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DEPARTMENT OF TRANSPORTATION
OFFICE OF PLANNING AND RESEARCH

RESEARCH PROJECT

No. 98-32-02

Materials-Related Forensic Analysis and Special Testing, Pennsylvania Department of Transportation

"Metallurgical Investigation of Reinforcing Steel"

Final Report
December 2000

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13. ABSTRACT (Maximum 200 words)
Subject: Final Report. The purpose of Work Order No. 98-32-02 02 is to investigate and determine the cause of the reinforcing steel bend failures of #5 bar stirrups and the cause for the presence of longitudinal crack-like defects in #11 bars, with a rapid response effort. Determine chemical composition, microstructure, and tensile properties of rebar samples. Determine hardness, microstructure, and composition of broken bar near break area. Perform fractographic examination of fracture surface of broken bar (visual and SEM) to identify possible material defects and fracture mechanism(s). Prepare metallographic cross-section through fracture region if warranted. Prepare report including test results and probable cause.

14. SUBJECT TERMS
reinforcing steel bend failures, chemical composition, microstructure, tensile properties of rebar samples, hardness, microstructure, and fractographic examination , SEM, metallographic cross-section through fracture region

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"Metallurgical Investigation of Reinforcing Steel"

PREPARED BY: MICHAEL BOYLE, VICE PRESIDENT, P.R.,
VALLEY FORGE LABORATORIES, INC.
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LEHIGH UNIVERSITY

DATE: December 12, 2000

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The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the U. S. Department of Transportation, Federal Highway Administration or the Commonwealth of Pennsylvania at the time of publication.

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WORK ORDER 98-32-02
METALLURGICAL INVESTIGATION OF REINFORCING STEEL

STATEMENT OF THE PROBLEM

During the construction of a bridge deck on SR 0228, Section 241 in District 10-0, epoxy-coated reinforcing steel was found to break during field bending by mandrel and arm strength. The steel was traced to product produced by Co Steel (New Jersey). Due to schedule considerations the fabricator replaced all the steel on the site from the same "heat" number. Steel from another manufacturer, SMI (North Carolina) was also shipped to the District 10-0 jobsite. Initially, both sources were investigated.

Initial findings issued by PennDOT's MTD are summarized here:

Steel Supplier:	Co-Steel (bar#'s: 1, 2, 3)	SMI (bar#'s: 1, 2, 3)	**Remarks:**
Yield, psi	64.912; 65,784; 64.296	63,755; 64.265; 64.429	**PASS**
Ultimate tensile strength	106.645; 107,355; 106.477	107,906: 108.135; 108,019	**PASS**
Elongation	12%: 12%; 12%	12%; 12%: 13%	**PASS**
Bend Test w/ 2.1875" Dia. Mandrel	First bar broke in half. Other two passed	Third bar broke in half. Other two passed	**FAILURE**
Additional Samples:	Stirrups w/ 90° bends	-----------------------------	**CRACKED**

Although the chemistry as stated by the fabricator is in compliance and ASTM A 615 strength characteristics are passing, the issue remains as to the cause of the bend failures.

The purpose of this Work Order was initially directed to investigate and determine the cause of the reinforcing steel bend failures of #5 bar stirrups and subsequently to determine the cause for the presence of longitudinal crack-like defects in #11 bars, with a rapid response effort as per Research Project No. 98-32. This investigation was eligible for inclusion in Contract 359832 under the topic, "Forensic Analysis Special Testing," and was related to potential construction failure(s) due to the nature of construction work in progress

Following the Notice-to-Proceed on August 22, 2000 the immediate concerns were addressed in TASK I. The meeting at MTD on September 5, 2000 and the concurrent laboratory investigation at ATLSS Engineering Research Center at Lehigh University resulted in the issuing of the September 20, 2000 Monthly Report. Prior to the VFL Notice-to-Proceed on August 22, 2000 PennDOT personnel conducted an ongoing statewide series of inspections. The review of the results of the statewide inspections and elements of the September 5, 2000 meeting were anticipated in the scope of the Work Order as TASK II. Subsequently, the issues related to the presence of longitudinal crack-like defects in #11 bars were taken up with additional samples.

Two reports were issued by ATLSS Engineering Research Center. The initial report addresses the TASK I issues and is so located in this FINAL REPORT. The second report summarizes the events as well as the findings of TASK II, TASK III and is here located in TASK IV.

SCOPE OF SERVICES

TASK I:

Valley Forge Laboratories in cooperation with ATLSS Research Laboratories as prequalified member of Research Project No. 98-32, examined and analyze samples made available by MTD on and after 8/18/00.

The following report was initially issued on September 20, 2000 as a Monthly Report.

LEHIGH
University

Center for Advanced Technology
for Large Structural Systems
117 ATLSS Drive
Imbt Laboratories
Bethlehem, PA 18015-4729
(610) 758-3535 Fax (610) 758-5553
http://www.lehigh.edu/~inatl/inatl.html

September 18, 2000

Mr. Michael Boyle
Valley Forge Laboratories, Inc.
Six Berkeley Road
Devon, PA 19333

Re: Metallurgical Investigation of Reinforcing Steel - Task I
PennDOT Work Order 98-32-02

Dear Mike:

Following is a summary of my evaluation of the failed reinforcing bar from the District 10-0 bridge site and characterization of material properties of the #5 reinforcing bars provided by PennDOT.

Introduction

As part of an investigation by Valley Forge Laboratories to determine the cause of a reinforcing bar fracture which occurred during construction of a bridge deck on SR 0228 Section 241 in District 10-0, ATLSS Engineering Research Center at Lehigh University was engaged as a team member to perform a fractographic and metallurgical evaluation of the failed reinforcing bar in addition to evaluating other reinforcing bars associated with the failure as outlined in Task I of Work Order 98-32-02 entitled "Metallurgical Investigation of Reinforcing Steel".

On August 22 test samples for evaluation were delivered to the ATLSS Laboratories which included the fractured #5 bar stirrup, tension and bend specimens tested by PennDOT-Material Testing Division on reinforcing bars obtained from the construction site, and additional samples to verify the results obtained by PennDOT on these materials.

It was reported that the failed #5 epoxy coated reinforcing bar fractured during field bending. Documentation indicated that the failed stirrup was supplied by Co-Steel, Sayreville, NJ (Heat No. N16416). Reinforcing bar from another supplier, SMI (Heat No. 27778) was also used at the jobsite and was included in the evaluation.

I. Fractured Stirrup

I.1 Fractographic Examination

An overall view of the the failed epoxy coated #5 reinforcing bar received for examination is shown in Figure 1. Enlarged views of the fracture area in the bend region of the bar and fracture surfaces are shown in Figures 2 and 3, respectively. As received, the crack surfaces were largely covered with a light layer of corrosion product suggesting that a crack may have existed in the bar for a period of time before complete fracture. The reddish-brown color was consistent with corrosion product formed by exposure of the crack surfaces to the weather. The bright fracture area near the inside radius of the bar delineates the uncracked cross-section prior to the final break and represents about 10% of the bar cross-section.

Indications of small surface cracks were also evident in the outer radius of the other bend in the stirrup (see Figure 4). These were all located in the toe area of the bar deformations similar to the location of the fracture in the failed bend (see Figure 3). A longitudional cross-section through these surface cracks verified the existence of fine cracks penetrating the reinforcing bar at these locations as shown in Figure 5. These cracks are also seen to form at the toe of the bar deformation. The depth of the cracks were about 0.015-0.025 in.

The corrosion product on one crack surface was removed by a brief ultrasonic cleaning in Alconox detergent prior to microscopic examination with the scanning electron microscope (SEM). The appearance of the crack surface after removing the corrosion product is shown in Figure 6. A low magnification (4.8X) view of the crack surface as imaged by the SEM is shown in Figure 7. Higher magnification views of the areas marked "a" and "b" representing the area originally covered with corrosion and the bright final fracture region, respectively, are shown in Figure 8. The region originally covered with corrosion product showed dimple fracture associated with ductile fracture over the entire region. No indication of a material defect or different fracture mechanism was observed at the toe of the bar deformation where the crack presumably initiated. In contrast, the final break region (region "b") showed cleavage fracture over the entire area, not uncommon in low toughness materials containing large initial cracks.

I.2 Physical Properties

The chemical composition and microstructure of the reinforcing bar material was obtained to determine if the cracking could be attributed to metallurgical causes. The chemical analysis was determined by a commercial testing laboratory using standard spectrographic methods. The lab test report is reproduced in Appendix A with the stirrup analysis identified as "Field". The analysis indicates that the bar material is comparable to a 1044 carbon steel. The phosphorus content conforms to the product analysis requirements of ASTM A615 reinforcing bar (0.075 max.). Considering its scrap base, no excessively high levels of alloying elements or residual alloying elements were found to be present which might explain the development of cracks in the bend region of the stirrup.

The microstructure of the stirrup material is shown in Figure 9. The microstructure consists predominantly of pearlite with small amounts of ferrite outlining the prior austenite grain boundaries and is typical of an as-rolled 1044 steel.

II. Laboratory Test Specimens

II.1 Fractographic Examination

Initial bend tests performed by PennDOT Material Testing Division on #5 reinforcing bar from the same heat as the failed stirrup (Co-Steel Heat No. N16416) resulted in one failed specimen in three tests. Reinforcing bar from a different manufacturer (SMI Heat No. 27778) also used in the affected bridge deck was also tested and also resulted in one premature fracture in three tests. Both fractures were examined fractographically for comparison to the fracture in the failed stirrup. The two fractured test specimens and corresponding fracture surface appearance are shown in Figures 10 and 11. In both cases the bar failed after bending approximately 90 degrees. Test #1 from Heat No. N16416 developed a thumbnail tear prior to fracturing brittlely. The fracture initiated at the toe of a bar deformation as also observed in the failed stirrup. Test #3 from Heat No. 27778 developed a similar thumbnail tear before fracturing brittlely, however, the tear formed in a smooth area between bar deformations. SEM examination of the crack surfaces verified the fracture mechanisms in both cases and did not reveal a material defect at the crack origin in either bar.

II.2 Physical Properties

Chemical composition and microstructure of the two failed bend specimens were determined for comparison to the failed stirrup along with a specimen which passed the bend test. The results of the chemical analyses are provided in Appendix A . The analyses labeled N16416-1 and 27778-3 correspond to the "failed" bend specimens and N16416-2 and 27778-1 corresponds to the "pass" bend specimens for each heat of material. Both heats of steel from the two manufacturers have similar compositions comparable to a 1044 carbon steel with similar levels of alloy and residual elements. There is also no distinct difference in compositions between bars from the same heat which passed or failed the bend test. There is also no difference between the composition of the failed stirrup and any of these other bars. No distinct difference in microstructures of these materials was observed as well as shown in Figure 12.

III. Mechanical Property Tests

Initial tension tests #5 bar from Co-Steel Heat No. N16416 and SMI Heat No. 27778 performed by PennDOT Material Testing Division both resulted in tensile properties which satisfied ASTM A615 Gr. 60 reinforcing bar. As indicated above the first bend test performed on Co-Steel Heat N16416 failed in bending, however, two subsequent re-tests both passed the bend test. Similarly, one bend test of three bars from SMI Heat No. 27778 also failed the bend test.

Tension and bend tests were repeated on these materials to verify the initial PennDOT test results. Results of the tests are tabulated in Table 1 along with the initial PennDOT test results for comparison.

TABLE 1 MECHANICAL PROPERTY TEST RESULTS
(#5 Epoxy Coated Bars)

Steel Supplier/Heat #	Y.S. (ksi)	T.S. (ksi)	Elong. (%)	Bend Test	Notes
Co-Steel / N16416 ( )= PennDOT Test	65.48 66.13 65.00 (69.91) (65.78) (69.30)	108.22 107.42 107.10 (106.45) (107.35) (106.48)	12.5 13.2 12.5 (12.0) (12.0) (12.0)	PASS PASS PASS (FAIL)* (PASS) (PASS)	*Fracture along toe of deformation
SMI / 27778 ( )= PennDOT Test	64.03 64.19 63.71 (63.76) (64.27) (64.43)	107.90 107.90 107.74 (107.91) (108.14) (108.02)	13.2 11.8 12.5 (12.0) (12.0) (13.0)	PASS PASS FAIL** (PASS) (PASS) (FAIL)**	**Fracture between deformations

The tension tests from both heats of bars satisfied Gr. 60 strength requirements and were consistent with the earlier PennDOT test results. Interestingly, all three Co-Steel Heat N16416 bend tests were satisfactory and as also occurred in initial PennDOT tests one of three bend specimens from SMI Heat 27778 failed the bend test. Additional bend testing of Co-Steel Heat No. 16416 bars by PennDOT not reported here have produced a larger frequency of bend test failures than shown in the table.

IV. Bar Deformations

Since cracking in the failed stirrup and failed bend specimen from Co-Steel Heat N16416 appeared to initiate at the toe of bar deformations in both cases, the profile of the deformations of the bars was examined in detail.

Figure 13 shows a typical bar deformation toe profile obtained from the failed stirrup. The toe of the deformation is seen to be scalloped and rises steeply to the crest of the deformation. A typical deformation profile observed in the SMI Heat 27778 bar is shown in Figure 14 for comparison. In this case the bar deformation rises gradually without any scalloping at the toe. A similar scalloped toe profile was observed in other bar samples from Co-Steel Heat No. 16416 (see Figure 15). The toe profile observed in bars from this heat are clearly more unfavorable as strain concentrators and may be the cause for the cracks observed in the bend area of the failed stirrup and high incidence of bend test failures in bars from this particular heat.

The observed irregular toe profiles are believed to be caused by wear of the rolls which introduce the bar deformation over their life. It is interesting that the scalloped toe profile was observed on only one side of the reinforcing bar. The toe profile in the opposing set of deformations appeared smoother similar to the SMI bar deformations (see Figure 16). This suggests that one roll may become worn sooner than the other. This may also help explain the statistical nature of the bend test results in Heat N16416 where some tests pass and some fail since the set of deformations exposed to tension in the bend test would be random. .

V. Summary and Conclusions

1. Fractographic examination of the failed #5 reinforcing bar stirrup indicated that the fracture initiated at the toe of a bar deformation in the bend area and propagated by a ductile tearing mechanism. Corrosion product on the crack surface indicated that the

crack existed in the bar prior to its final failure and covered approximately 90% of the cross-section. Metallographic examination of the other bend area in the stirrup revealed shallow cracks in the outer radius of the bar at the toe of bar deformations which appeared to be introduced during bending. The large tear observed at the fracture likely propagated from a similar shallow crack during latter handling.

2. Characterization of the fracture and physical properties of the failed stirrup did not indicate a metallurgical cause for the cracks observed in the bend areas of the stirrup. Characterization of the physical and mechanical properties of bars produced from the same heat of steel as the stirrup (Co-Steel Heat No. 16416) indicated that the bars had similar metallurgical properties as the fractured stirrup and conformed to the mechanical property requirements of ASTM A615 Gr. 60. Although satisfying the specification requirements bend tests performed by PennDOT on a larger test sample showed a high incidence of failures with fractures developing at the toe of bar deformations.

3. Characterization of the physical and mechanical properties of #5 bars produced by a different manufacturer (SMI Heat No. 27778) indicated similar physical and mechanical properties as the Co-Steel heat and also satisfied A615 Gr. 60 requirements.

4. Examination of the bar deformations in the failed stirrup indicated an irregular profile in the toe area of the deformation where cracks were observed to form. Identical irregular profiles were also observed in other bars from this heat of steel. A smooth profile was observed in bars from the SMI heat of steel. The irregular profile would elevate the strain concentration at the toe location during bending and is likely the cause for the cracks observed in the failed stirrup and also for the increased occurrence of fractures observed in bend tests of bars from this heat of steel.

Sincerely yours,

Eric J. Kaufmann

Eric J. Kaufmann
Senior Research Engineer, ATLSS

encl

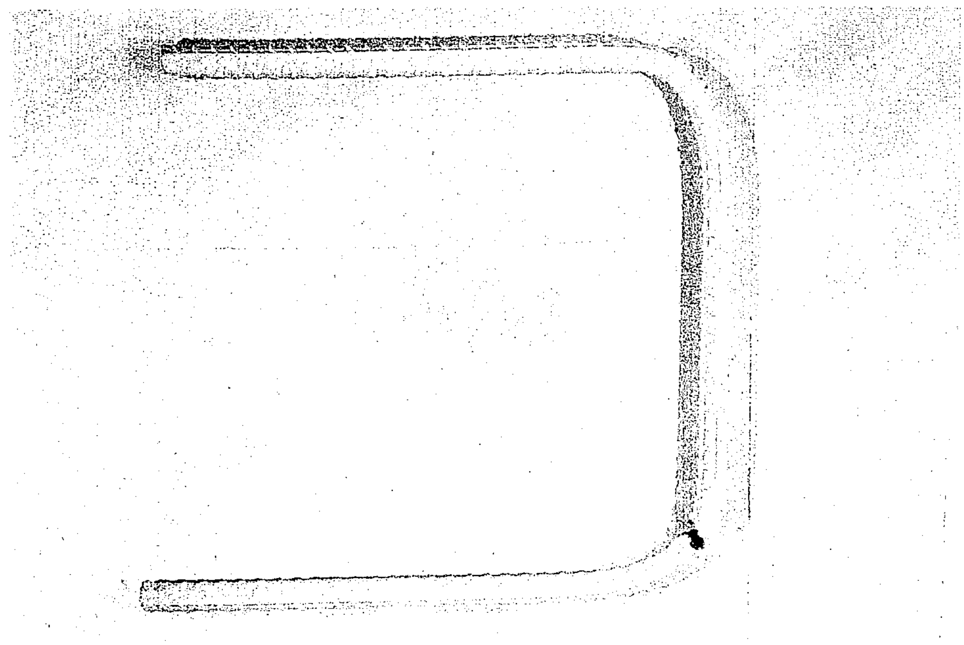


Figure 1 - Fractured #5 Bar Stirrup Removed From Bridge Deck Under Construction on SR 0228, Section 241 (District 10-0).
(8/00/17-2)

Figure 2 - Enlarged View of Fracture in the Bend Region of the Stirrup.
(8/00/17-4)

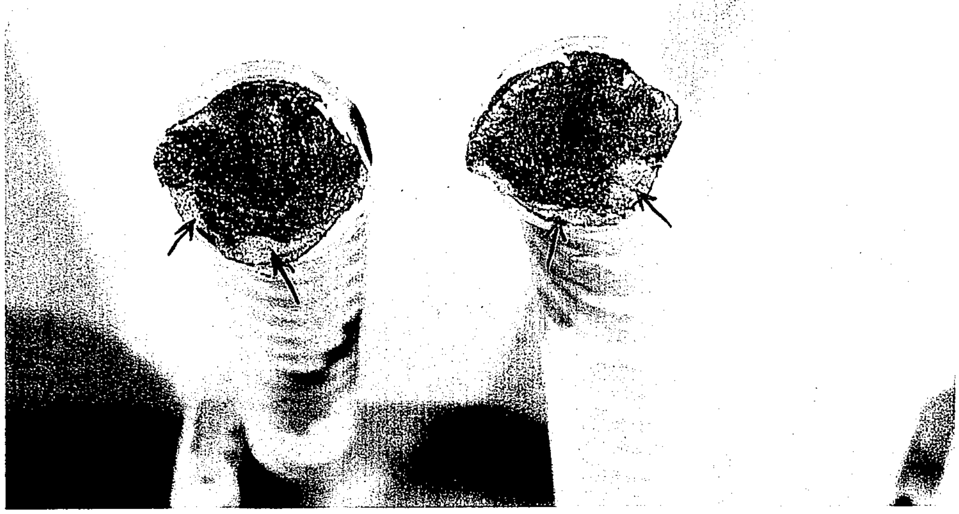


Figure 3 - Corrosion Covered Crack Surfaces (Arrows Show Final Break Region).
(8/00/17-6)

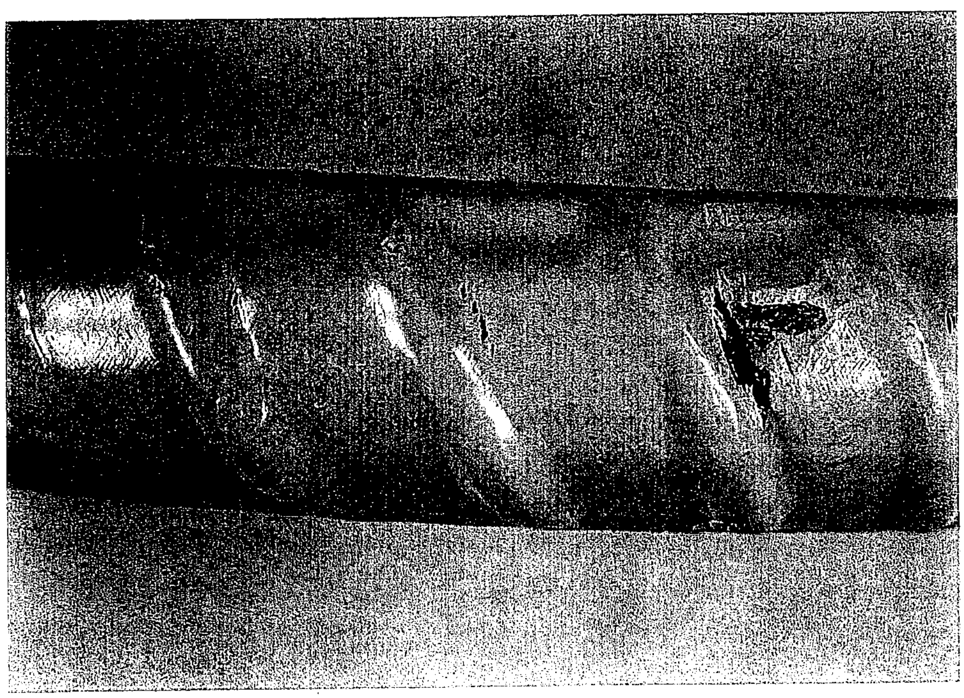


Figure 4 - Small Surface Cracks at Deformations on the Outer Radius
of the Unfractured Bend of the Stirrup.
(9/00/5-2)

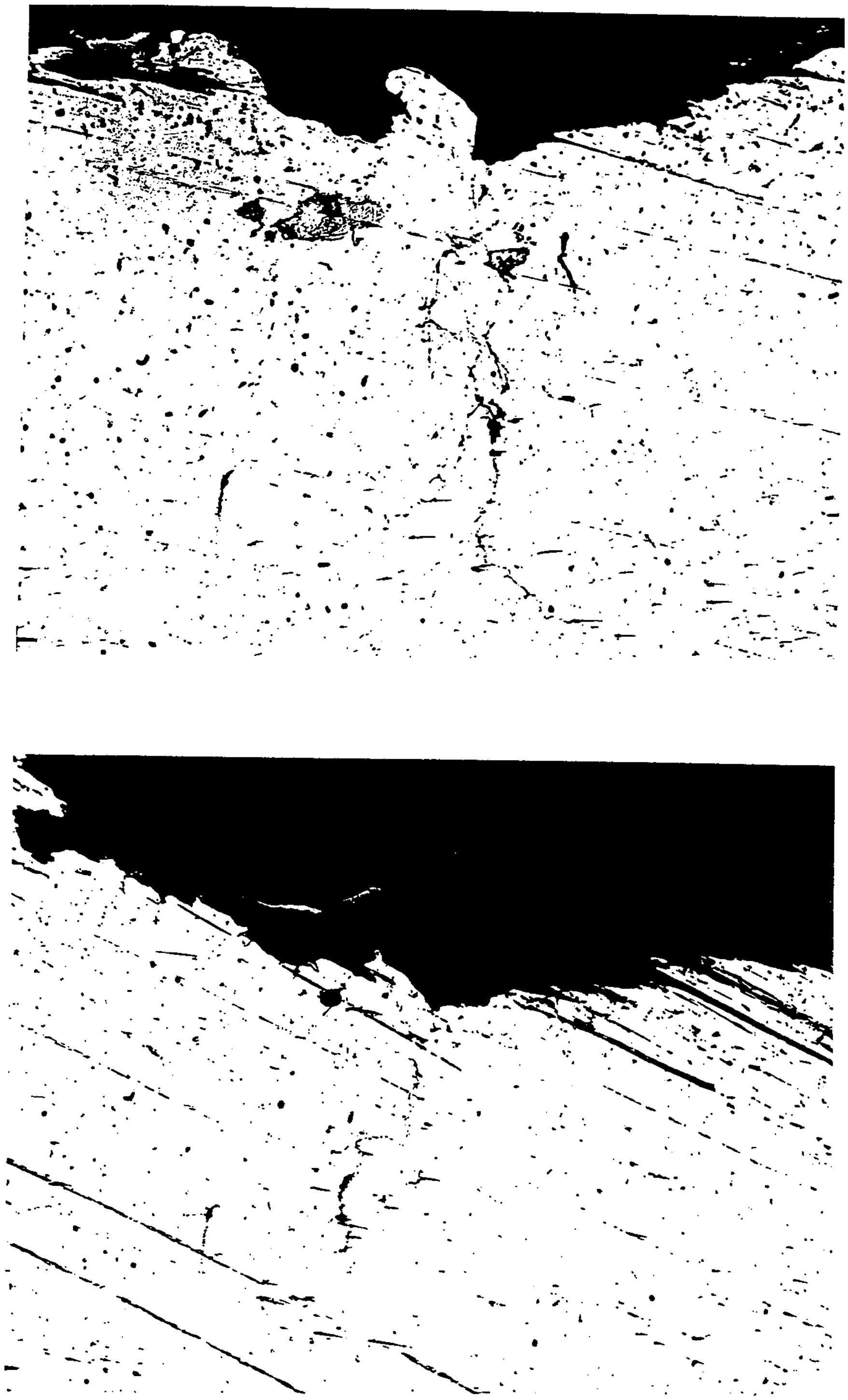


Figure 5 - Cross-sectional View of the Surface Cracks in the Bend Region of the Stirrup Along the Toe of the Bar Deformations (see Figure 4).
[Mag. 100X]

Figure 6 - Appearance of the Crack Surface After Removing Corrosion Product.
(8/00/17-12)

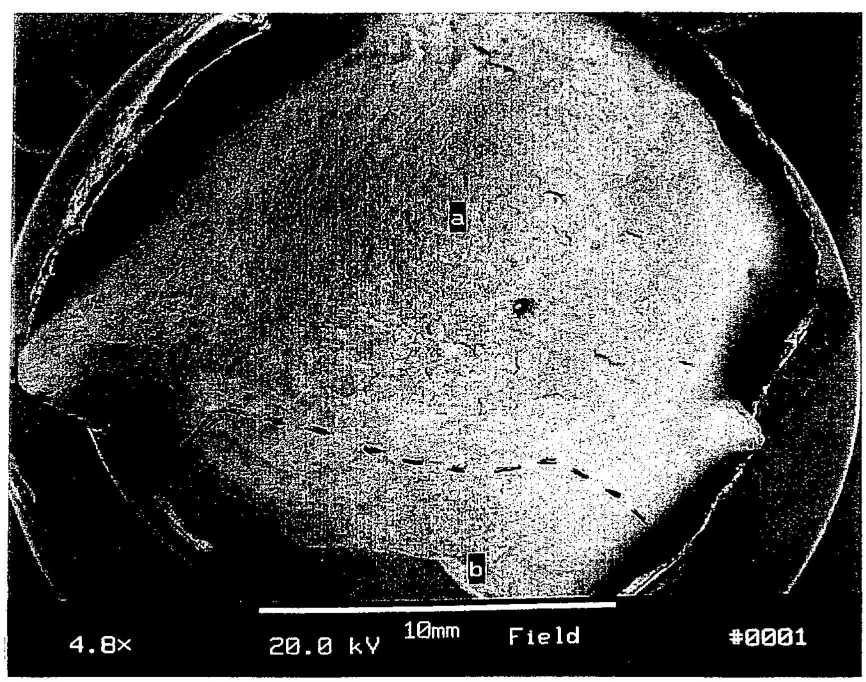


Figure 7 - SEM View of the Crack Surface. [Mag. 4.8X]
(Dashed Line Delineates Original Crack and Final Break Regions)

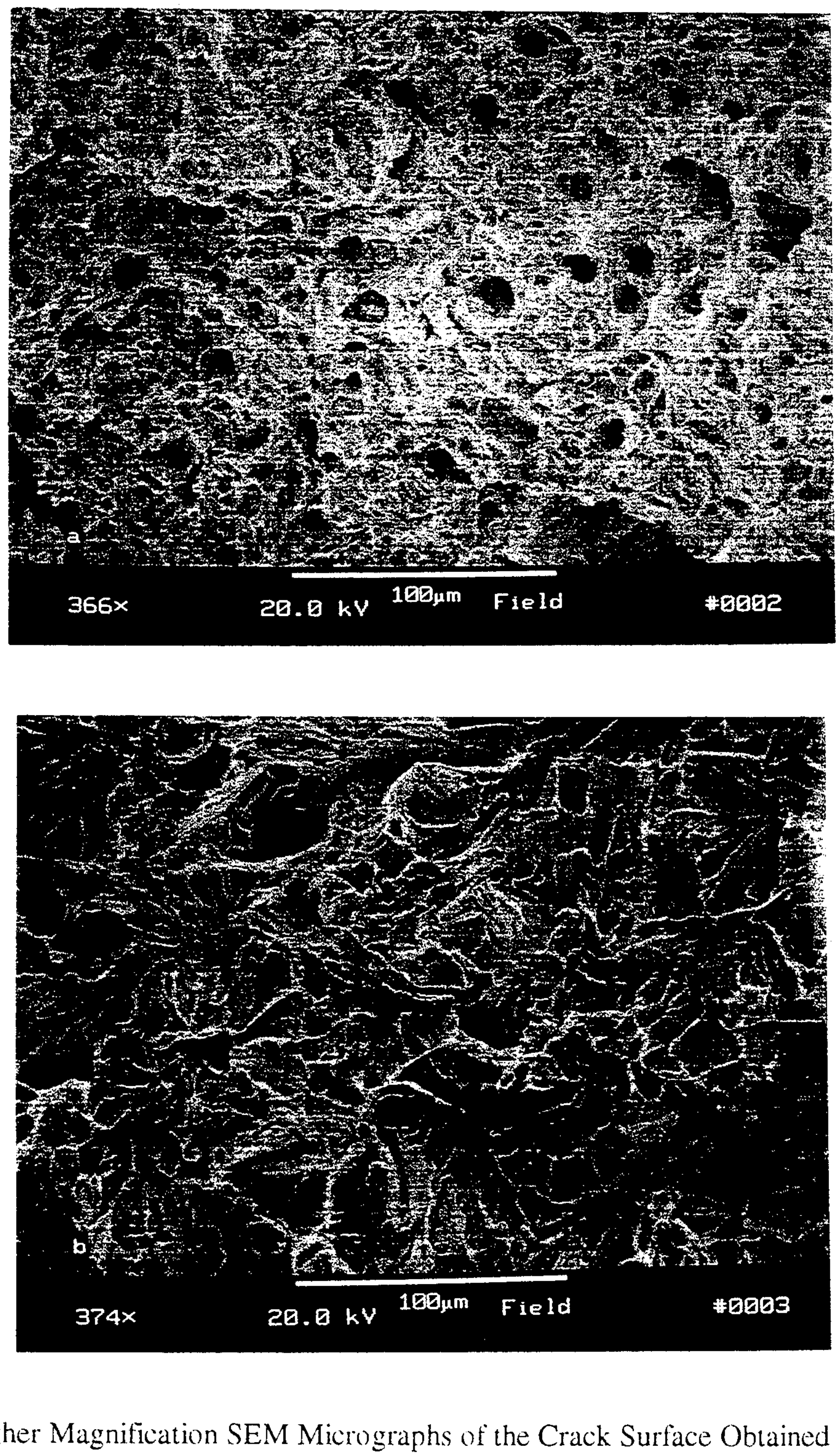


Figure 8 - Higher Magnification SEM Micrographs of the Crack Surface Obtained in the Original Crack Region (Area "a" in Figure 7) Showing Dimple Fracture (Top) and in the Final Break Region (Area "b" in Figure 7) Showing Cleavage Fracture (Bottom).
[Mag. 366X & 374X]

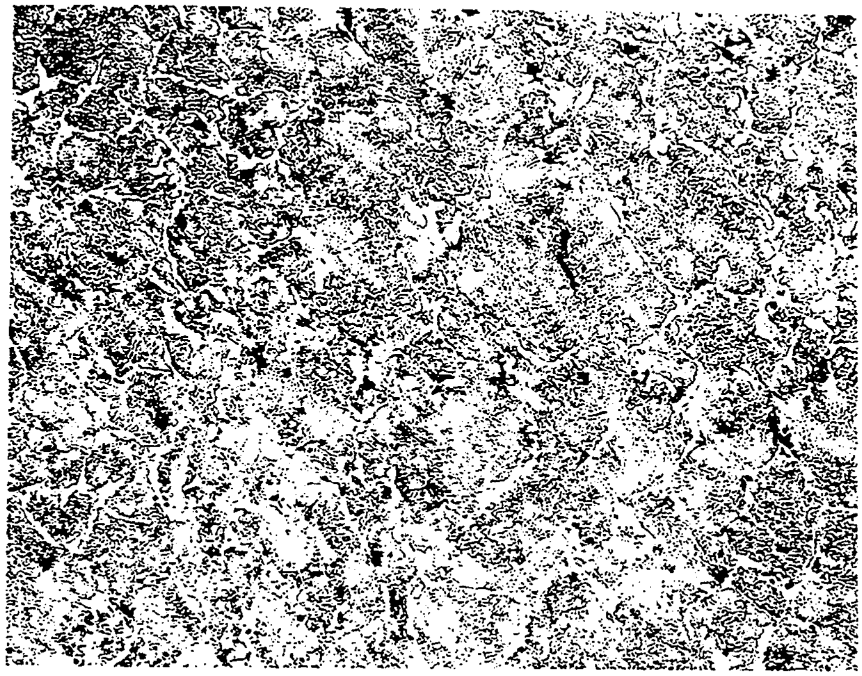


Figure 9 - Microstructure of the Failed Stirrup. [Mag.400X]

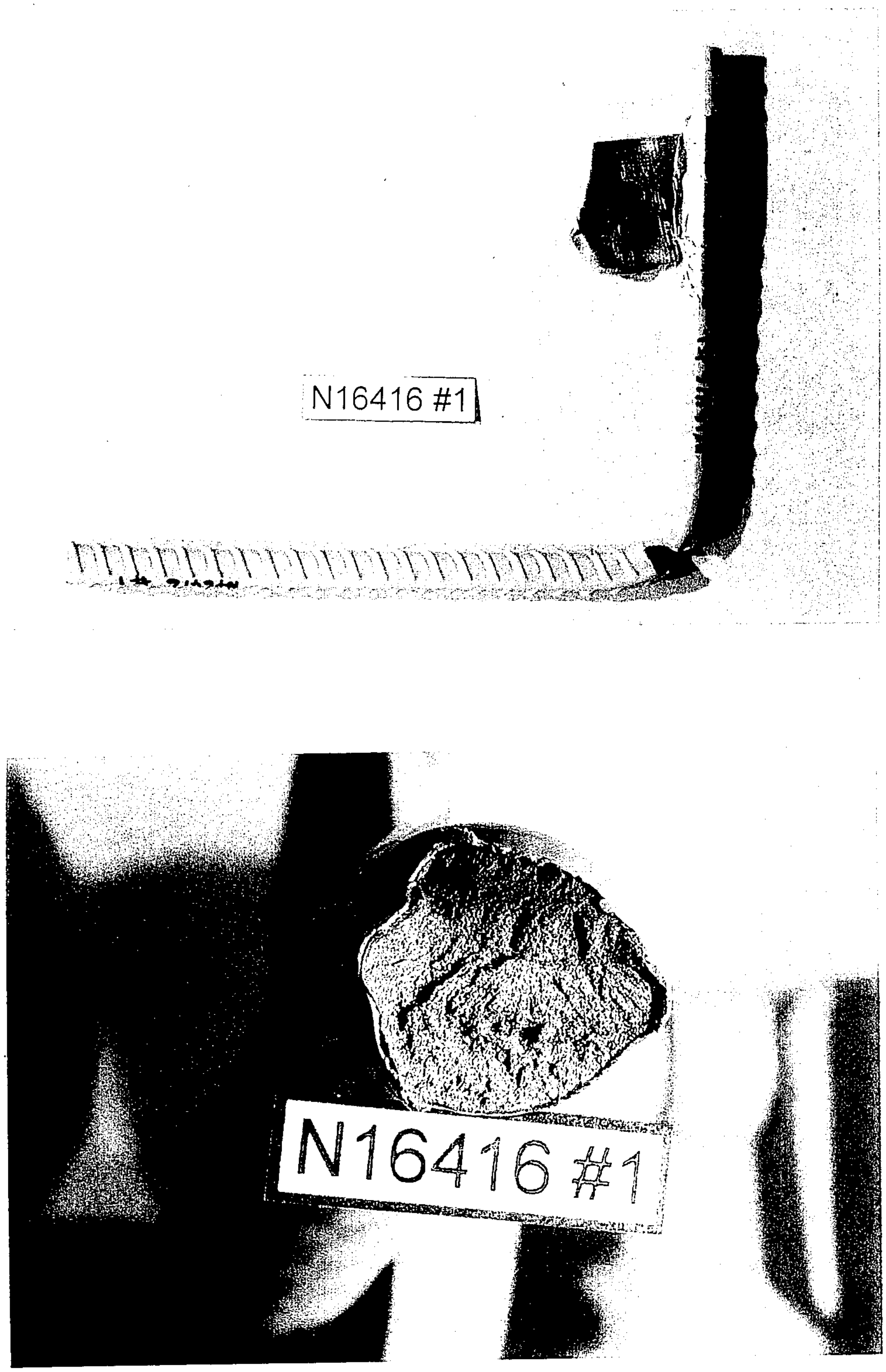


Figure 10 - Failed #5 Bar Bend Test Specimen (Co-Steel Heat No. N16416).
(8/00/19-2 & 8/00/19-8)

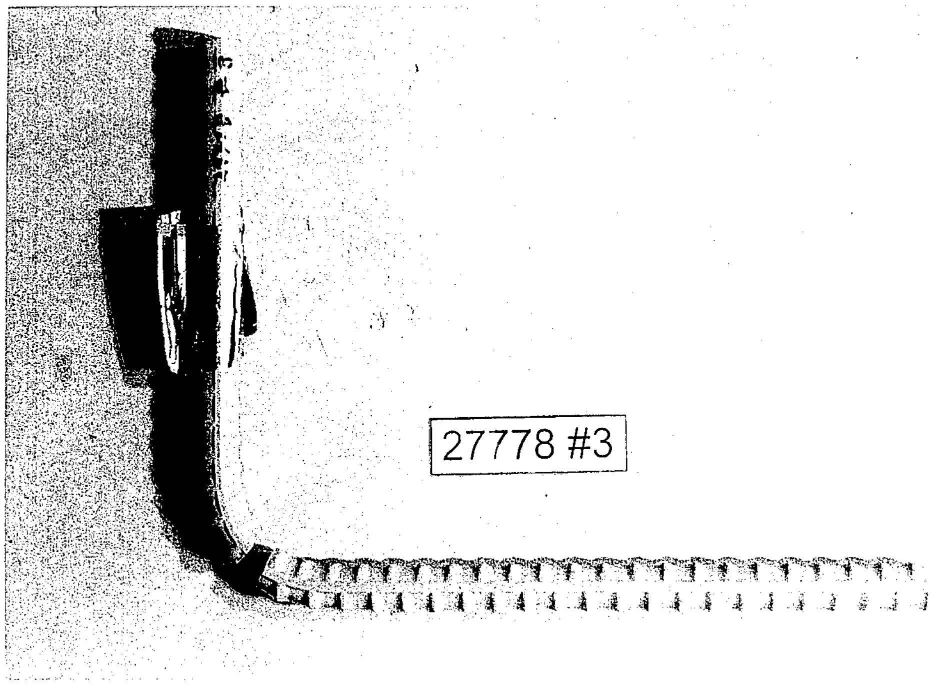
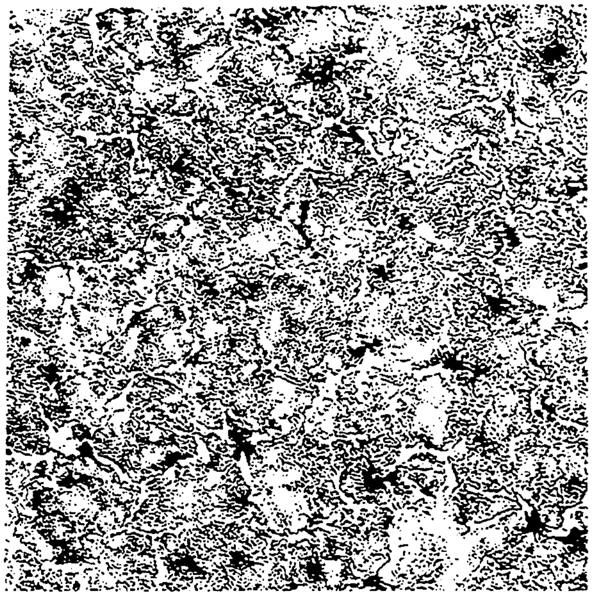
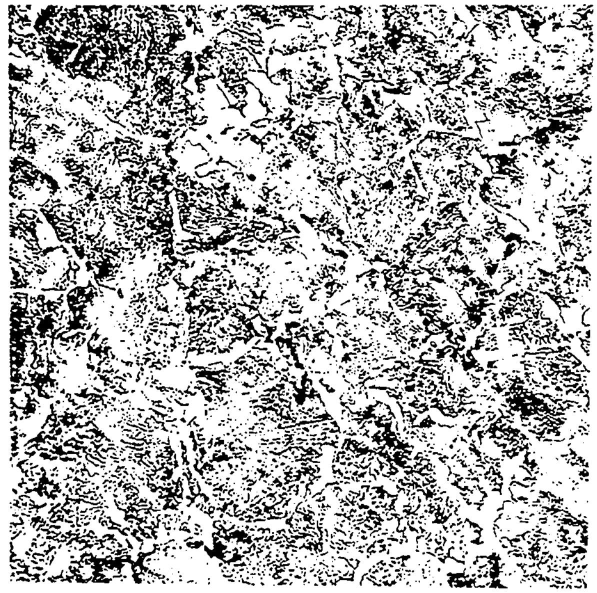


Figure 11 - Failed #5 Bar Bend Test Specimen (SMI Heat No. 27778).
(8/00/19-4 & 8/00/19-6)

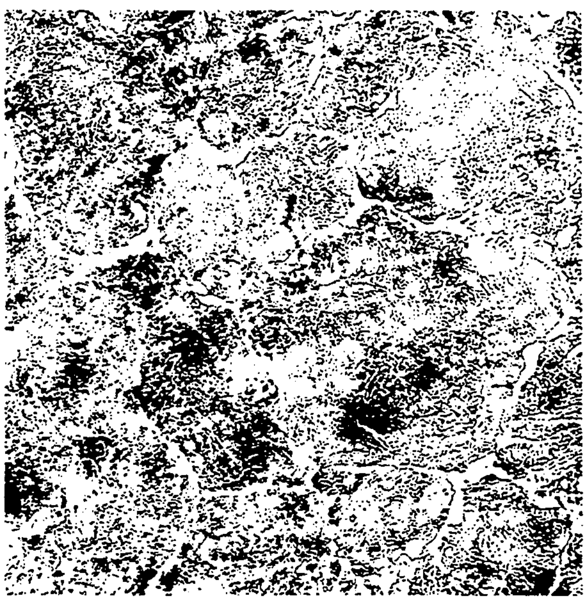


Bend Test-Pass

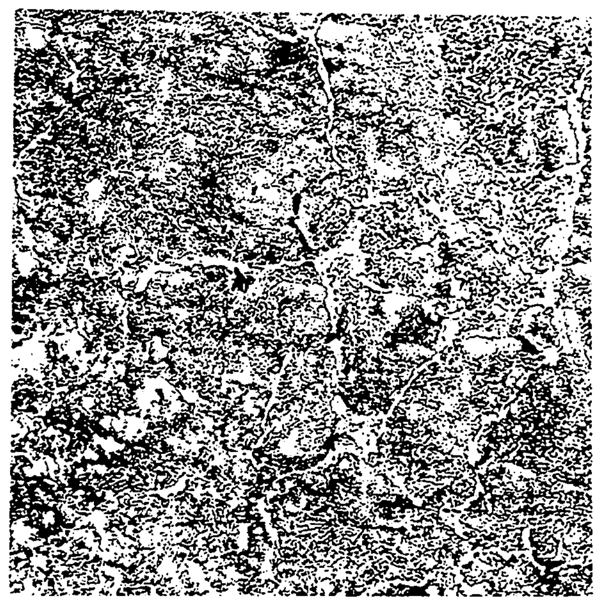


Bend Test-Fail

Co-Steel Heat No. N16416



Bend Test-Pass



Bend Test-Fail

SMI Heat No. 27778

Figure 12 - Microstructures of #5 Bars From Two Manufacturers. [Mag. 400X]

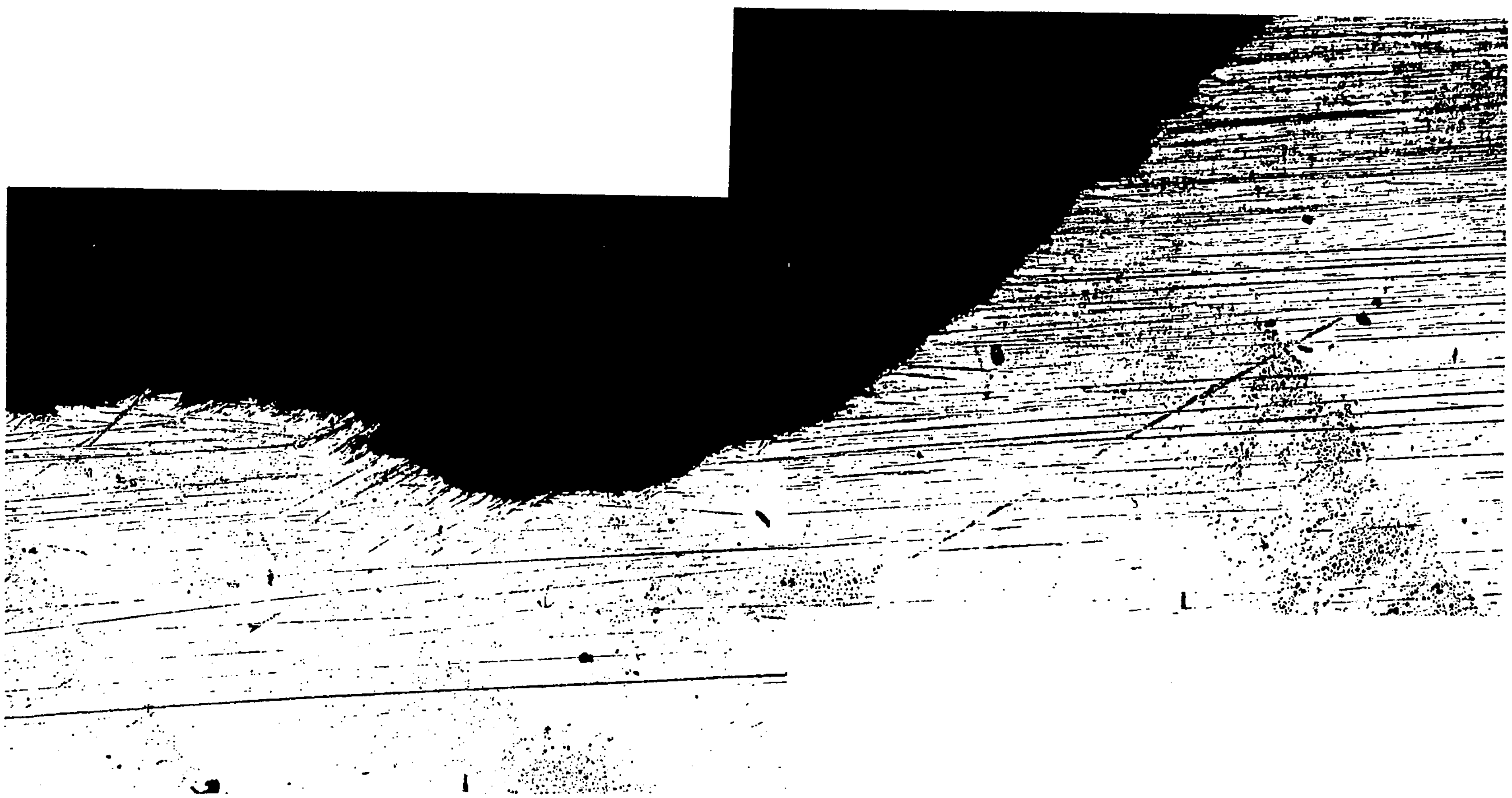


Figure 13 - Typical Toe Profile of Bar Deformation in Failed #5 Bar Stirrup Showing Scalloped Toe Condition.
(Co-Steel Heat No. N16416) [Mag. 100X]

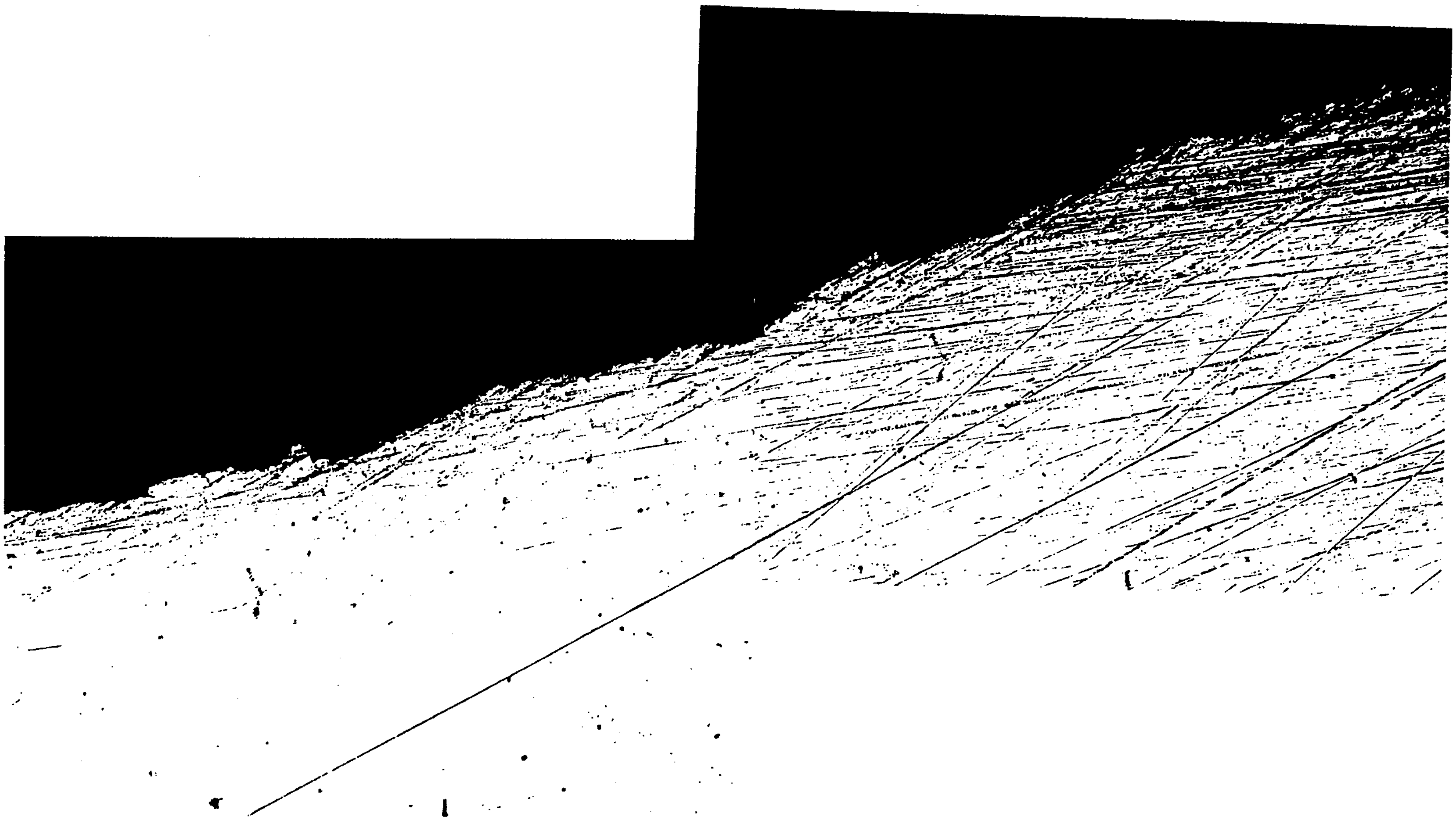


Figure 14 - Typical Toe Profile of Bar Deformation Showing Gradual Sloping Toe Condition.
(SMI Heat No. 27778) [Mag. 100X]

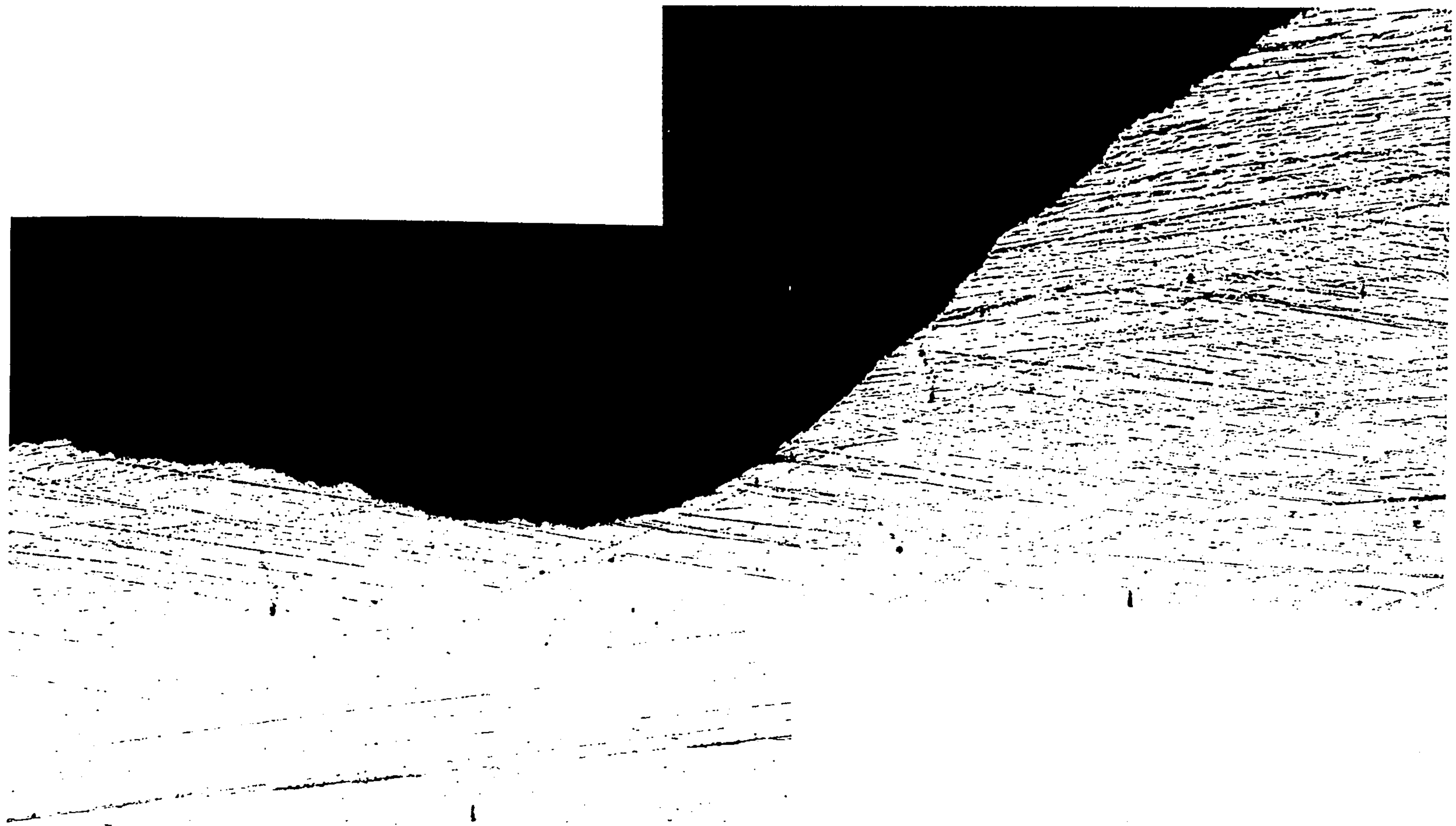


Figure 15 - Typical Toe Profile of Bar Deformation in Bar Showing Scalloped Toe Condition.
(Co-Steel Heat No. N16416) [Mag. 100X]

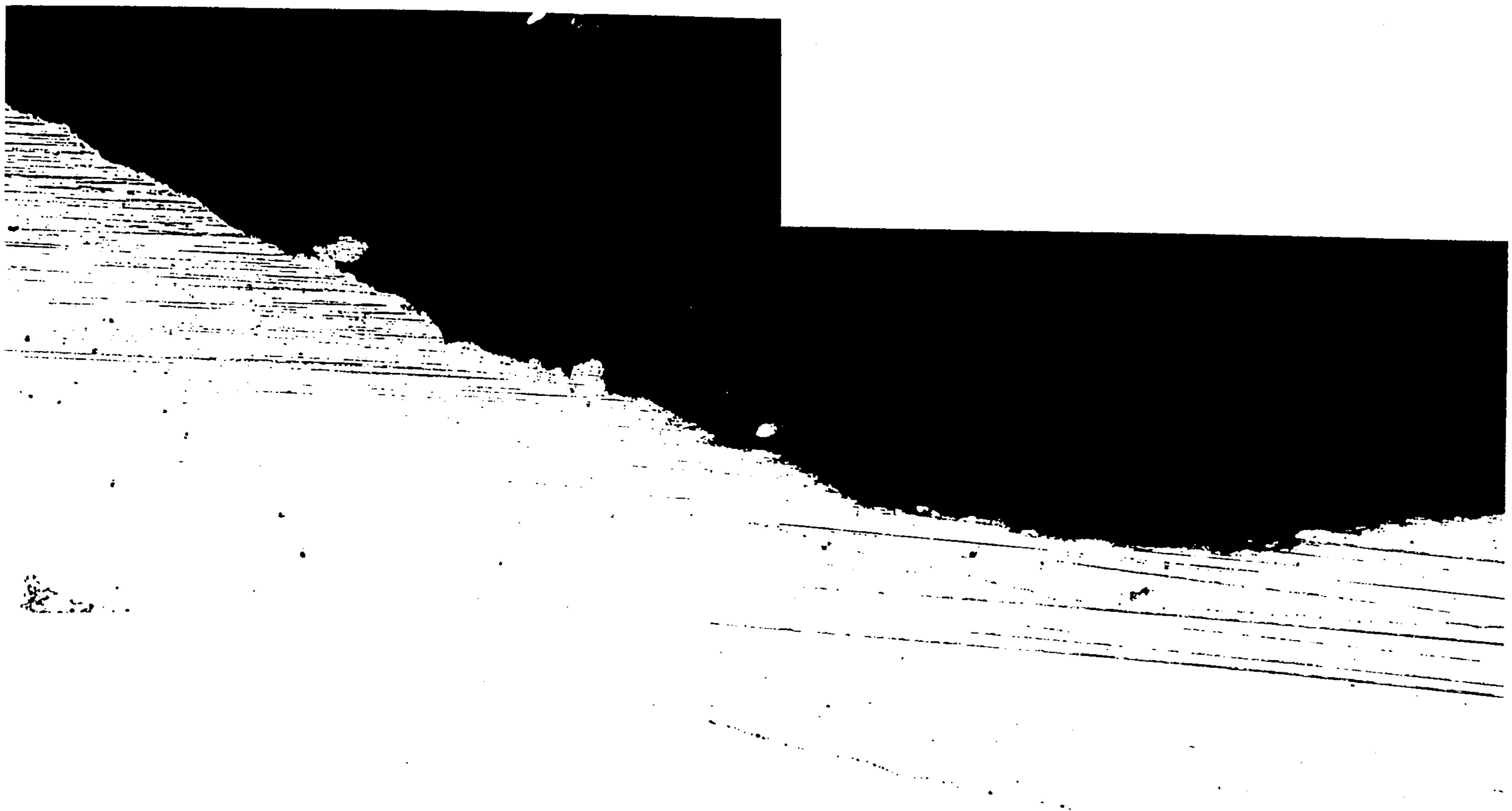


Figure 16 - Typical Toe Profile of Opposite Bar Deformation Without Scalloped Toe Condition (see Figure 15).
(Co-Steel Heat No. 16416) [Mag. 100X]

TASK I
APPENDIX A

Certified Test Report

LABORATORY TESTING INC.
2331 Topaz Drive, Hatfield, PA 19440
TEL: 800-219-9095 • FAX: 800-219-9096

LHU001-00-08-17796

ACCREDITED #0117-01, 02, 03

NADCAP Materials Testing Laboratory NDT (PT, MT, RT, UT)

SOLD TO
Lehigh University
Alumni Memorial Building
27 Memorial Drive West
Bethlehem, PA 18015-3039

SHIP TO
Lehigh University
ATLSS Engr. Research Center
117 ATLSS Dr Imbt Lab
Bethlehem, PA 18015-3039
ATTN: Eric Kaufmann

CUSTOMER P.O.	CERTIFICATION DATE	SHIP VIA
22331	8/30/2000	FAX AND MAIL

DESCRIPTION

5 pcs. Test Pieces, Steel, Identified as N16416-1, N16416-2, 27778-1, 27778-3 and Field
Five pieces of the submitted samples were analyzed in accordance with Customer's Instructions with the following results:

ELEMENT	27778-1	27778-3	N16416-1	N16416-2	FIELD
C	0.45%	0.44%	0.43%	0.44%	0.44%
Mn	0.89%	0.90%	1.02%	1.02%	1.02%
P	0.011%	0.011%	0.016%	0.015%	0.015%
S	0.032%	0.033%	0.042%	0.042%	0.043%
Si	0.20%	0.20%	0.19%	0.19%	0.19%
Cr	0.11%	0.11%	0.080%	0.080%	0.080%
Ni	0.13%	0.13%	0.11%	0.11%	0.11%
Mo	0.074%	0.074%	0.064%	0.064%	0.064%
Al	<0.001%	<0.001%	<0.001%	<0.001%	<0.001%
Co	0.006%	0.006%	0.007%	0.008%	0.008%
Cu	0.37%	0.37%	0.52%	0.52%	0.52%
Nb	0.001%	<0.001%	0.002%	0.001%	0.001%
Ti	0.001%	0.001%	0.001%	0.001%	0.001%
V	0.004%	0.004%	0.004%	0.004%	0.004%
W	<0.001%	<0.001%	<0.001%	<0.001%	<0.001%
Pb	<0.001%	<0.001%	0.002%	<0.001%	0.002%
Sn	0.022%	0.023%	0.019%	0.019%	0.019%
As	0.006%	0.006%	0.008%	0.007%	0.008%
Zr	<0.001%	<0.001%	<0.001%	<0.001%	<0.001%
Ca	<0.001%	<0.001%	<0.001%	<0.001%	<0.001%
Sb	0.004%	0.004%	0.006%	0.005%	0.006%
B	0.0002%	0.0002%	0.0005%	0.0005%	0.0006%
Fe	97.7%	97.7%	97.5%	97.5%	97.5%

The services performed above were done in accordance with LTI's Quality System Program Manual Revision 14 dated 10/8/99. These results relate only to the items tested and this report shall not be reproduced, except in full, without the written approval of Laboratory Testing, Inc. L.T.I. is accredited by A2LA in the Chemical, Mechanical and Nondestructive Fields of Testing. L.T.I. is accredited by NADCAP in the Material's Testing and NDT, MT, PT, RT and UT.

Arnold L. Horoff
QA Manager

By: *Arnold L. Horoff*
Authorized Signature

TASK II

VFL and ATLSS representatives attended the September 5, 2000 meeting with PennDOT to discuss findings and further developments resulting from the statewide PennDOT inspections.

TASK III

Additional samples were provided to ATLSS by MTD for evaluation of the presence of longitudinal crack-like defects in #11 bars.

TASK IV

Eric Kaufmann, Principal Investigator at ATLSS prepare a report investigating the presence of longitudinal crack-like defects in #11 bars. The ATLSS report, here identified as the TASK IV Report was issued to VFL and PennDOT under separate cover. The Prime Researcher, Michael J. Boyle, prepared and submitted monthly progress reports and the FINAL REPORT. The following report was initially issued on September 25, 2000.

LEHIGH
University

Center for Advanced Technology
for Large Structural Systems
117 ATLSS Drive
Imbt Laboratories
Bethlehem, PA 18015-4729
(610) 758-3535 Fax (610) 758-5553
http://www.lehigh.edu/~inatl/inatl.html

September 25, 2000

Mr. Michael Boyle
Valley Forge Laboratories, Inc.
Six Berkeley Road
Devon, PA 19333

Re: Metallurgical Investigation of Reinforcing Steel - Task III
PennDOT Work Order 98-32-02

Dear Mike:

Following are the results of my evaluation of #11 reinforcing bar samples which PennDOT delivered to our laboratories as part of the above referenced investigation. Although unrelated to the original focus of the investigation reported on in my letter report dated 18 September, state-wide inspections of reinforcing bars at current construction sites detected #11 bars at one site which contained longitudinal crack-like defects. These defects typically extended several feet in length and clearly penetrated to significant depths in the bars. The bars were maunfactured by Co-Steel, Sayreville, NJ, the same manufacturer as the #5 epoxy coated reinforcing bars investigated earlier. The evaluation of the bars focused on 1) their conformance to ASTM A615 specification requirements, 2) the effect of these defects on servicability, and 3) the origin of the defects.

I. Test Samples

Six #11 bar samples approximately four feet in length containing longitudinal crack-like defects were provided for evaluation. The heat number of the bars was indicated to be N15361. Visually, the severity of the defects varied ranging from long continuous splits extending the full length of the sample (see Figure 1) to intermittent fine cracks (see Figure 2).

II. Mechanical Properties

Tensile and bend tests were performed to determine whether the bars satisfied the requirements of ASTM A615 Gr. 60. Due to fixturing requirements the bend tests were performed at the manufacturer's facility on September 7 and witnessed by myself and Mr. Chris

Sepko of PennDOT. Continuous and intermittently cracked bars were selected for tension and bend testing. For bend testing the side of the bar containing the crack-like defect was positioned at the outer radius of the bend to subject the defect to maximum tensile strains. Table 1 provides a summary of the test results.

TABLE 1 MECHANICAL PROPERTY TEST RESULTS
(#11 Bars Heat No. 15361)

Sample No.	**Y.S. (0.5%) (ksi)**	**T.S. (ksi)**	**Elong. (%)**	**Bend Test (9.625" dia. Pin)**
ASTM A615 Gr. 60	60 min.	90 min.	7 min.	7d (9.87")
1	70.32	104.6	12.3	-
2	71.49	104.2	13.4	-
3	71.66	106.7	14.7	-
4	-	-	-	PASS
5	-	-	-	PASS
6	-	-	-	PASS

Both the tensile and bend test results indicated that the bars satisfied the mechanical property requirements of ASTM A615 Gr. 60. The longitudinal crack-like defects did not appear to adversely affect the straining behavior of the bars in tension or bending. Figure 3 shows a typical bend test specimen after bending. An enlarged view of the outer radius area containing a longitudinal defect is shown in Figure 4 where it can be seen that the crack-like defect has not extended or opened.

Cracks oriented longitudinal to the primary stress direction are often non-propagating as was observed in this case. The shape of the crack in the vicinity of the crack tip, however, can influence behavior. Longitudinal cracks can propagate if the crack is curved or convoluted. In materials with limited fracture toughness, such as A615 reinforcing bar, these can affect fracture behavior. The test results suggest that the defects in the bars are planar and longitudinally oriented.

III. Chemical Composition

The chemical composition of two bar samples was checked to determine if the cause of the defects was compositional in origin. The analyses were performed by a commercial laboratory using standard spectrographic methods. The lab test report is reproduced in Appendix A. The two analyses are similar and consistent with a 1043 carbon steel. Although there are no limitations in the specification for sulfur, the analyses show a fairly high level (0.048-0.058). Residual element content is not unusually high and is not likely cause for the longitudinal defects observed.

IV. Metallographic Examination

Figure 5 shows an etched cross-section through a longitudinal defect. An enlarged view of the defect is shown in the lower photograph. The depth of the defect is approximately 1/8 in. and is relatively planar and longitudinal. Figure 6 shows a higher magnification view of the crack (100X). The material adjacent to the crack is largely ferrite (white etching) in comparison to the general pearlitic (dark etching) microstructure of the material. This decarburized area in which the defect resides suggests that the defect existed prior to hot-rolling of the bar and was likely associated with a surface defect in the original continuously cast billet. Closer examination of the crack region showed a clustering of non-metallic inclusions along the crack path also consistent with this conclusion. Apparently the defect in the billet was not detected prior to hot-rolling into bars and subsequently remained through the rolling process.

V. Summary and Conclusions

1. The mechanical properties (tension and bend) of the #11 bar samples provided which contained longitudinal crack-like defects satisfied the ASTM A615 Gr. 60 specification requirements. The defects did not appear to affect the strength or ductility characteristics of the bars.

2. The chemical composition and microstructure was found to be typical for this grade of material and did not indicate a cause for the development of the defects.

3. Metallographic examination of the defect condition provided evidence that the origin of the defects was a surface defect in the original cast billet which was not detected during manufacturing and was subsequently rolled into the reinforcing bar.

4. Considering the observed planar shape and longitudinal orientation of the defect it is unlikely that they would deteriorate the mechanical properties of the bars under service conditions. Possible effects on long term corrosion resistance may need to be considered.

Please feel free to contact me if you have any questions.

Sincerely yours,

Eric J. Kaufmann

Eric J. Kaufmann
Senior Research Engineer, ATLSS

encl

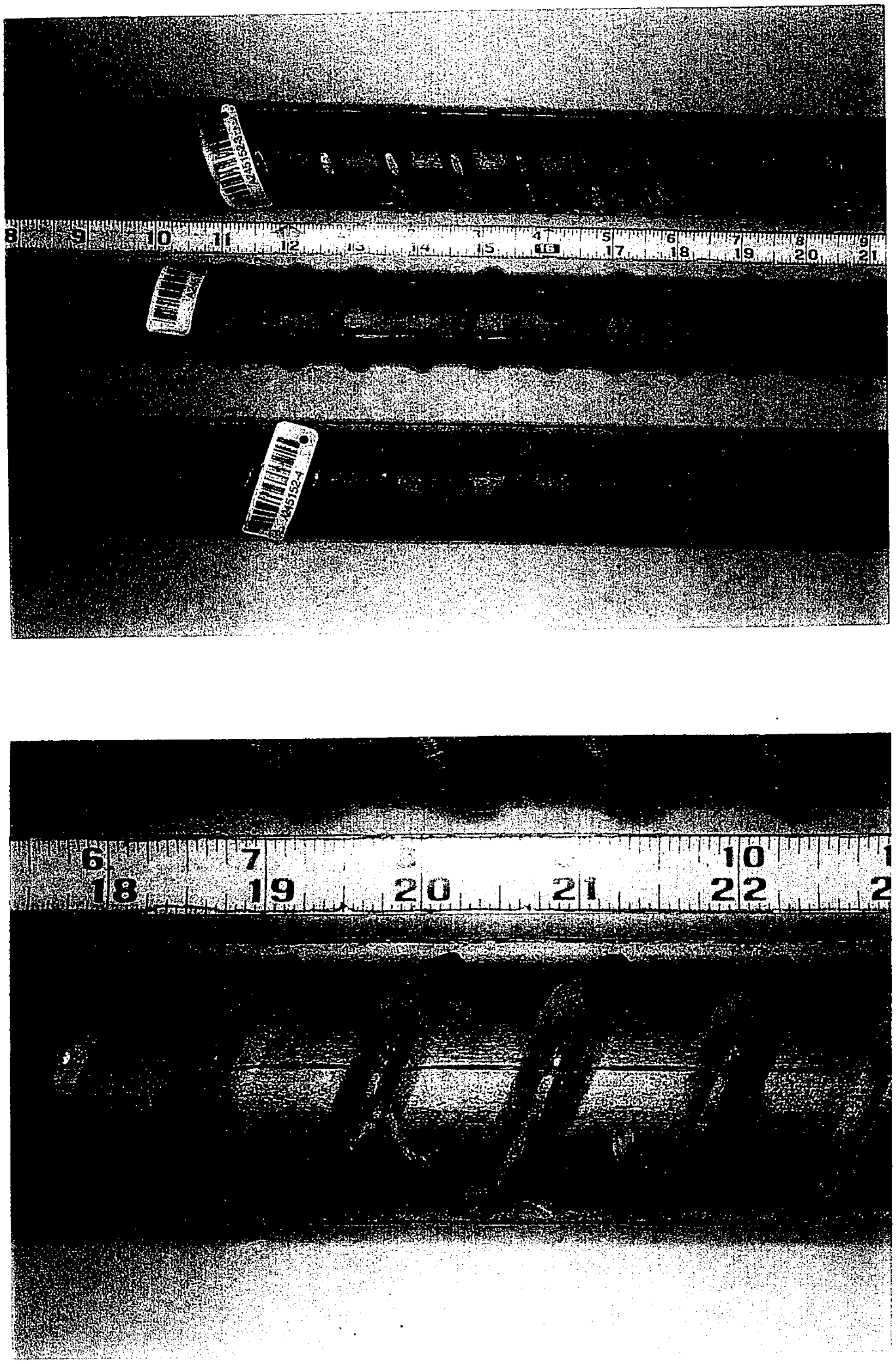


Figure 1 - #11 Bar Samples Showing Continuous Longitudinal Crack-Like Defects.
(9/00/5-6 & 9/00/5-8)

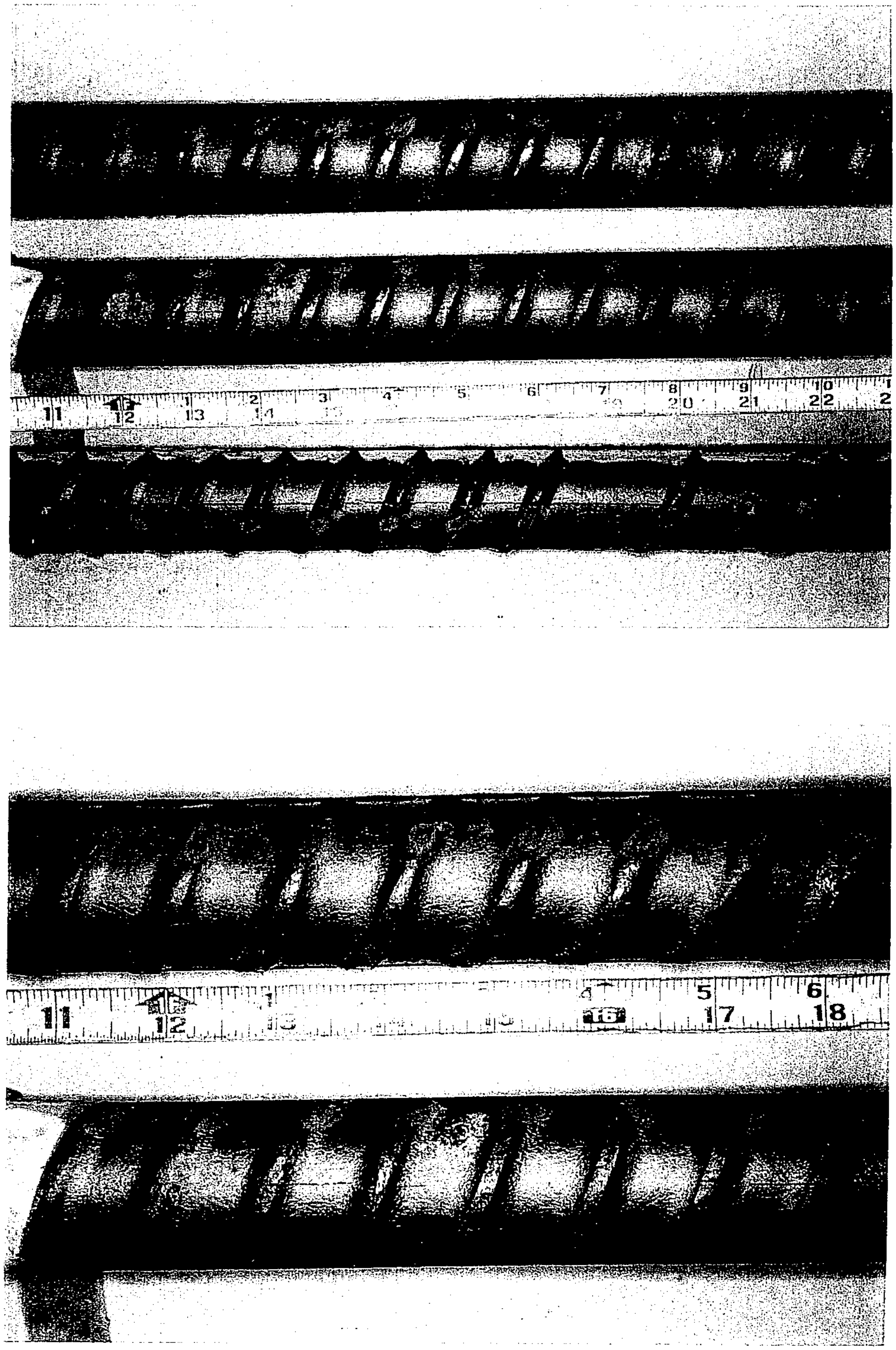


Figure 2 - #11 Bar Samples Showing Fine Intermittent Longitudinal Crack-Like Defects.
(9/00/5-10 & 9/00/5-12)

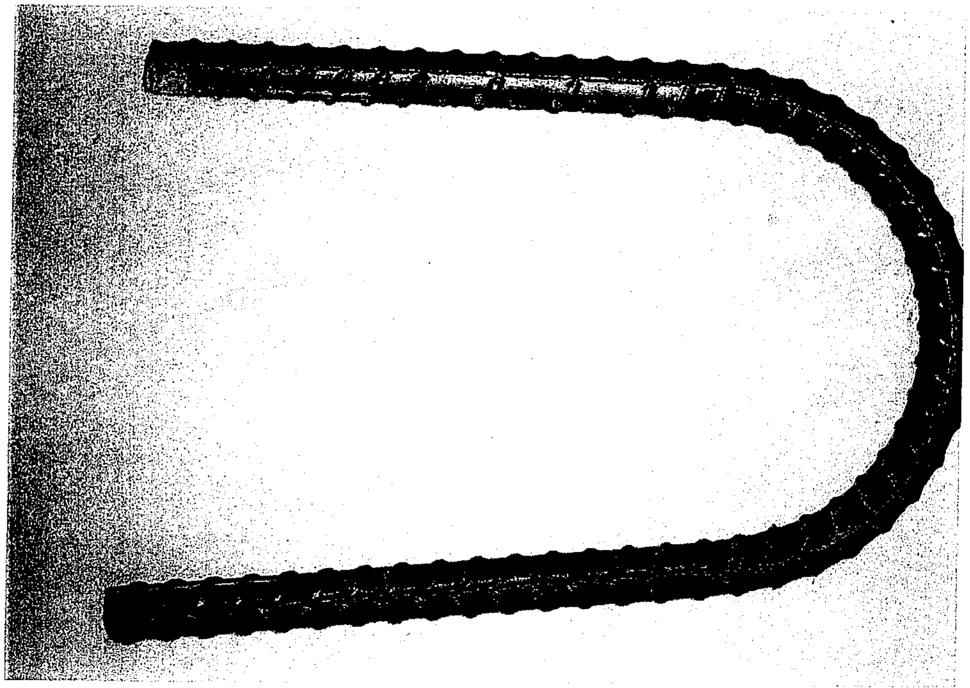


Figure 3 - #11 Bar Bend Test Specimen.
(9/00/12-6)

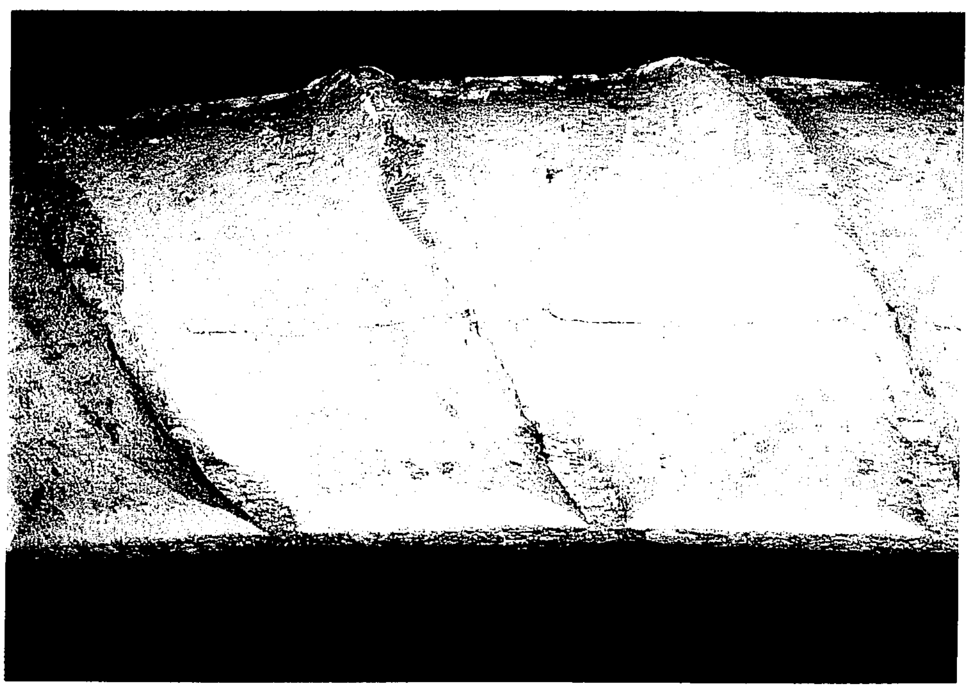


Figure 4 - Enlarged View of Bend Region Showing Original Longitudinal Defect.
(9/00/12-9)

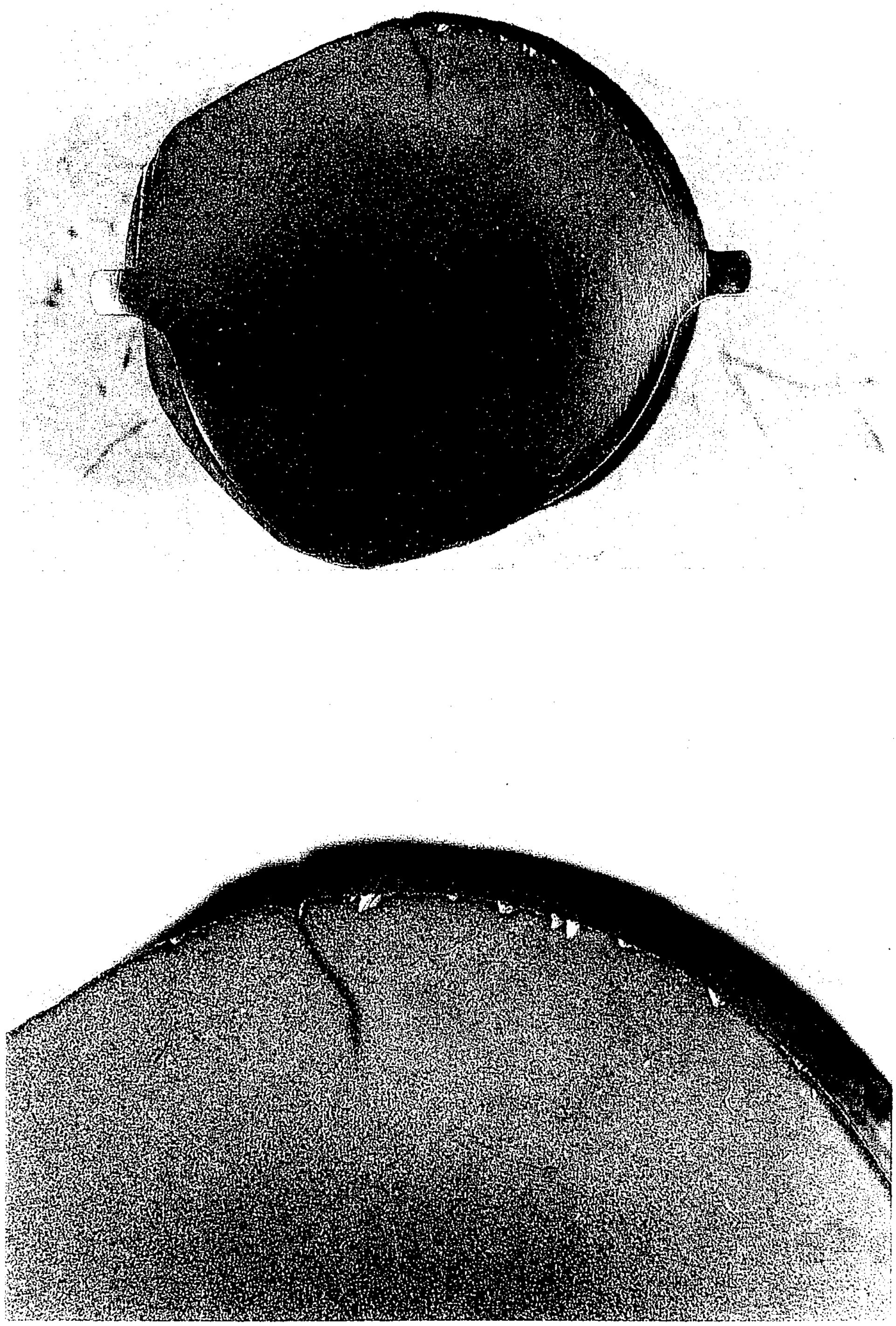


Figure 5 - Cross-Sectional View of a #11 Bar Longitudinal Defect.
(9/00/12-2 & 9/00/12-5)

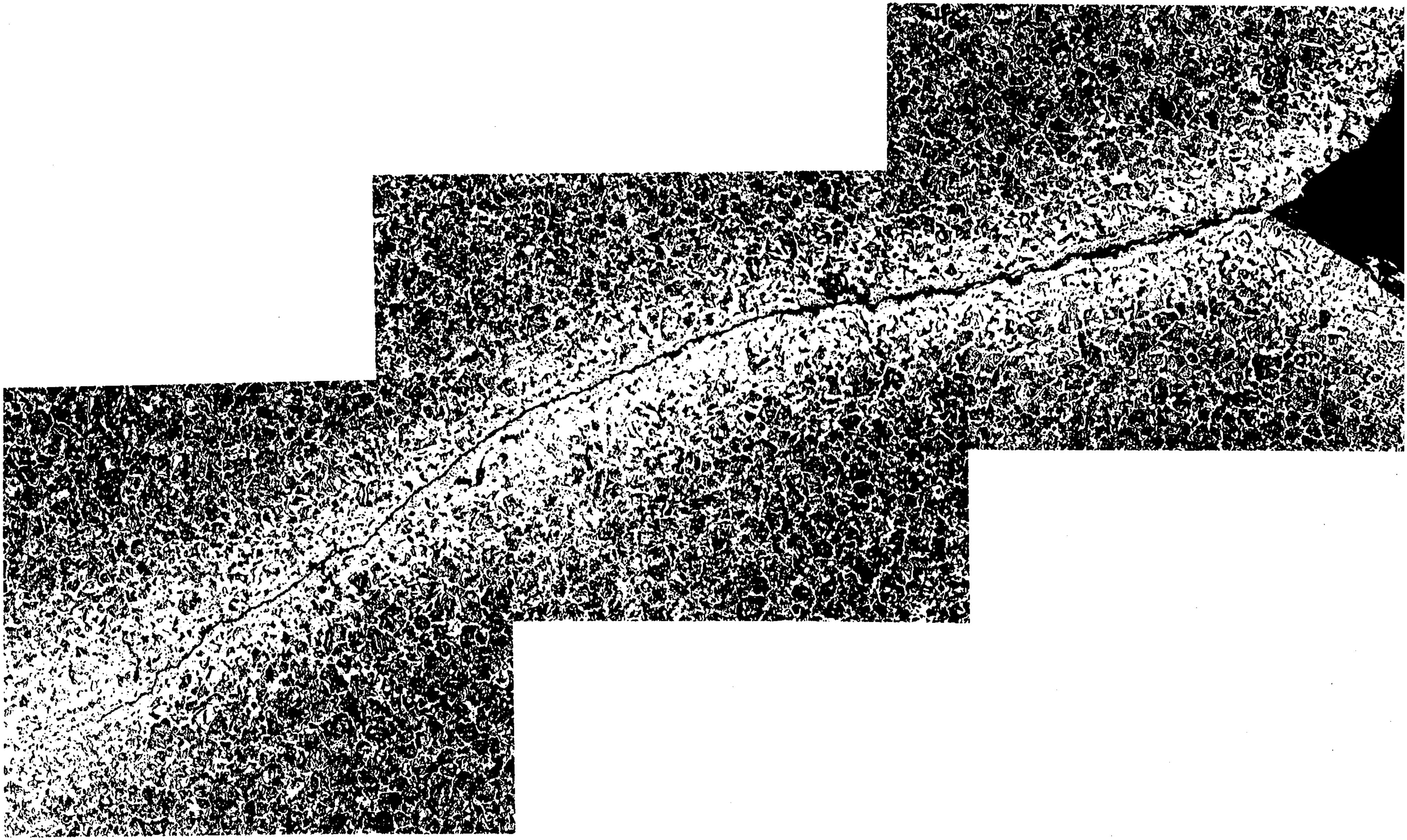


Figure 6 - Etched View of a Longitudinal Defect. Note Decarburized Region Adjacent to Crack-Like Defect. [Mag. 100X]

TASK IV

APPENDIX B

LABORATORY TESTING INC.

Certified Test Report

LHU001-00-09-18719

2331 Topaz Drive, Hatfield, PA 19440
TEL: 800-219-9095 • FAX: 800-219-9096

ACCREDITED #0117-01, 02, 03

NADCAP Materials Testing Laboratory NDT (PT, MT, RT, UT)

SOLD TO
Lehigh University
Alumni Memorial Building
27 Memorial Drive West
Bethlehem, PA 18015-3039

SHIP TO
Lehigh University
ATLSS Engr. Research Center
Imbt Labs 117 ATLSS Drive
Bethlehem, PA 18015-3039
ATTN: E. Kaufmann

CUSTOMER P.O.	CERTIFICATION DATE	SHIP VIA
32360	9/12/2000	FAX AND MAIL

DESCRIPTION

2 pcs. Test Pieces, Steel, Identified as 15361-1 and 15361-2, Item #1

Reference: Accnt. No. 297061, Expense Code 4060

Two pieces of the submitted samples were analyzed in accordance with Customer's Instructions with the following results:

ELEMENT	15361-1	15361-2	ELEMENT	15361-1	15361-2
C	0.43%	0.41%	Ti	0.001%	0.001%
Mn	0.92%	0.99%	V	0.041%	0.045%
P	0.016%	0.015%	W	<0.001%	<0.001%
S	0.058%	0.048%	Pb	0.005%	0.006%
Si	0.23%	0.21%	Sn	0.020%	0.027%
Cr	0.11%	0.14%	As	0.008%	0.008%
Ni	0.17%	0.17%	Zr	<0.001%	<0.001%
Mo	0.074%	0.067%	Ca	<0.001%	<0.001%
Al	0.001%	0.001%	Sb	0.0063%	0.0079%
Co	0.009%	0.013%	B	0.0006%	0.0006%
Cu	0.48%	0.67%	Fe	97.4%	97.2%
Nb	0.002%	0.002%			

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Sherri L. Lengyel
QA Coordinator

By: *Sherri L. Lengyel*
Authorized Signature