NBSIR 76-981 (R)

Examination of Steel Components from the Yadkin River Bridge, Siloam, North Carolina

T. Robert Shives

Mechanical Properties Section
Metallurgy Division
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National Bureau of Standards
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Failure Analysis Report

Prepared for
Bureau of Aviation Safety
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Bureau of Aviation Safety
National Transportation Safety Board
Washington, D. C. 20594

U.S. DEPARTMENT OF COMMERCE, Rogers C.B. Morton, ***Secretary***
James A. Baker, III, ***Under Secretary***
Dr. Betsy Ancker-Johnson, ***Assistant Secretary for Science and Technology***

NATIONAL BUREAU OF STANDARDS, Ernest Ambler, ***Acting Director***

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SUMMARY

The Bureau of Aviation Safety, National Transportation Safety Board, submitted six bar segments from the collapsed bridge over the Yadkin River in Siloam, North Carolina, to the NBS Mechanical Properties Section for examination. Three of the six bars had fractured in the field. All six of the bars were found to consist of two components that had apparently been forge welded together. Two of the three bars that had fractured in the field had partially fractured through forge welded junctions between two bars.

Laboratory tensile tests were performed on two as-received bars which already contained flaws at the junctions. These tests resulted in fracture at the junction in one bar, and away from the junction in the second bar. Another test of the second bar resulted in fracture at the junction. All of the failures at junctions (two in the field and two in the laboratory) plus the one field fracture not occurring at a junction exhibited very little ductility.

Three other laboratory tensile tests resulted in fractures not at junctions that exhibited good ductility.

The field fracture that did not pass through a junction may have been due to impact loading. The other field fracture that was examined had passed through a junction. This fracture appeared to be either a high strain rate fracture or a fracture due to stress corrosion cracking.

Stress corrosion cracking was the probable mechanism of formation for a pre-existing crack adjacent to a junction in a bar that was tested in tension in the laboratory.

Variations in the chemical composition, microstructure, and hardness, and poor forge welding in the bars indicate a lack of control over the material and the fabrication process.

Examination of Steel Components from the Yadkin River Bridge, Siloam, North Carolina

1. GENERAL INFORMATION

1.1 Reference

Bureau of Aviation Safety, National Transportation Safety Board (NTSB), Washington, D.C. This investigation was conducted at the request of Mr. Michael L. Marx by letters dated May 20, 1975 and August, 1975.

1.2 Accident Identification

The submitted components were from a bridge over the Yadkin River in Siloam, North Carolina, that collapsed on February 23, 1975.

1.3 Parts Submitted

On May 20, 1975, parts of three fractured steel components from the collapsed Yadkin River Bridge were submitted by the NTSB to the NBS Mechanical Properties Section for examination. These parts are shown as received by NBS in figure 1. (The NTSB had sectioned one of the components before sending it to NBS.) The components were identified as follows:

Bar L4E-U5E B6
Bar L3E-U4E B5
Bar U8L8W B1

On July 28, 1975, an unbroken bar segment from each of three additional steel components from the bridge was submitted for examination. Two of these bar segments were attached to a turnbuckle. These parts are shown as received in figure 2. They were identified as follows:

Bar Y1 L4W-U5W
Bar X1(A) L6E to U5E
Bar X1(B) L6E to U5E

Except for the threaded regions, the bars were essentially square in cross section and measured about 7/8 to 1 inch on a side.

In addition, 0° and 90° radiographs of the latter three bars were submitted. Radiographs of two bars other than those submitted were also included.

1.4 Parts Designation

In this report, the designations of the components as submitted will be shortened to the following NBS designations:

As submitted designation	NBS designation
L4E-U5E B6	B6
L3E-U4E B5	B5
U8L8W B1	B1
Y1 L4W-U5W	Y1
X1(A) L6E to U5E	X1A
X1(B) L6E to U5E	X1B

2. PURPOSE

The Bureau of Aviation Safety requested that the NBS Mechanical Properties Section perform tensile tests on bars B6, Y1, X1A, and X1B. Tests at high speed were suggested to give results characteristic of a high strain rate fracture process. The modes of the fractures produced by these tests and the modes of the field fractures of bars B1 and B5 were to be determined. The field fracture surface of bar B6 had been examined by the NTSB before it was submitted to NBS and was not included in this investigation. The nature of the flaws indicated by the radiographs of bars X1A and X1B was also to be determined. If deemed necessary, other tests or analyses such as chemical analysis, cross-sectioning, and tensile testing could be conducted.

3. RESULTS OF EXAMINATIONS, TESTS, AND ANALYSES

3.1 Relationship of Flaws and Bar Fabrication Technique

Features on the submitted radiographs indicated the presence of a flaw (flaws) in bars X1A and X1B at an angle of about 35° to the longitudinal axis of the bar. In addition, there was a flaw indicated in bar X1A that was about 90° to the longitudinal axis of the bar. This flaw terminated at the 35° angle flaw. The flaw in bar X1A that was 90° to the longitudinal axis could be seen at the surface of the bar (figure 3) and will be discussed later.

The flaws at 35° to the longitudinal axis were actually discontinuities in junctions between two bars that had apparently been forge welded together. (Henceforth in this report, the term "forge welded" implies "apparently forge welded.") The evidence for the existence of the junctions was revealed in a metallographic examination (Section 3.4 of this report). An example of one of the forge welded junctions appears in figure 4 where a heavily etched longitudinal section through bar Y1 is shown. The junction goes from the lower left to the upper right in the figure. No flaw was evident on the radiograph of bar Y1. The junction was essentially continuous or sound except for small regions such as that indicated by the arrow in figure 4. Presumably, these flaws were too small to be detected by radiography.

All six of the submitted components consisted of two bars that had been joined by forge welding.

3.2 Tensile Tests

Uniaxial tensile tests were conducted on bars B6, X1A, X1B, and Y1. Each of the four bars was tested with the full as-received width and thickness. No machining was done except for the removal of some burrs and paint near the ends of the specimens to facilitate gripping in the testing machine.

The junctions in bars X1A and X1B were located about seven inches from a turnbuckle to which they were attached when submitted, as evidenced by the flaws shown on the radiographs. For the tensile testing, it was assumed that the junction in bar Y1 was in a similar location (as measured from the end of the threads). At this point in the investigation, the metallographic work revealing the junction in bar Y1 had not been performed. In the tensile tests of each of these three bars, the junction (or the assumed location of the junction) was positioned approximately midway between the grips of the tensile testing machine.

Bar B6 had fractured in the field through its junction; therefore, for the tensile test, the approximate center of the submitted piece was placed about midway between the testing machine grips.

All tests were conducted at a machine cross head speed of 16 inches per minute, the maximum cross head speed of the machine employed.

The maximum tensile loads sustained by the bars are as follows:

Bar	Maximum load, lbs
B6	48,000
X1A	9,100
X1B (first test)	48,000*
(second test)	26,300*
Y1	49,100

* Bar X1B failed first near the bottom grip and away from the junction. The remainder of the bar containing the junction was tested in tension a second time. The second test resulted in failure at the junction. The maximum load sustained in the second test was much less than that sustained in the first test.

Bar B6 (figure 5) necked considerably in the vicinity of the fracture, indicating that the material possessed good ductility. Reduction in area at the fracture was approximately 45%. The fracture was essentially perpendicular to the longitudinal axis of the bar except for the 45° shear lip around the perimeter.

Bar X1A failed at the junction through the flaws indicated by the radiograph. The part of the fracture that was perpendicular to the longitudinal axis of the bar passed through a pre-existing crack (the flaw that intersected the surface of the bar as shown in figure 3). A significant portion of the fracture followed the path of the two-bar interface (about 35° to the longitudinal axis of the bar). There was essentially no necking or reduction in area in the vicinity of the fracture. The fracture of bar X1A can be seen in figure 6.

Bar Y1 failed in a ductile manner, exhibiting considerable necking in the vicinity of the fracture (figure 7). The path of this fracture tended towards 45° to the longitudinal axis of the bar. The fracture did not occur at the assumed location of the junction in the bar.

As mentioned above, bar X1B fractured the first time it was tested in a region away from the flaw indicated by the radiograph. There was considerable necking in the vicinity of this fracture, indicating good ductility for the material in this part of the bar (figure 8a).

The remaining part of bar X1B containing the junction was retested. The bar then failed at the junction through the flaw indicated by the radiograph. A large part of this fracture followed the path of the junction (about 35° to the longitudinal axis of the bar). There was essentially no necking in the region of the fracture indicating a low ductility fracture. This fracture can be seen in figure 8b.

3.3 Fractographic Examination

3.3.1 Submitted Field Fractures

3.3.1.1 Visual and Macroscopic Examination

The fracture surfaces of bars B1 and B5 are shown in figures 9 and 10, respectively. Both of these bars had failed in the field. The fracture surfaces of both bars were corroded, but those of bar B5 appeared to be considerably more corroded than those of bar B1. Neither bar exhibited any visible reduction in area at the fracture.

As can be seen in figures 1 and 9, the fracture path in bar B1 is essentially perpendicular to the longitudinal axis of the bar along most of the fracture (region A, figure 9), but then makes an abrupt change in direction (arrow B, figure 9) and follows a path more closely paralleling the longitudinal axis of the bar (region C, figure 9). Region C of the fracture surface is smooth and is probably more accurately described as part of a junction in the bar. This junction was produced when the loop in the end of the component was made by bending the bar back upon itself, the seam being located where the loop was closed. The loop can be seen in figure 1.

Except for a small region near the center, the fracture path in bar B5 is essentially perpendicular to the longitudinal axis of the bar. The features of one part of the fracture (region A, figure 10) appear to be finer than those of the rest of the fracture.

3.3.1.2 Scanning Electron Microscope Examination

One fracture surface each from bars B1 and B5 was examined with the scanning electron microscope (SEM). In bar B1, the fracture crack appears to have initiated about 0.7 inch from the end of the junction where the loop in the bar closed. Arrows B and D in figure 9 indicate on the opposing fracture surfaces the approximate location of the fracture crack origin. Adjacent to the apparent origin, the fracture surface features were masked with a film of what appeared to be corrosion product. An SEM fractograph from this area is shown in figure 11. There was a relatively small area (region 1, figure 9) near the fracture origin that exhibited apparent dimpled rupture as the dominant fracture mode. An SEM fractograph from this area is shown in figure 12.

Cleavage was the predominant mode for the remainder of the fracture surface of bar B1. An SEM fractograph from the region of the fracture surface exhibiting cleavage is shown in figure 13.

Before examination of the fracture surface of bar B5 with the SEM, corrosion product was removed by replication techniques in order to reveal the fracture features. The fracture mode in region A, figure 10, was mostly cleavage (figure 14) with some areas of primarily dimpled rupture (figure 15). There are several large holes or pores that can be seen in figure 15. The mode of the upper portion of the fracture as it is oriented in figure 10 is predominantly dimpled rupture (similar to figure 15). The step in the fracture is along the junction between the two components of the bar.

3.3.2 Laboratory Produced Tensile Fractures

3.3.2.1 Visual and Macroscopic Examination

The fracture surfaces of the four NBS laboratory produced tensile fractures that were examined are shown in figure 16. The fractures of bars B6 and Y1 had the appearance of ductile overload. The fracture through bar X1B that did not pass through the junction in the bar also had the appearance of ductile overload. This fracture is not shown in figure 16 and it was not examined in detail.

The fracture surfaces of bars X1A and X1B (the fracture at the junction in the bar) exhibited considerable evidence of the discontinuities in the junctions through which the fractures passed. As seen in figure 17, this evidence is especially prominant in the center portion of the fracture in bar X1A, where the fracture surface is characterized by a wavy appearance with regions of very smooth material and regions of sponge-like material. As mentioned earlier, the fracture in bar X1A (figure 17) also passed through a pre-existing crack (see figure 3) that was essentially perpendicular to the longitudinal axis of the bar. The pre-existing crack penetrated to the junction, but did not follow its path. The part of the fracture surface containing the pre-existing crack was covered with corrosion product as can be seen in figure 17.

3.3.2.2 Scanning Electron Microscope Examination

Dimpled rupture was the predominant fracture mode over essentially the entire fracture surfaces of both bars B6 and Y1. An SEM fractograph from bar B6, which is representative of both fractures, appears in figure 18. This fracture mode is consistent with the significant reduction in area of these bars at the fractures.

The fracture surface of bar X1A was examined both in the area of the pre-existing crack and in an area not containing the pre-existing crack. The area not containing the pre-existing crack was on the same plane as the pre-existing crack and adjacent to it. The fracture surface was cleaned by repetitive replication with cellulose acetate before examination in order to remove enough of the corrosion product so that the fracture features could be seen.

In the part of the fracture containing the pre-existing crack, the fracture mode was mixed, consisting of cleavage, apparent intergranular cracking, and a small amount of dimpled rupture (figure 19). In the area not containing the pre-existing crack, the fracture mode was predominantly dimpled rupture (figure 20).

The part of the fracture through bar X1A that followed the junction was not examined with the SEM, but the features of this part of the fracture were macroscopically similar to those exhibited by bar X1B in a similar area. The fracture of bar X1B is discussed below.

The upper part of the fracture of bar X1B, as the bar is oriented in figure 16, exhibited mostly cleavage. This part of the fracture did not follow the path of the 35° angle junction and is essentially perpendicular to the longitudinal axis of the bar. Figure 21 is an SEM fractograph of the part of the fracture where cleavage predominated.

For the most part, the remainder of the fracture followed the flaw or junction in the bar and exhibited the features of the flaw (figure 22). In regions where the forge welding appeared to be partially successful, the fracture surface showed a mixture of dimpled rupture (similar to figure 20 for bar X1A) where the junction was sound, and the features of the flaw where the junction was not sound.

3.4 Metallographic Examination

Metallographic (or macrographic) examination of longitudinal sections through each of the six bars revealed that all contained a junction or interface where two separate components had been forged together. The flaws

35° to the longitudinal axes of bars X1A and X1B that were indicated on the radiographs were discontinuities in these interfaces. Except for the field fracture through bar B1, all of the apparent low ductility fractures followed the paths of the junctions in part. And in bar B1, the fracture path partially followed a seam or interface where the bar had been bent back upon itself to form a loop.

An etched longitudinal section showing the fracture path through bar B6 appears in figure 23. This fracture path is typical of those in the apparent low ductility fractures (except for that of bar B1). Where the fracture path is about 35° to the longitudinal axis of the bar, the fracture path essentially coincides with the junction or interface between the two components of the bar. Where the fracture path deviates from the interface, as in the lower left in figure 23, the interface can be seen (arrows, figure 23).

The profile of the fracture in bar B1 is shown in figure 24. The fracture appears to be primarily transgranular, but it may be intergranular in places. The fracture profile in the pre-existing crack portion of the fracture in bar X1A is shown in figure 25. The fracture appears to be partially transgranular and partially intergranular. The fracture profile of bar B5 (not shown) in an area where the fracture did not follow the interface between the two components also appeared to be partially transgranular and partially intergranular.

There was at least one secondary crack close to and essentially parallel to the fracture in bars X1A (figure 26) and B5. Both of these secondary cracks appeared to be somewhat intergranular in nature.

In bar Y1, which failed in a ductile manner, the fracture did not pass through the junction. The radiograph of this bar did not reveal the presence of flaws at the junction because the junction was apparently sound over all but a very small portion of its length, as was shown in figure 4.

A photomicrograph of part of the section shown in figure 4 exhibits a change in microstructure at the junction (figure 27). The junction is essentially vertical in the center of figure 27. The microstructure on both sides of the junction consists of pearlite and ferrite, but the microstructure to the left of the junction in figure 27 appears to have a higher carbon content (more pearlite) than the microstructure at the right.

The microstructure of all the bars consisted primarily of ferrite and pearlite, but the relative amounts of these two constituents varied considerably from bar to bar, and in some cases, between the two components of a single bar. Examples of some of these variations in microstructure have been presented in previous figures. Another variation is shown in figure 28 where some Widmanstätten structure is evident.

In bars X1A and B5, there was a surface layer that appeared to have much less carbon than the rest of the material in the part of the component that was examined. This condition in bar B5 can be seen in figure 29.

3.5 Chemical Analysis

Chemical analyses were made by a commercial laboratory on samples of one component from each of three of the submitted bars. Referring to figure 1, bar B1 was analyzed to the left of the fracture, but to the right of the junction; bar B5 was analyzed to the left of the fracture which was at the junction; and bar B6 was analyzed to the right of the fracture which was at the junction. The results (weight per cent) of these analyses are as follows:

Element	Bar B1	Bar B5	Bar B6
Carbon	0.19	0.22	0.41
Manganese	0.48	0.47	0.61
Phosphorus	0.013	0.016	0.016
Sulfur	0.034	0.027	0.023
Silicon	< 0.05	< 0.05	0.15
Nickel	< 0.05	< 0.05	0.08
Chromium	< 0.05	< 0.05	< 0.05
Molybdenum	< 0.05	< 0.05	< 0.05
Copper	< 0.05	< 0.05	< 0.05

The chemical composition of the samples from bars B1 and B5 are very similar. The sample from bar B6 is significantly different, especially in carbon and manganese.

3.6 Hardness Measurements

Diamond pyramid hardness measurements at a load of 2 1/2 kg (HV2 1/2) were made on a longitudinal section through bar B6 in the vicinity of the fracture. These measurements were made to determine whether the hardness might change across the junction. The hardness of the apparent low carbon component of the bar averaged about 131 HV2 1/2 (about 73 HRB), whereas the hardness of the apparent higher carbon component averaged 185 HV2 1/2 (about 90 HRB).

4. DISCUSSION

Perhaps the most interesting feature revealed in the examination of the forged bars from the collapsed Yadkin River Bridge was that each of the six submitted bars was actually composed of two separate components that had been apparently forge welded together at an angle of about 35°. The junction between the two components of a bar was quite evident in the results of the metallographic examination. In some cases, the interface could be seen more easily because of rather pronounced differences in the microstructure on either side of the interface. At the one interface where hardness was measured, it too, was significantly different on either side.

The flaws at about 35° to the longitudinal axes of bars X1A and X1B that were indicated on the radiographs were discontinuities in the forge welded junctions. The flaw at about 90° to the longitudinal axis of bar X1A that was indicated on the radiograph was a pre-existing crack. A comparison of laboratory tensile test results from bar X1A with flaws at the junction with the results from a bar with no significant flaw at the junction (bar Y1) indicates that the flaws significantly reduced the tensile load carrying capacity of bar X1A.

The maximum load sustained by bar X1A in the laboratory test was much less than that sustained by bar X1B (fracture through the junction) because the combined pre-existing crack and junction discontinuity in bar X1A was a larger flaw than the junction discontinuity in bar X1B.

The tensile tests of bar X1B led to some unexpected results. In the initial test, failure occurred away from the junction when the bar had sustained a load comparable to the maximum load sustained by bars Y1 and B6. The fracture was quite ductile. The second test, however, resulted in a low ductility fracture at the junction and at a much reduced load. It is not clear why the bar sustained the higher load initially nor why failure did not occur at the junction. The first tensile test may have initiated the fracture at the junction, and the second test completed it.

Based on a comparison of the tensile test load carrying capacities between a bar with an essentially sound junction (bar Y1) and a bar segment with no junction (bar B6), the junction of the two components had no observable adverse effect on the tensile strength of the bar if the junction was sound.

The laboratory produced fractures that did not fail at a junction exhibited good ductility, whereas both field and laboratory fractures that passed through a junction exhibited little ductility and tended to partially follow the junction between the two components of a bar. The fracture mode was predominantly cleavage, which is consistent with the observed low ductility.

The fracture in bar B1, the only submitted field fracture that did not pass through a junction, was a low ductility fracture. There did not appear to be as large a buildup of corrosion product as there was on the fracture surface of bar B5 (field fracture at a junction), indicating that the fracture in bar B1 may have been more recent. No secondary cracking was noted in the longitudinal section that was examined metallographically and the primary fracture mode was cleavage. From these observations, it may be inferred that the fracture in bar B1 was due to impact loading. The strain rate in impact loading would be much higher than that of the NBS tensile tests.

In bar X1A, both the pre-existing crack and a secondary crack parallel to the fracture and about 1/8 inch from it had an intergranular appearance in places, suggesting stress corrosion cracking as a possible crack mechanism in this bar.

The fracture surface of bar B5 appeared to have corroded considerably more than the fracture surface of bar B1, indicating that the fracture of B5 was probably the older fracture. The appearance at the step in the fracture indicates that there may have been a flaw at the junction in this region through which the fracture passed. There is some evidence of intergranular cracking at the fracture and at a secondary crack parallel to the fracture suggesting, as in bar X1A, stress corrosion cracking as a possible crack mechanism for at least the initial part of the fracture.

On the other hand, the features of the fracture surface of bar B5 were somewhat like those from the laboratory fracture through the junction in bar X1B, indicating that the fracture through bar B5 may have been a high strain rate fracture.

The differences in chemical composition, microstructure, and hardness among various bars indicate that there was little control over the materials employed or the condition of the materials at the time of fabrication. The presence of flaws at the junctions between two components of a bar suggests that the forge welding process employed was not always completely successful.

5. CONCLUSIONS

1. All six of the submitted bars consisted of two components that had been apparently forge welded together.

2. The flaws at about 35° to the longitudinal axes of bars X1A and X1B that were indicated on the radiographs were discontinuities in the junctions between two components that had been apparently forge welded together.

3. Two of the three submitted failed bars had fractured through one of the interfaces or junctions between two components.

4. All three of the submitted fractures were low ductility fractures.

5. Relatively high strain rate (16 inches per minute) uniaxial tensile tests conducted in the laboratory on full cross section bar segments resulted in high ductility fractures where the fractures did not pass through a junction or interface between two components (bars B6, Y1, and X1B).

6. Similar tensile tests resulted in low ductility fractures in bars X1A and X1B where the fractures passed through a junction.

7. Based on the results of the NBS tensile tests, sound junctions had no observable adverse effect on the tensile strength of the bars containing them.

8. The flaws at the junction in bar X1A significantly reduced the load carrying capacity of that bar.

9. The field fracture through bar B5 appeared to be either a high strain rate fracture or a fracture due to stress corrosion cracking.

10. The field fracture through bar B1, the only field fracture that did not pass through a junction in a bar, may have been caused by impact loading.

11. There was a pre-existing crack adjacent to the junction in bar X1A. The suggested mechanism for this crack is stress corrosion cracking.

12. Variations in microstructure, chemical composition, and hardness among the different components and the flaws in some junctions indicate that control was poorly maintained over the quality of the material used in the bars, the condition of that material, and the forge welding process employed.

6. ACKNOWLEDGEMENT

Mr. L. C. Smith of the NBS Mechanical Properties Section performed the metallographic specimen preparation and the photography and made the hardness measurements. Mr. W.A. Willard of the Mechanical Properties Section and Mr. Smith conducted the tensile tests.

Figure 1. Components from the Yadkin River Bridge, Siloam, North Carolina as received at NBS on May 20, 1975. Bar B1 is at the top, bar B5 is at the center, and bar B6 is at the bottom. (See Sec. 1.4 for parts designations.)
X 1/4

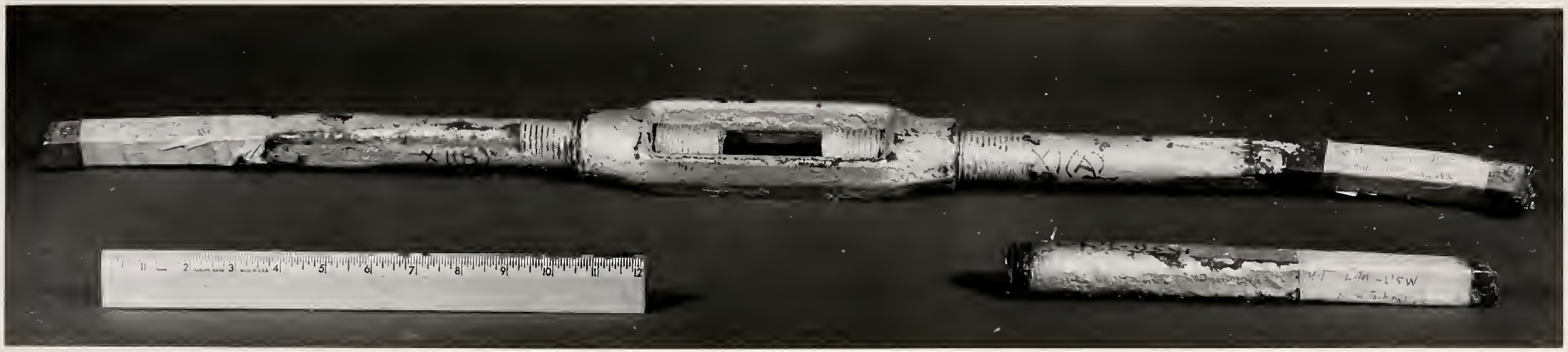

Figure 2. Components from the Yadkin River Bridge, Siloam, North Carolina as received at NBS on July 28, 1975. Bar X1A is at the top right attached to the turnbuckle, bar X1B is at the top left attached to the turnbuckle, and bar Y1 is at the bottom right. (See Sec. 1.4 for parts designations.)
X 1/4

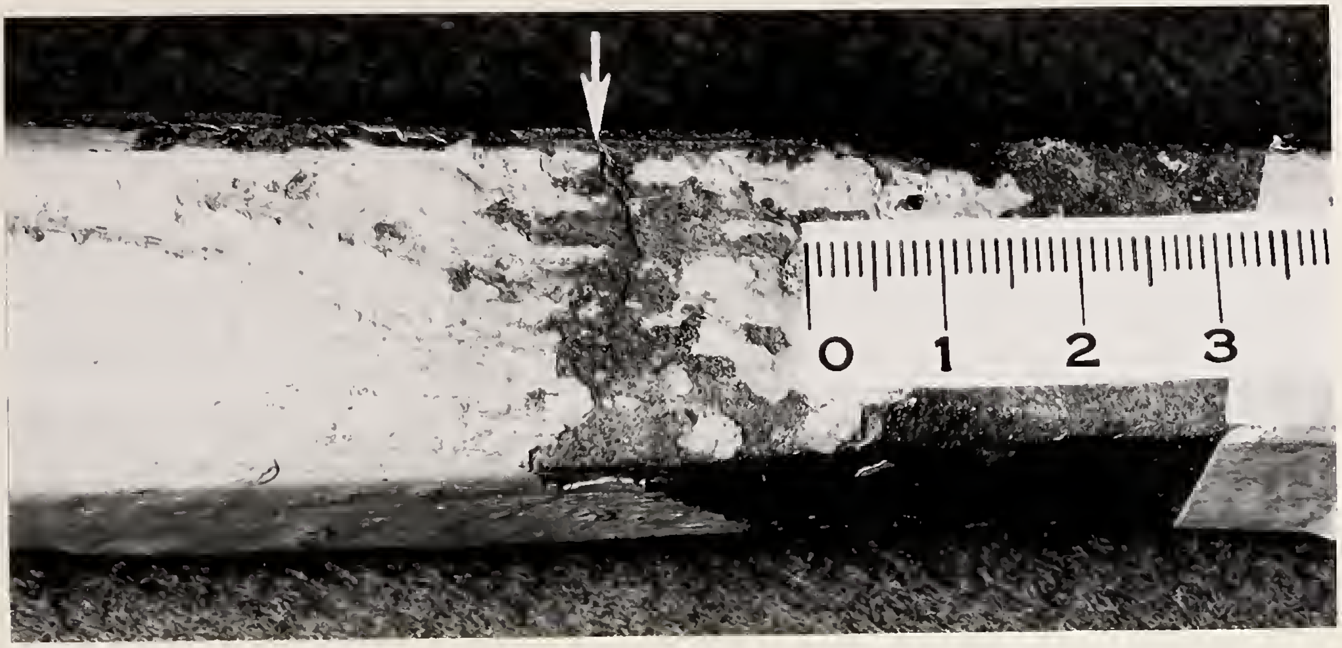

Figure 3. Part of bar X1A at the junction where two bars were forge welded together. The arrow indicates a flaw which intersected the surface of the bar X 1 1/2

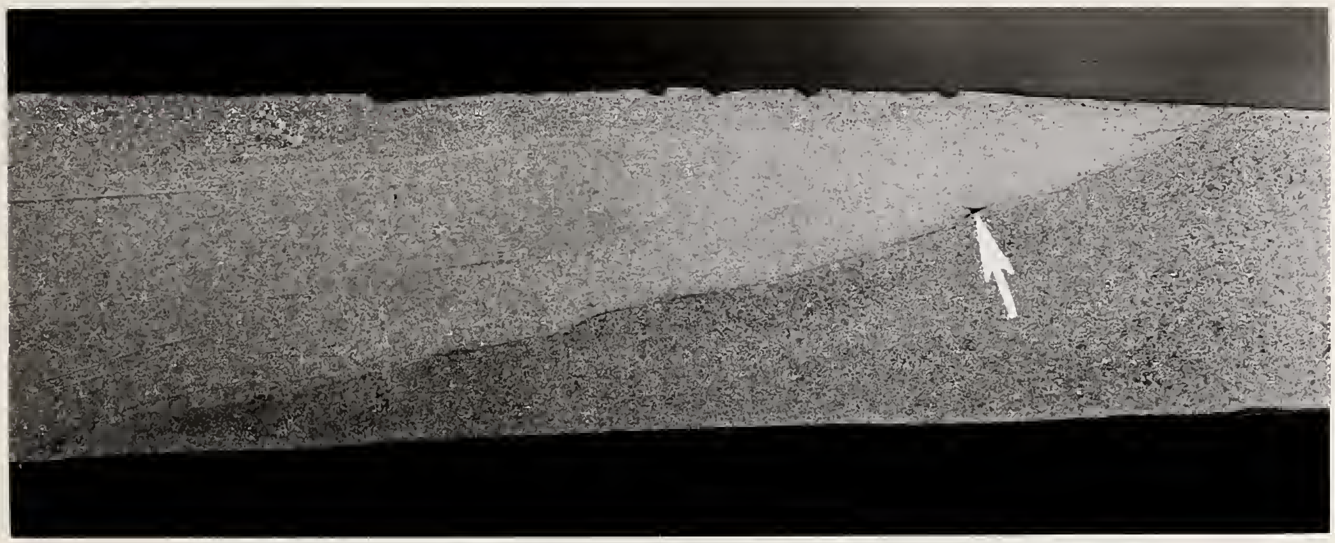

Figure 4. Heavily etched longitudinal section through bar Y1 showing the junction between the two components of the bar that had been forge welded together. The junction goes from the lower left to the upper right. In this section, the junction appears to be sound except for the small flaw indicated by the arrow. Etchant: 10% nitric acid X 1 2/3

Figure 5. Fracture profile of bar B6 showing necking which occurred during the laboratory tensile test. X 1

Figure 6. Fracture profile of bar X1A. X 1

Figure 7. Fracture profile of bar Y1. X 1

a

b

Figure 8. Fracture profile of bar X1B. X1
a) Fracture away from the junction.
b) Fracture through the junction.

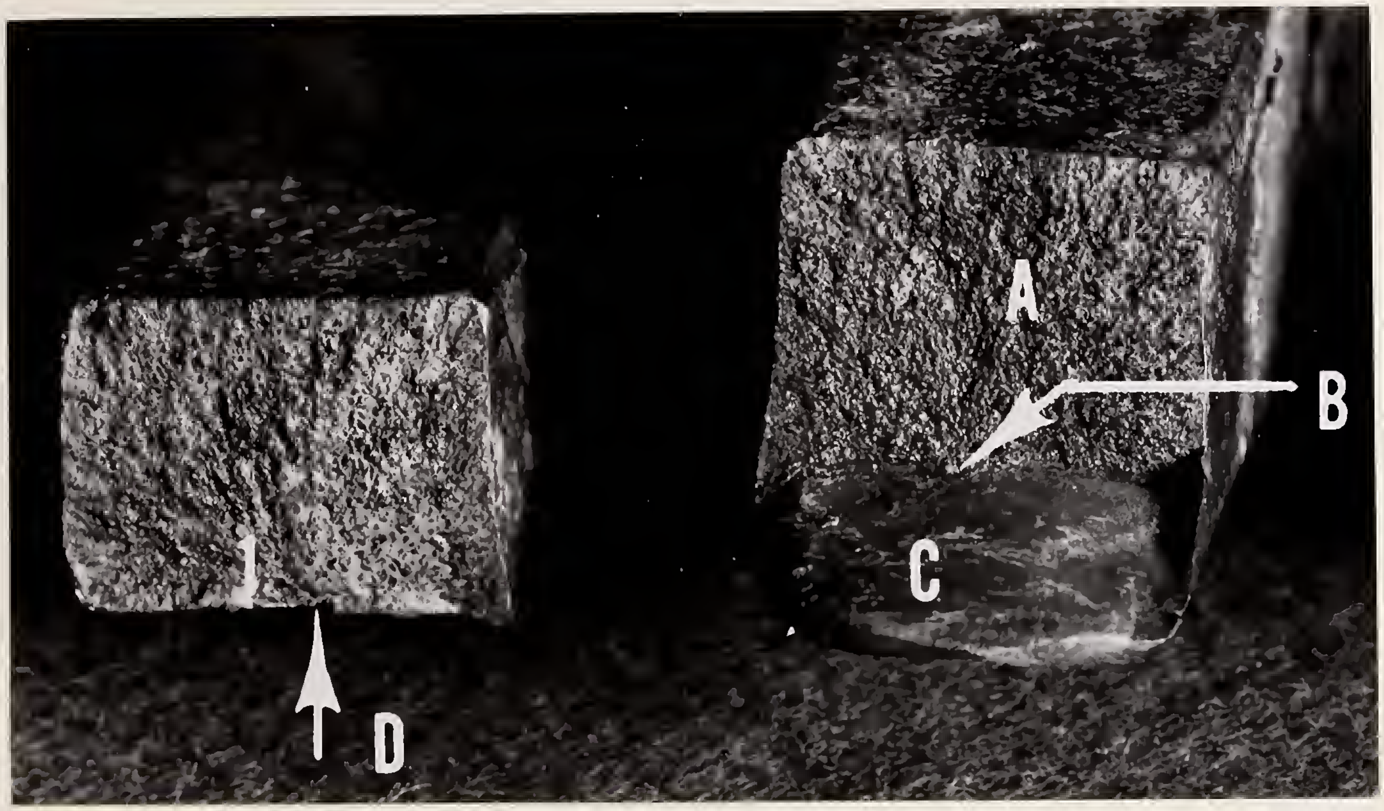

Figure 9. Opposing fracture surfaces of Bar B1. X 2

A is region of fracture perpendicular to the longitudinal axis of the bar.
Arrow B indicates apparent fracture origin and location of change in direction of fracture path.
C is region of fracture following junction.
Arrow D indicates apparent fracture origin.
Region 1 is small area where the fracture mode appears to be dimpled rupture.

Figure 10. Opposing fracture surfaces of bar B5. X 1

The fracture features appear to be finer in region A than on the rest of the fracture surface.

Figure 11. SEM fractograph of area adjacent to the apparent fracture origin in bar B1. What appears to be corrosion product is masking the fracture features. X 370

Figure 12. SEM fractograph of area near the apparent fracture origin in bar B1. Mode of fracture appears to be dimpled rupture. X 380

Figure 13. SEM fractograph from bar B1 showing the fracture surface away from the apparent origin. The predominant fracture mode is cleavage. X 175

Figure 14. SEM fractograph from bar B5 (region A, figure 10) showing mostly cleavage and some dimpled rupture. X 210

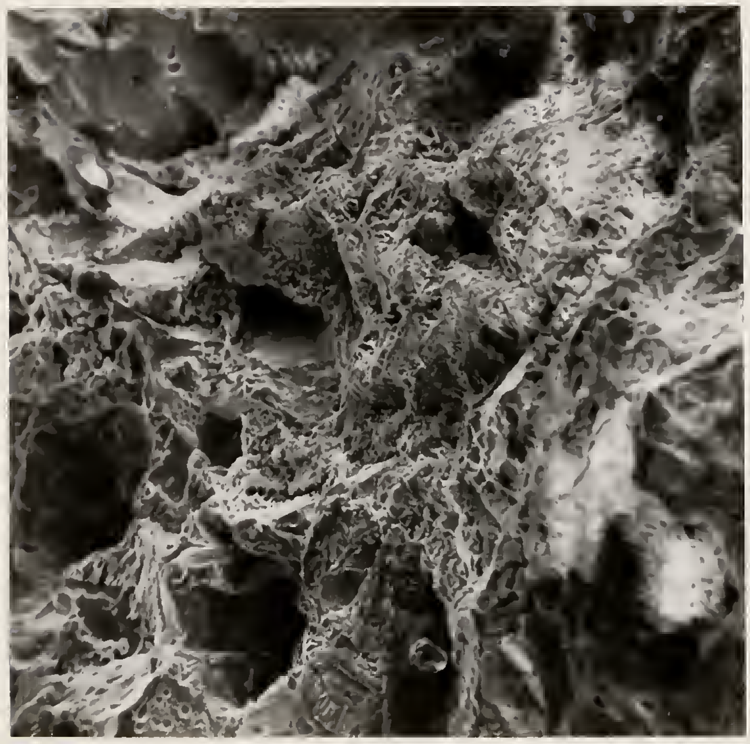

Figure 15. SEM fractograph from bar B5 (region A, figure 10) exhibiting mostly dimpled rupture and some cleavage. There are several large holes or pores. X 540

a b c

Figure 16. Fracture surfaces produced in the laboratory at NBS.

a. Bar Y1, X 1.
b. Bar X1A, X 1.
c. Bar X1B (fracture at junction), X 1.
d. Bar B6, X 4.

d

Figure 17. Surface of the laboratory produced fracture through bar X1A. The heavily corroded portion near the top of the fracture surface is the pre-existing crack. The center portion of the fracture (about 35° to the longitudinal axis of the bar) is essentially along the junction of the two parts of the bar. X 1

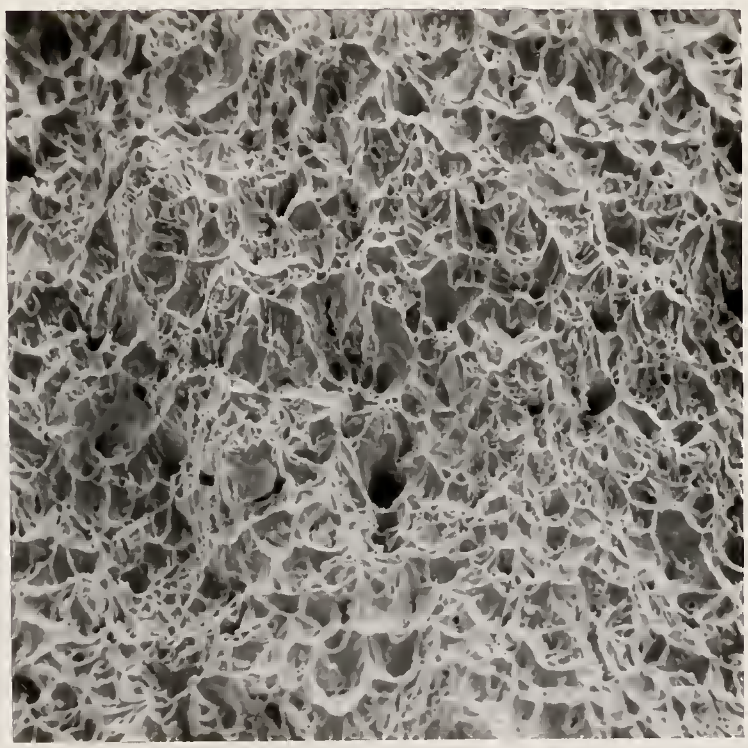

Figure 18. SEM fractograph from laboratory produced tensile fracture in bar B6. Dimpled rupture is the primary fracture mode. X 490

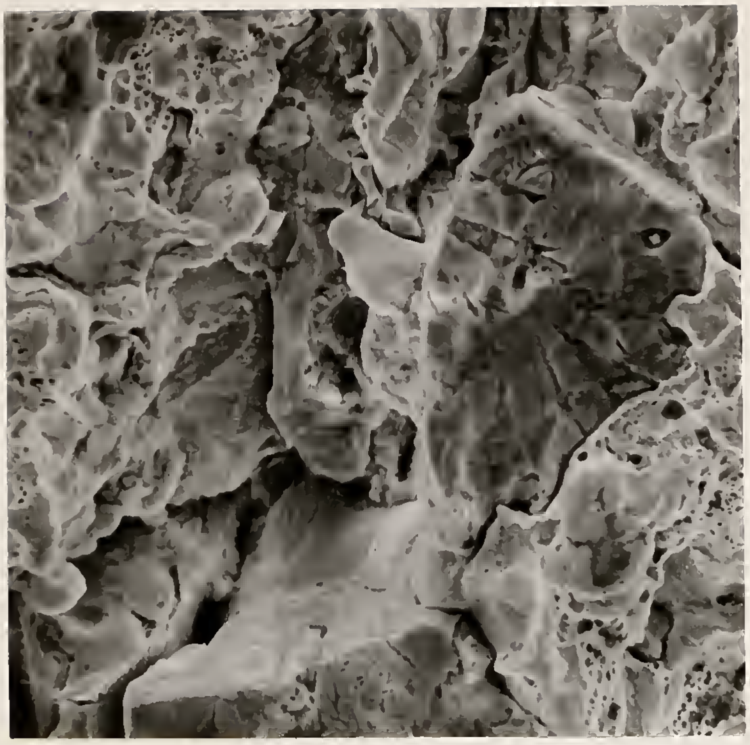

Figure 19. SEM fractograph of bar XlA in the region containing the pre-existing crack. The mode of fracture is mixed, consisting of cleavage, apparent intergranular cracking, and some dimpled rupture. X 525

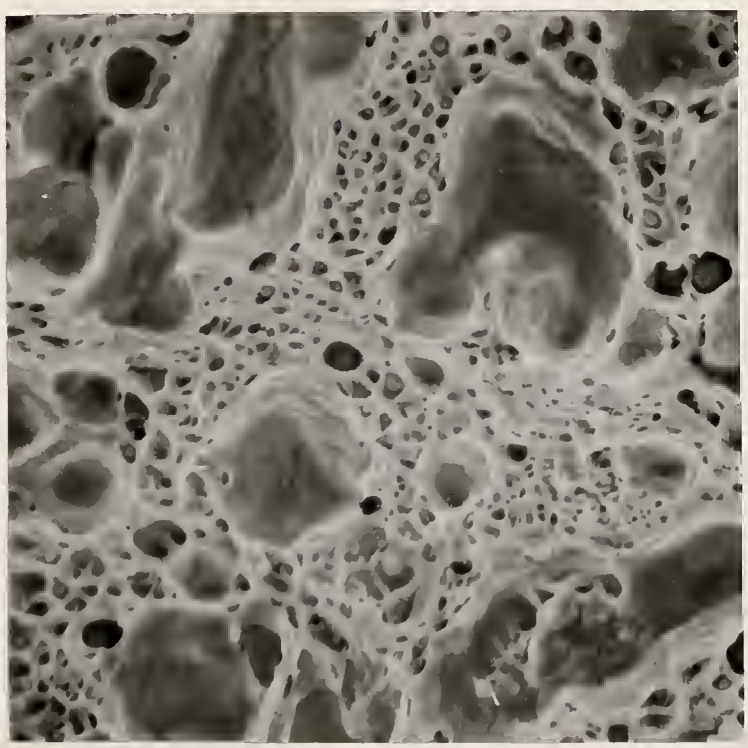

Figure 20. SEM fractograph of bar XlA in the remaining ligament in the plane of the pre-existing crack (see figure 17). Dimpled rupture is the primary fracture mode. X 2000

Figure 21. SEM fractograph of the part of the fracture of bar X1B that exhibited cleavage as the primary fracture mode. X 200

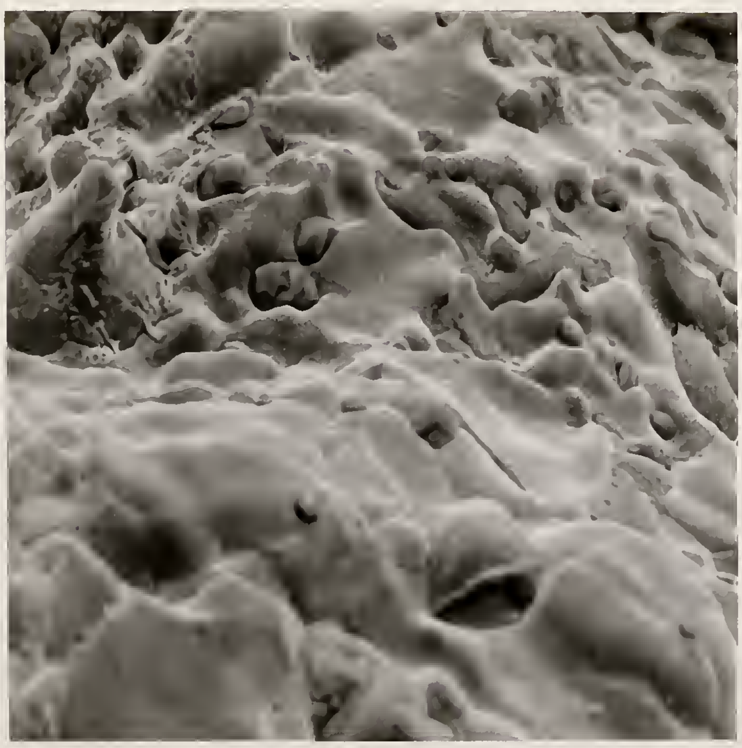

Figure 22. SEM fractograph of bar X1B where the fracture was following a flaw in the junction between two bars that had been forge welded together. X 550

Figure 23. Etched longitudinal section through bar B6 showing the fracture profile. The longitudinal axis of the bar is vertical. The fracture followed the junction between the two components of the bar where the fracture is about 35° from the longitudinal axis of the bar. Where the fracture deviates from the junction at the lower left, the junction can be seen (arrows).
Etchant: 10% nitric acid X 3

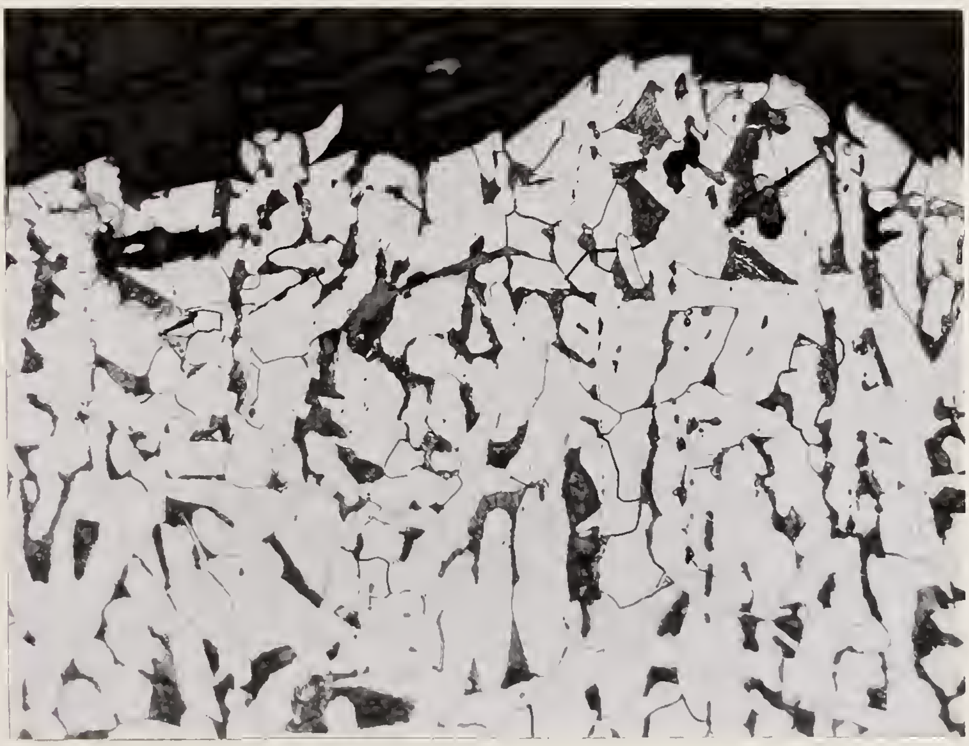

Figure 24. Profile of the fracture through bar B1. The longitudinal axis of the bar is essentially vertical.
Etchant: 1% nital X 200

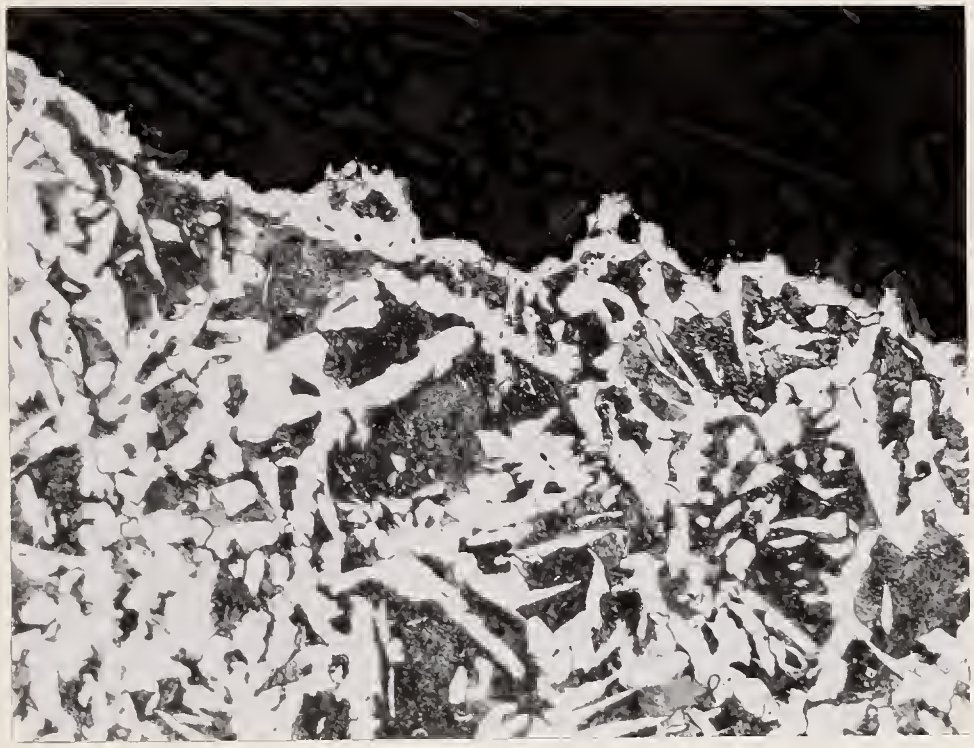

Figure 25. Profile of the fracture in the pre-existing crack portion of the fracture through bar X1A. The longitudinal axis of the bar is essentially vertical.
Etchant: 1% nital X 200

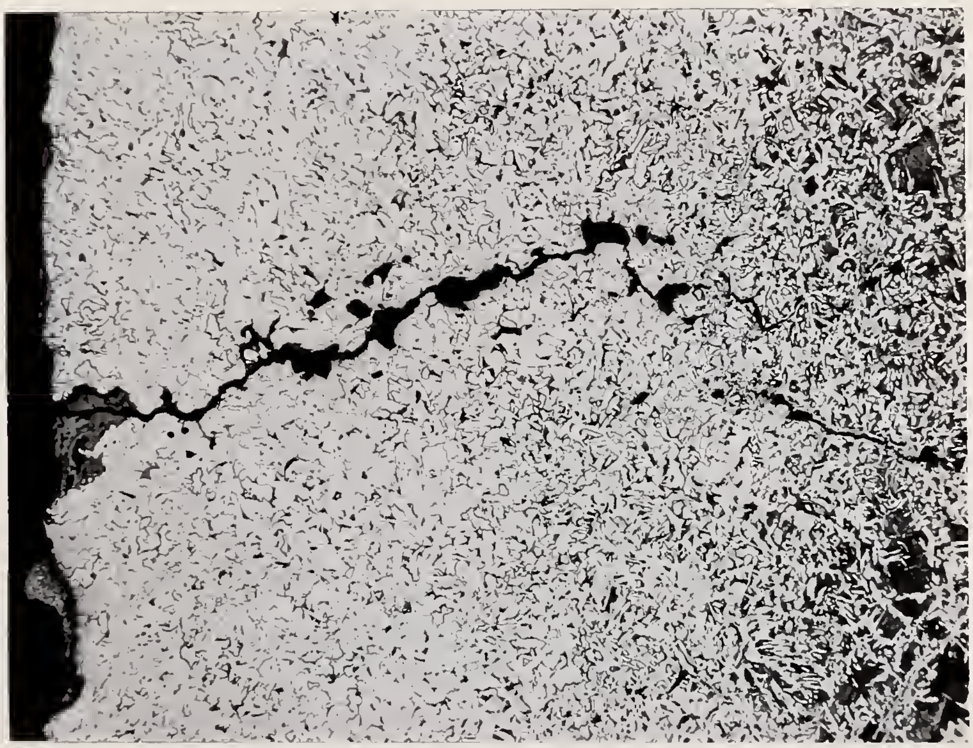

Figure 26. Longitudinal section through bar X1A showing secondary crack parallel to the fracture. The longitudinal axis of the bar is vertical.
Etchant: 1% nital X 40

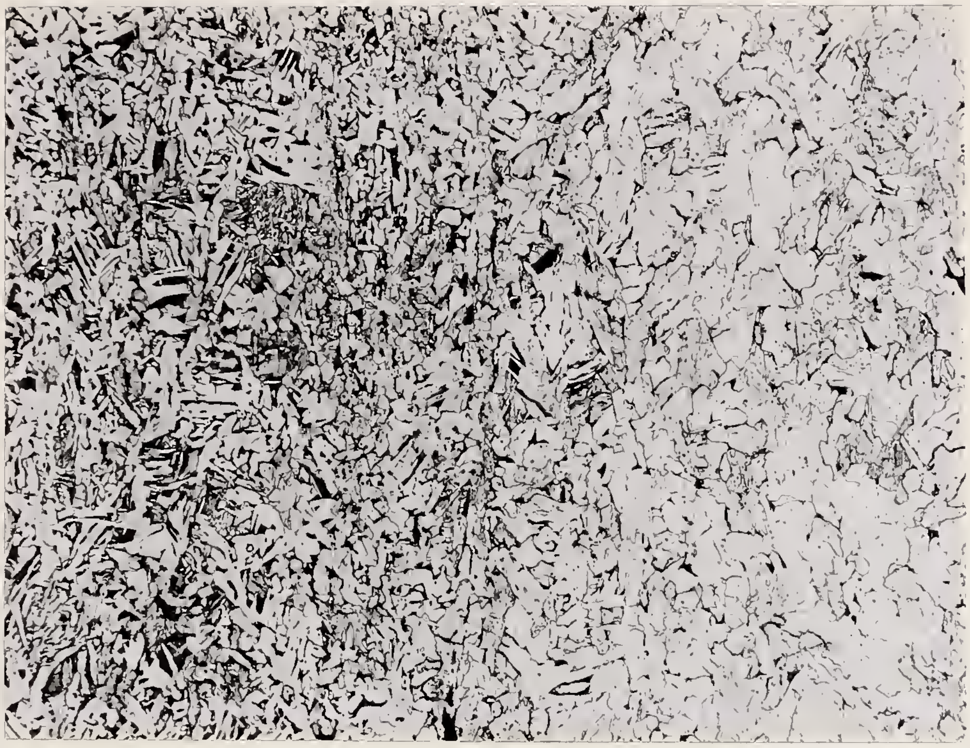

Figure 27. Part of the longitudinal section shown in figure 4 at a higher magnification and at a different orientation. The junction between the two components is vertical in the center of the photomicrograph. The microstructure is different on either side of the junction.
Etchant: 1% nital X 50

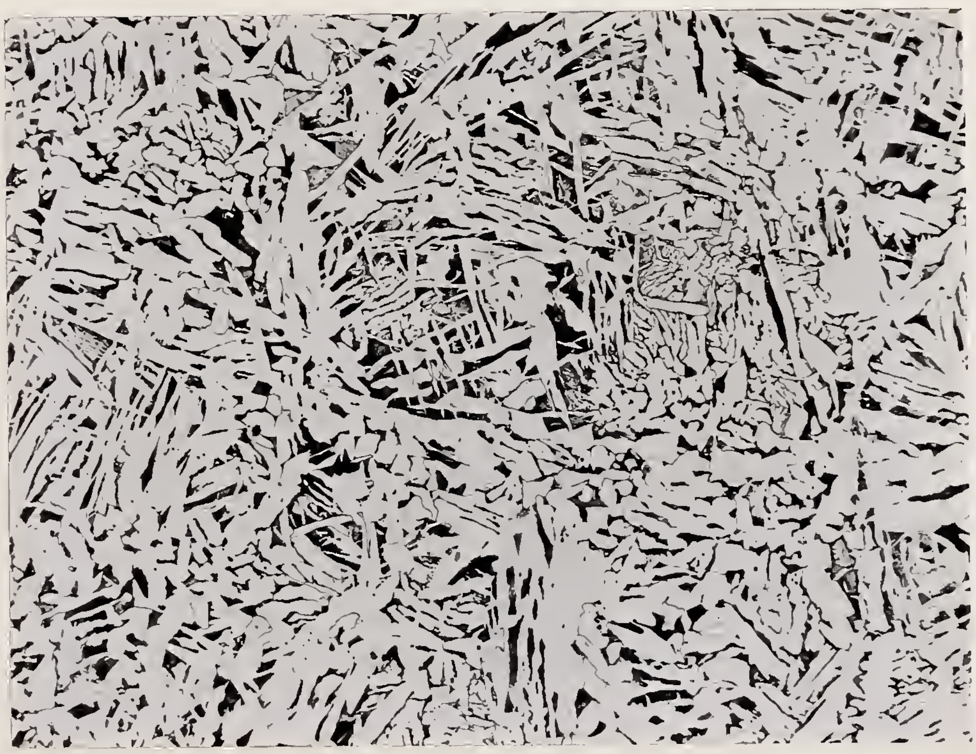

Figure 28. Transverse section through one of the components of bar B6 exhibiting a Widmanstaaten structure.
Etchant: 1% nital X 100

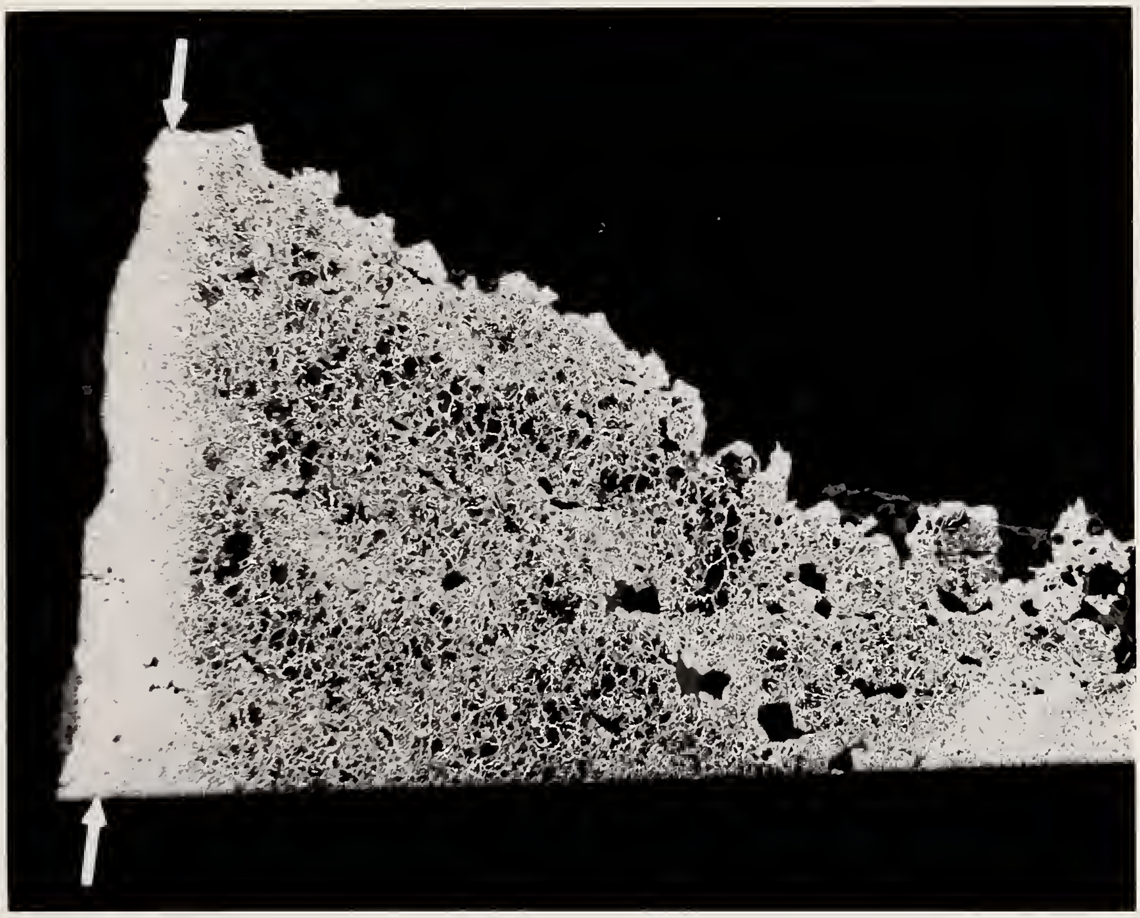

Figure 29. Longitudinal section through bar B5. The longitudinal axis of the bar is vertical in the figure. The surface of the bar is vertical at the left. The arrows indicate a region along the surface that is low in carbon compared to the rest of the material in the component.
Etchant: 1% nital X 12

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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 Bureau of Aviation Safety, National Transportation Safety Board, submitted six bar segments from the collapsed bridge over the Yadkin River in Siloam, North Carolina, to the NBS Mechanical Properties Section for examination. Three of the six bars had fractured in the field. All six of the bars were found to consist of two components that had apparently been forge welded together. Two of the three bars that had fractured in the field had partially fractured through forge welded junctions between two bars.

Laboratory tensile tests were performed on two as-received bars which already contained flaws at the junctions. These tests resulted in fracture at the junction in one bar, and away from the junction in the second bar. Another test of the second bar resulted in fracture at the junction. All of the failures at junctions (two in the field and two in the laboratory) plus the one field fracture not occurring at a junction exhibited very little ductility.

Three other laboratory tensile tests resulted in fractures not at junctions that exhibited good ductility.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Brittle fracture; ductile fracture; forge welding; impact; stress corrosion cracking

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