced in the laboratory indicated that failure was probably brought about as a result of a single event, impact loading from an external source.

17. KEY WORDS (Alphabetical order, separated by semicolons)

Brittle fracture; gas main pipe; welded steel pipe.

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