FINAL REPORT

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METALLURGICAL EVALUATION OF AIRCRAFT EXHAUST SYSTEM COMPONENTS FAILED DURING GROUND TEST PROGRAM

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Prepared by:
J. R. Kaye
T. J. Hogland
H. P. Weinberg

Value Engineering Company
2316 Jefferson Davis Highway
Alexandria, Virginia 22301

FOREWORD

This report was prepared by the Value Engineering Company for the Federal Aviation Administration. The work effort was part of a program of the Engineering and Safety Division, Aircraft Development Service, Washington, D. C. Engineering liaison and technical review for this project was furnished by the Propulsion Section, Aircraft Branch, Test and Evaluation Division, National Aviation Facilities Experimental Center, Atlantic City, New Jersey.

ABSTRACT

Twenty samples from small aircraft engine exhaust systems were investigated metallurgically to determine the differences, if any, between failures produced in a ground test program and failures from operating aircraft as described in Technical Report ADS-28. The work included samples fabricated from a new material (nickel-iron-chromium alloy) recommended as an improvement for applications such as exhaust systems. The purpose also requested further information regarding the metallurgical cause of failure of conventional stainless steel exhaust system components. The test failures and samples involving AISI 321 and 347 stainless steels were similar to the previously evaluated failures from operational aircraft. The samples showed the effects of high temperature corrosion, carburization, sigma phase and delta ferrite. In most cases, these conditions were similar to those exhibited by the components from operational aircraft. Crack-type failures were attributed to a type of fatigue, which was also the conclusion drawn by the investigation of the components which failed on aircraft. Test results disclosed that a material composed of 21 per cent chromium and 32 per cent nickel was far superior to AISI 321 or 347 stainless steel in regard to high-temperature oxidation or corrosion in exhaust systems. Those failures resulting from oxidation could be significantly reduced or eliminated by incorporation of this material.

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INTRODUCTION

Purpose

The purpose of this project is to determine the following:

1. The metallurgical cause(s) of failure of stainless steel exhaust system components.

2. The differences, if any, between these test failures evaluated and the previous field failures reported in Technical Report FAA-ADS-28 dated January 1965.

3. The advantages of Incoloy Alloy 800 as a possible improved material for exhaust system application.

Materials Tested:

The investigations were performed on Twenty (20) samples cut from failed exhaust system components fabricated from AISI 321, AISI 347, and a nickel-iron-chromium alloy designated as Incoloy Alloy 800. These components were run on an engine test stand for varying increments of time. A listing of samples is presented in Table I.

TABLE I

IDENTIFICATION OF SAMPLES FROM AIRCRAFT EXHAUST SYSTEMS

Sample No.	Material and Description
1	Failed Muffler Baffle, AISI 347, 43 Test Hours.
2	Failed Muffler End Plate, AISI 347, 43 Test Hours.
3	Failed Muffler End Plate, AISI 347, 43 Test Hours.
4	Failed Muffler Baffle, AISI 347, 160 Test Hours.
5	Failed Muffler Baffle, AISI 347, 160 Test Hours.
6	Battered Joint, Muffler-to-Manifold, AISI 347, 490 Test Hours.
7	Failed Muffler End Plate, AISI 347, 448 Test Hours.
8	Failed Stack Joint, AISI 321, 112 Test Hours.
9	Failed Muffler Wall, Heat Exchanger Surface, AISI 321, 555 Test Hours.
* 10 - 11	Failed Muffler Diffuser Cone, AISI 321, 600 Test Hours.
* 12 - 13	Muffler Wall, AISI 321, 600 Test Hours.
* 14 - 15	Muffler Diffuser Cone, Incoloy Alloy 800, 600 Test Hours.
* 16 - 17	Muffler Wall, Incoloy Alloy 800, 600 Test Hours.
18	Muffler Baffle, AISI 347, 490 Test Hours.
19	Muffler Wall, AISI 347, 490 Test Hours.
20	Muffler Wall, AISI 321, 600 Test Hours.

* NOTE: The sample was assigned two sample numbers when received. This was done because it was known that two specimens would be examined from each sample. For clarity the two numbers are treated as one numerical code.

DISCUSSION

Procedure

Samples were identified as to their component name, type of alloy and their number of test hours, as shown in Table I. The relationship of each section of the samples received to the whole component and to the entire exhaust system was not known at the time of the investigation.

The samples were visually inspected for general condition and photographed upon receipt. Location(s) of cracks, excessive oxidation and failures were noted.

Specimens were removed from each sample for chemical and metallographic analyses. Chemical analysis specimens were cut at convenient locations. In the case of welded sections, studs, etc., a sample was taken from each individual division of metal. Determination of carbon, chromium, nickel, titanium and columbium was made for each sample. Alloying elements were established by spectrographic methods. Metallographic specimens were removed at the location of the failure(s) and away from the failure for microstructural comparison. In some cases samples were cut in both transverse and longitudinal directions.

Results

The results of the chemical analyses of the samples are shown in Table II. The results of metallographic analyses and photomicrographs are presented in succeeding pages for each sample.

Sample No. 1

Sample No. 1 is a section of a failed Muffler Baffle as shown in Figure 1. Test data stated that this component was run for 43 test hours. The entire sample showed evidence of oxidation and was somewhat distorted. The end at which the failure occurred was severely oxidized and eroded, suggesting exposure to higher temperatures than the opposite end. Comparative measurements at several locations also showed slight evidence of material thinning near the failed area.

Metallographic specimens were cut from the edge of the burned area. Penetration of oxidation was observed to be greater on the inside surface,

TABLE II

CHEMICAL ANALYSIS OF SAMPLES

Sample No.	Specimen No.	C	Cr	Ni	Ti	Cb
1	1	0.064	17.93	11.20		0.85
2	1	0.049	17.75	10.78		0.83
	2	0.054	17.96	11.22		0.82
3	1	0.051	17.72	10.87		0.84
	2	0.069	18.01	11.10		0.86
4	1	0.059	17.93	10.96		0.84
5	1	0.073	17.96	11.00		0.86
6	1	0.054	17.95	10.96		0.81
	2	0.074	17.98	11.10		0.85
	3	0.067	18.26	10.96		0.90
7	1	0.059	18.12	11.06		0.80
	2	0.074	18.23	10.91		0.93
	3	0.043	17.96	10.89		0.84
8	1	0.063	17.83	9.56	0.50	
9	1	0.072	17.91	9.91	0.49	
	2	0.053	18.03	9.75	0.45	
	3	0.059	17.85	9.81	0.43	
10-11	1	0.063	18.01	9.90	0.47	
	2	0.075	17.80	9.83	0.73	
12-13	1	0.061	17.96	9.81	0.64	
	2	0.068	18.00	9.85	0.68	
14-15	1	0.049	18.01	9.90	0.51	
	2	0.043	21.64	32.81	0.40	
16-17	1	0.054	21.70	32.56	0.38	
	2	0.058	17.99	9.91	0.37	
18	1	0.059	17.73	11.40		0.80
19	1	0.057	17.81	11.00		0.81
20	1	0.076	17.69	9.11	0.58	
	2	0.061	17.79	9.23	0.54	

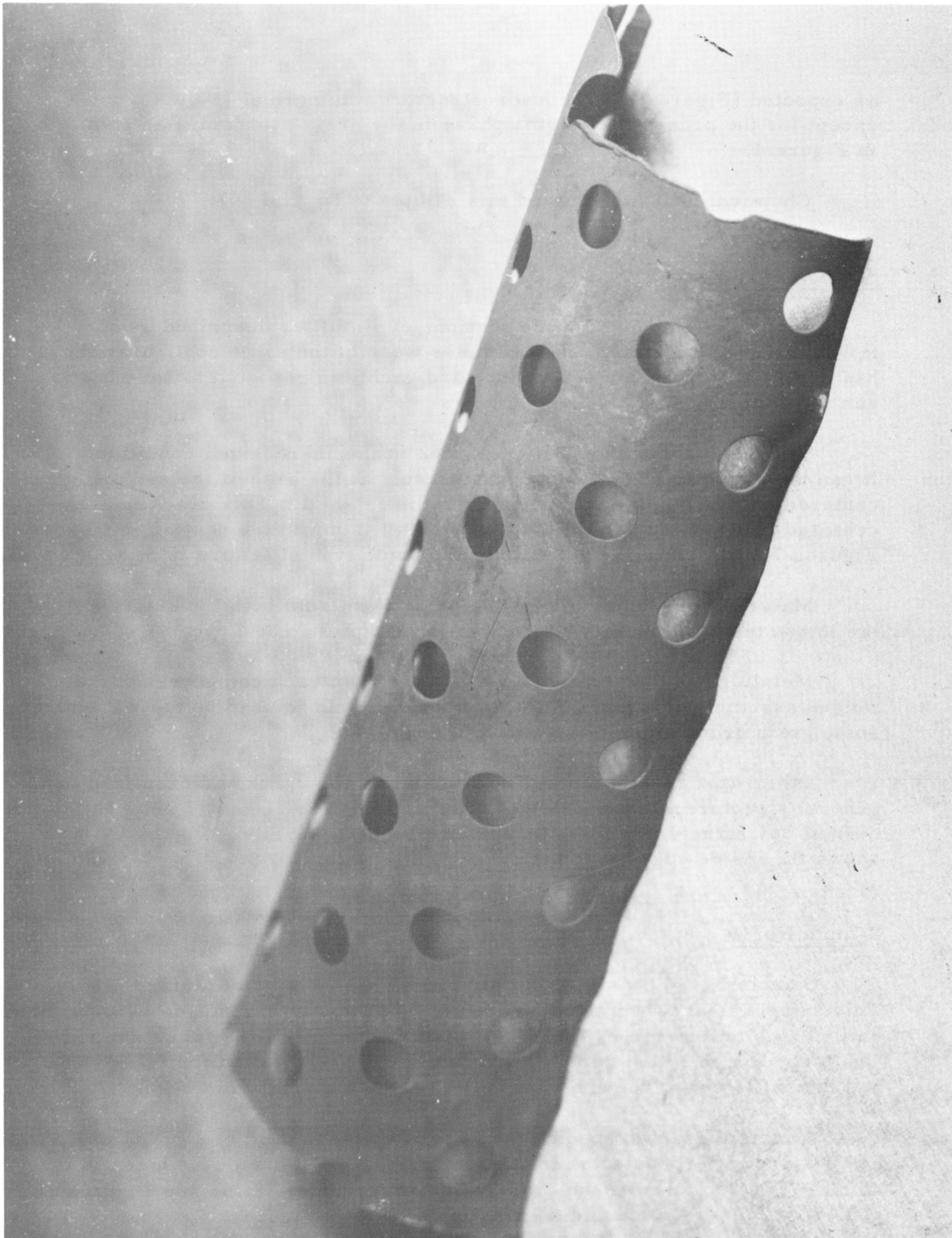

Figure 1.   Sample No. 1 - Muffler Baffle, 43 Test Hours

as expected (Figure 2). The microstructure was normal (Figure 3) except for the presence of sigma phase in the grain boundaries as shown in Figure 4.

Chemical analyses showed this sample to be AISI 347.

Samples No. 2 and 3

Samples No. 2 and 3 were sections of a muffler described as a failed Muffler End Plate. Both samples were of the same configuration, had essentially the same appearance and each was reported to have been run for 43 test hours.

Figures 5 and 6 show Sample No. 2 in the as-received condition. It can be seen that a severe crack is present at the base of the sample centered between the intake tube and the outer shell. This crack is almost centered between the two welds, however, it is not in the heat affected zone. Figures 7 and 8 show almost exactly the same type of failure in Sample No. 3.

Material for chemical analyses was taken from both the shells and the intake tube. The analyses showed all samples to be Type 347.

Metallographic specimens were taken from each component of the welded assembly. Figures 9 and 10 show the weld joint to be normal with some grain growth in the heat affected zone.

Other specimens were cut on one side of the crack and examined for general structure and the cause of failure. Figures 11 and 12 show the normal 347 structure with some evidence of delta ferrite. Figure 13 shows the inside edge along the crack in Specimen No. 3.

Sample No. 4

Sample No. 4 consisted of four pieces of a section of Muffler Baffle. This sample is shown in the as-received condition in Figure 14. The baffle exhibited severe oxidation and distorted edges at the failed section. The piece for chemical analysis was taken midway between the failed area and the baffle end. The analysis indicated the material to be AISI 347.

A metallographic specimen was cut to view the end of a crack which had developed perpendicular to the circumference of one of the holes in the baffle. Figure 15 shows the crack with two branches, (also see Figures 16 and 17). Columbium carbides are visible in these figures.

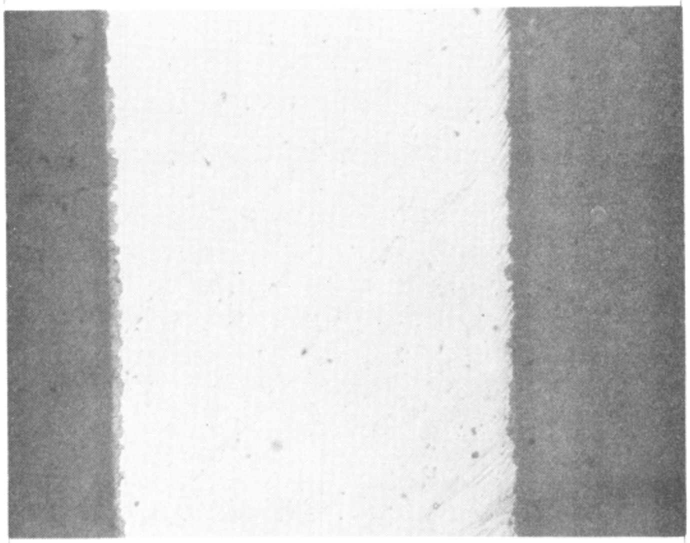

Figure 2

Sample No. 1 - Specimen No. 1

Showing both surfaces as polished. (Outside surface at right)

Magnification: 100X

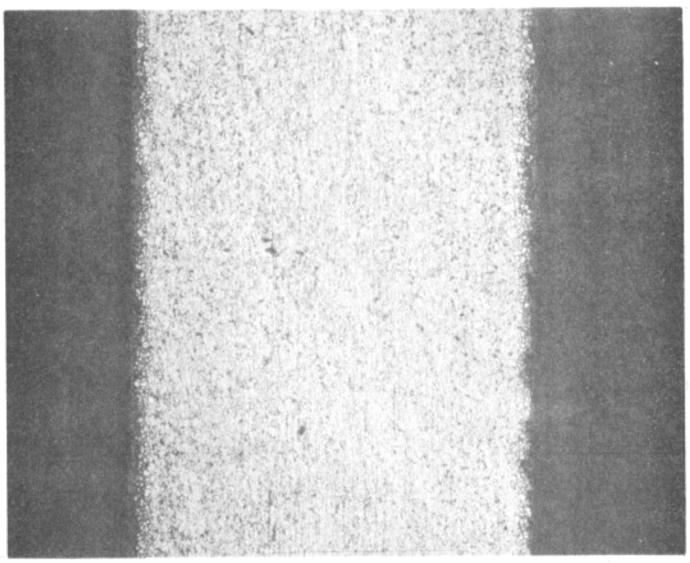

Figure 3

Sample No. 1 - Specimen No. 1

Structure of baffle adjacent to oxidized edge.

Magnification: 100X
Etchant: 10% Oxalic acid

Figure 4

Sample No. 1 - Specimen No. 1

Baffle showing sigma phase in grain boundaries.

Magnification: 500X
Etchant: 10% Oxalic acid

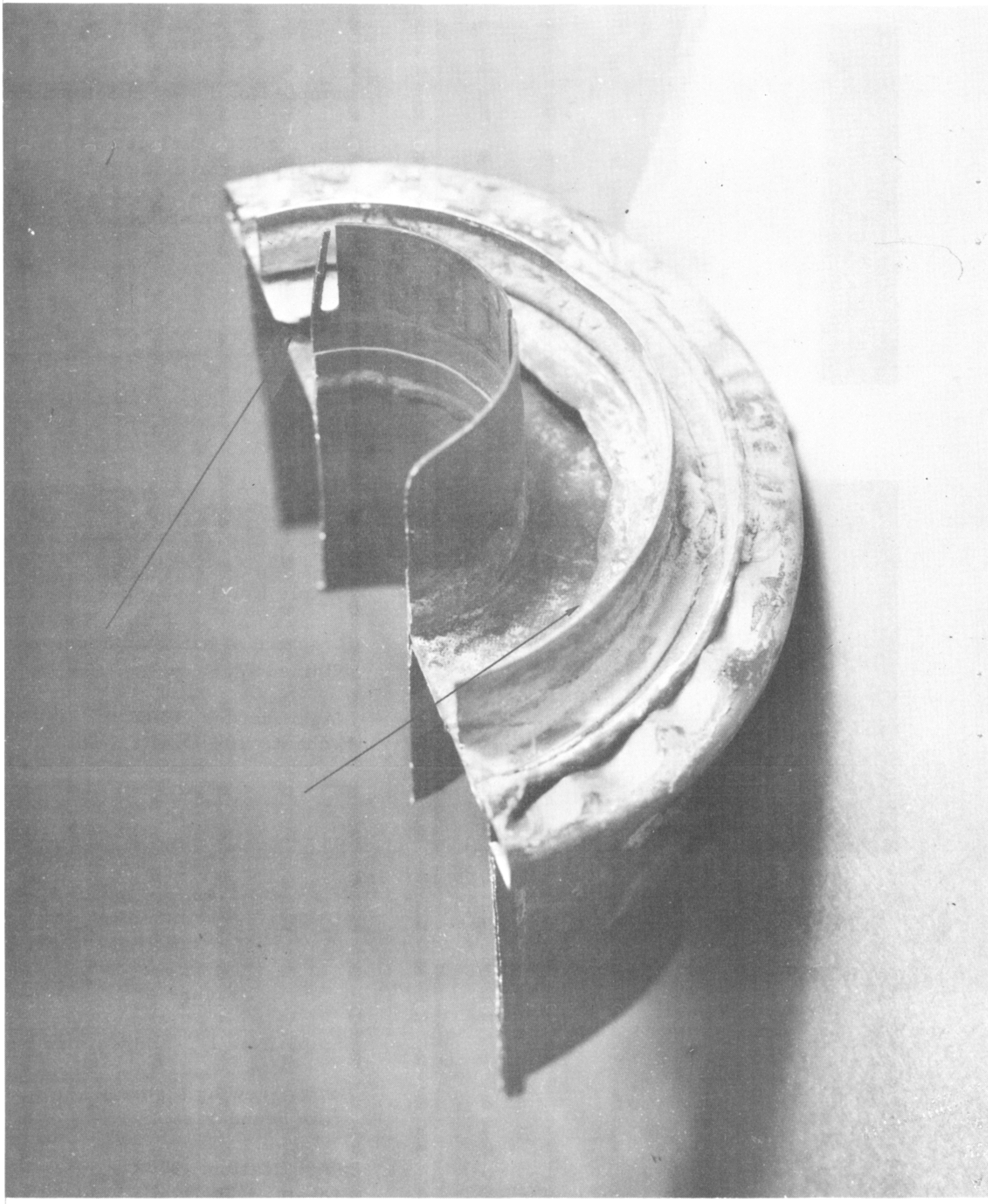

Figure 5. Sample No. 2 - Muffler End Plate, outside, 43 Test Hours
Arrows indicate extent of crack in sample.

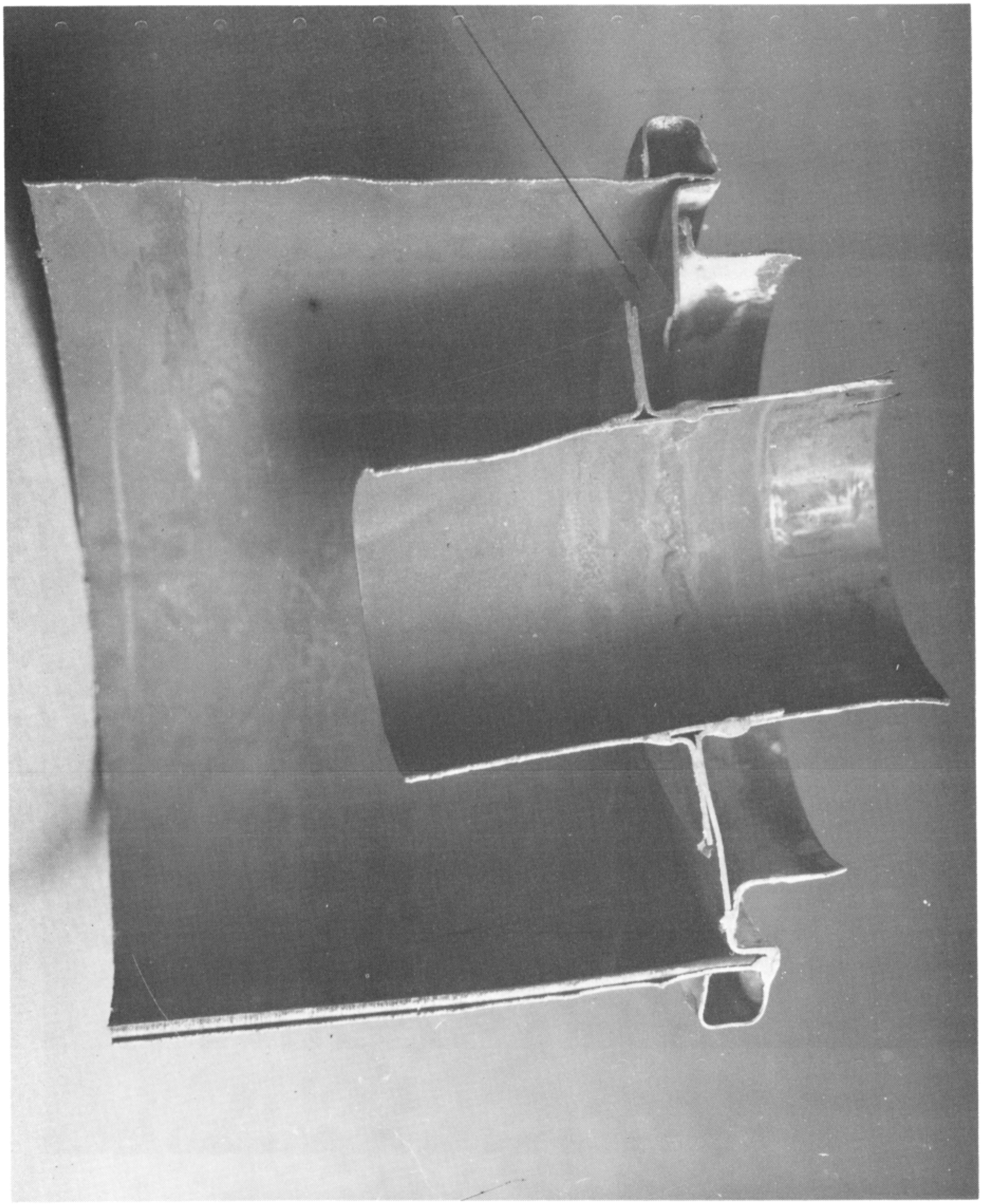

Figure 6. Sample No. 2 - Muffler End Plate, inside, 43 Test Hours
Arrow indicates crack in sample.

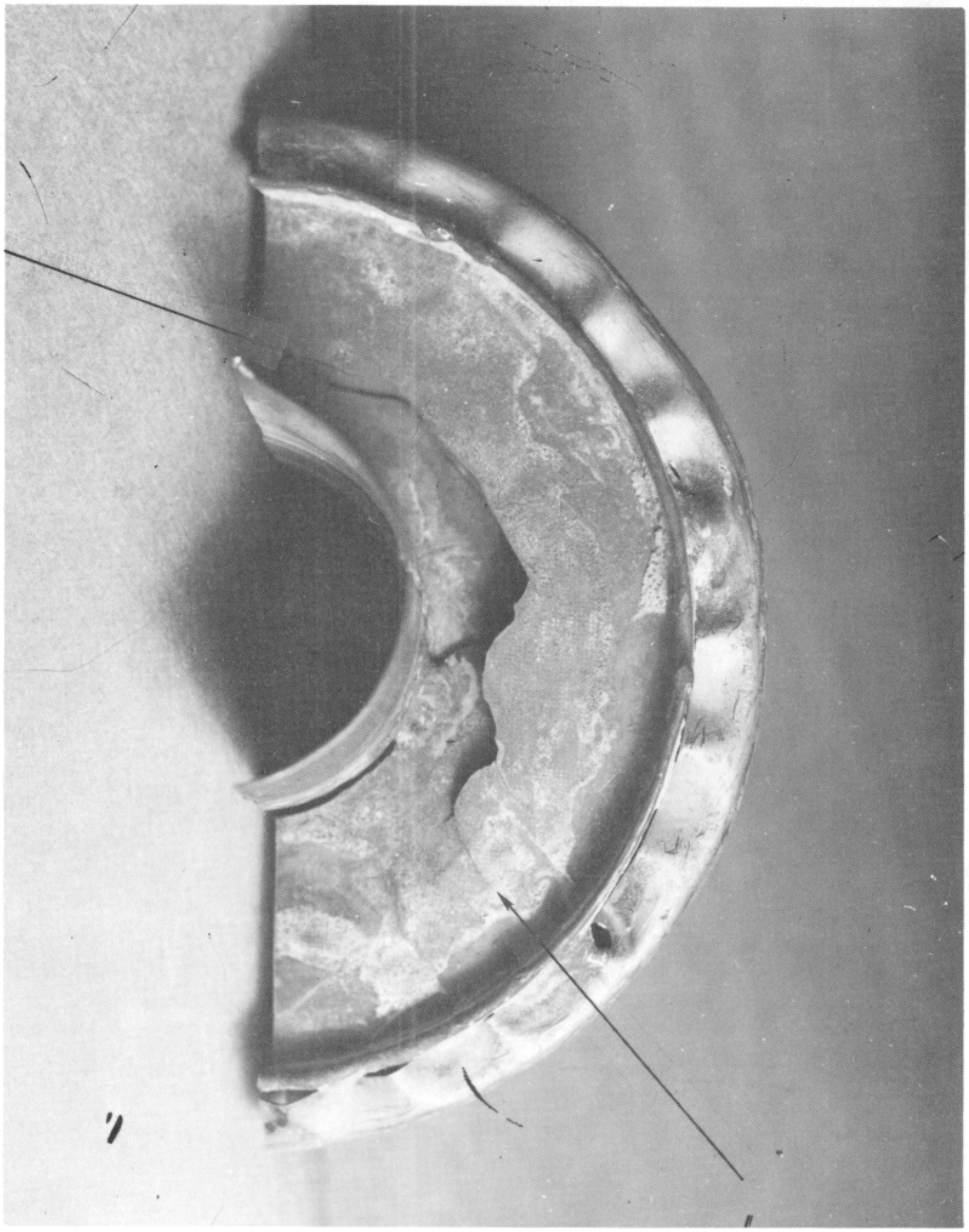

Figure 7. Sample No. 3 - Muffler End Plate, outside, 43 Test Hours
Arrows indicate extent of crack in sample.

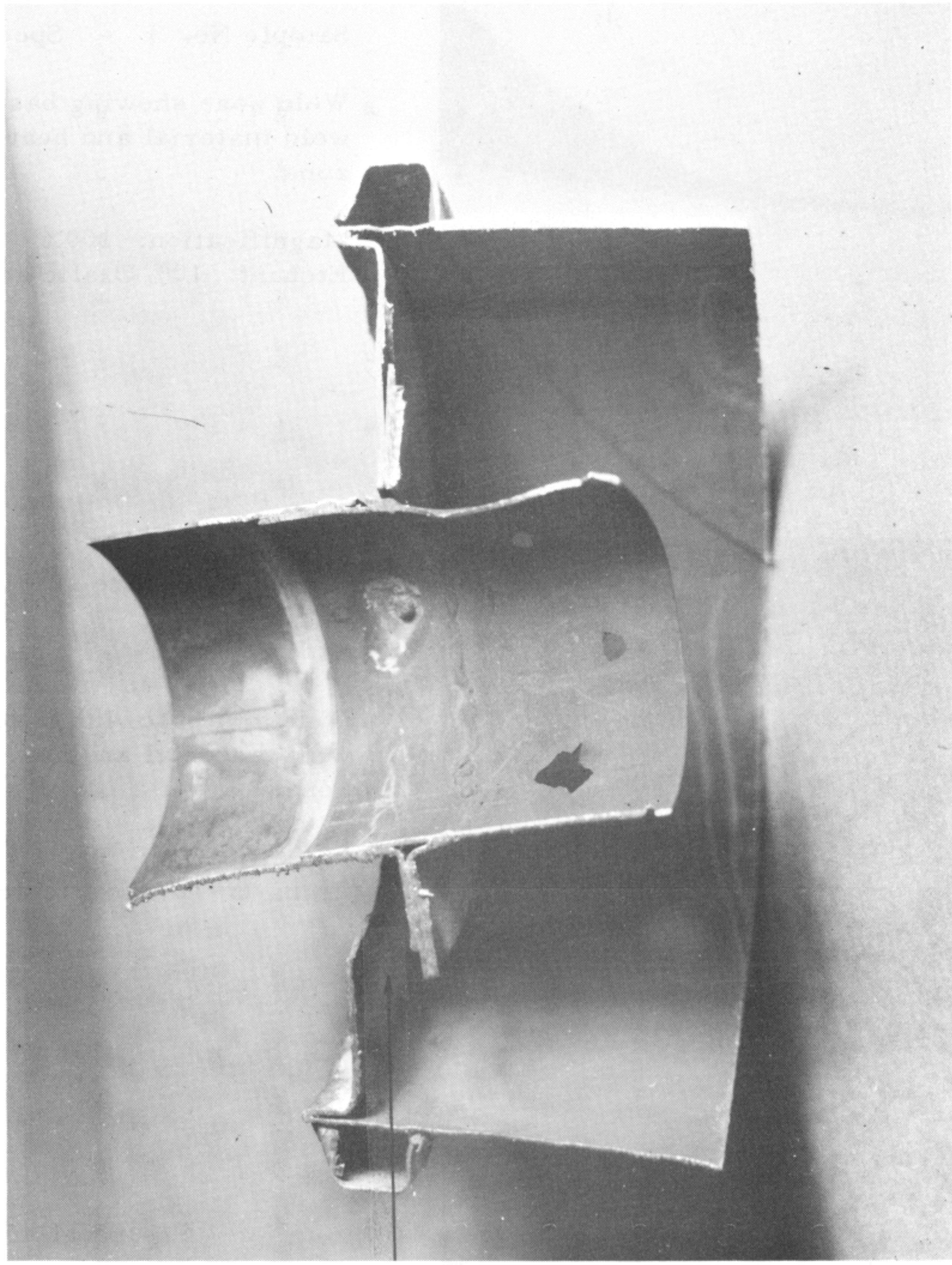

Figure 8. Sample No. 3 - Muffler End Plate, inside, 43 Test Hours
Arrow indicates crack in sample.

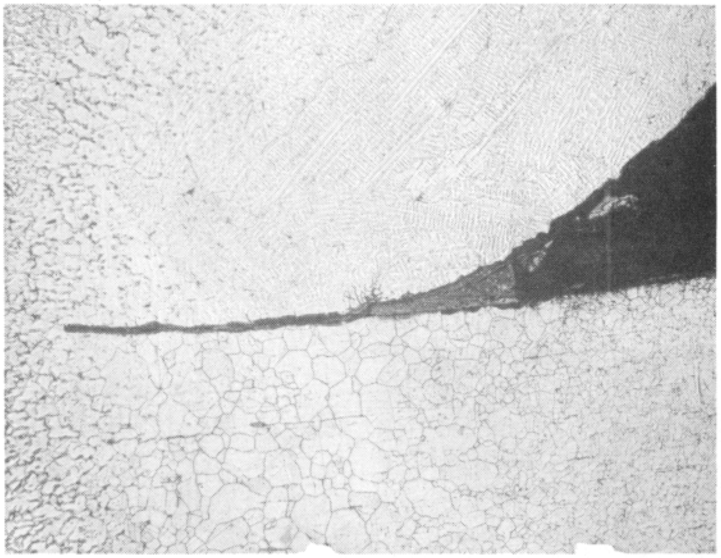

Figure 9

Sample No. 3 - Specimen No. 1

Weld zone showing base metal, weld material and heat affected zone.

Magnification: 100X
Etchant: 10% Oxalic acid

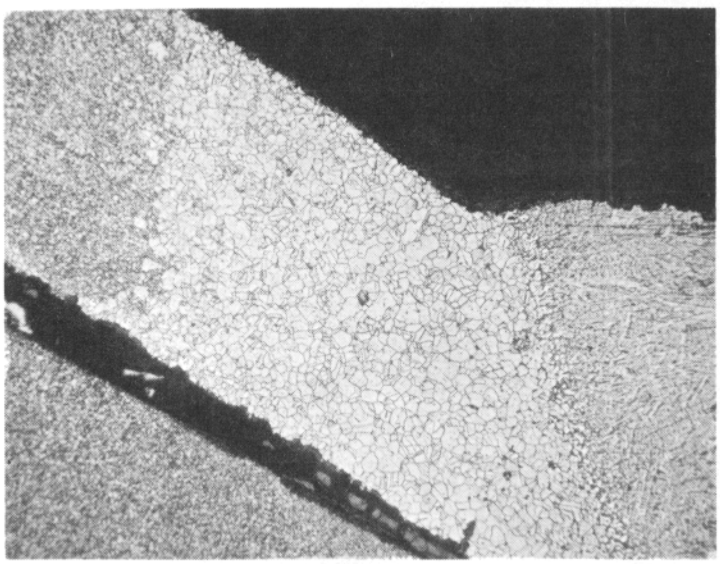

Figure 10

Sample No. 3 - Specimen No. 2

Weld zone showing base metal, weld material and heat affected zone.

Magnification: 50X
Etchant: 10% Oxalic acid

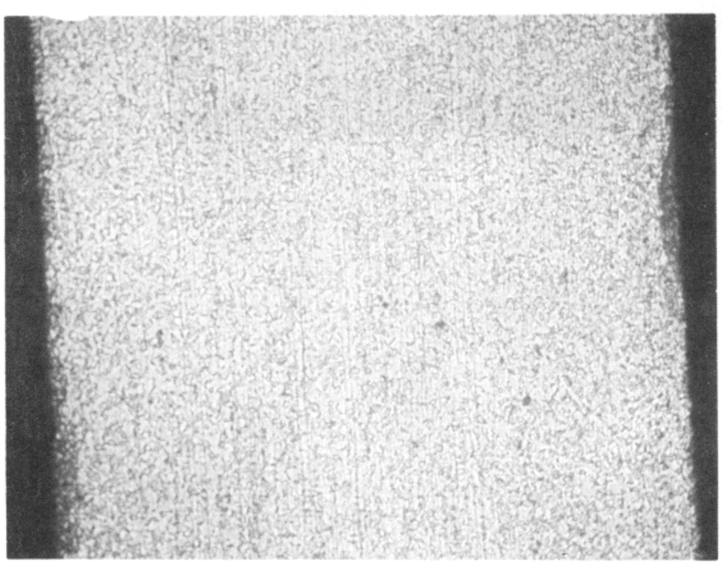

Figure 11

Sample No. 2 - Specimen No. 1

Showing general structure.

Magnification: 100X
Etchant: 10% Oxalic acid

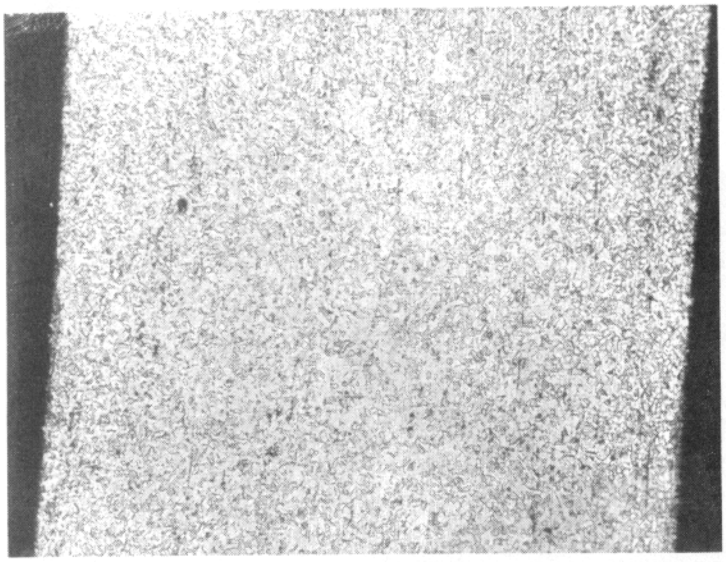

Figure 12

Sample No. 3 - Specimen No. 2

General structure.

Magnification: 100X
Etchant: 10% Oxalic acid

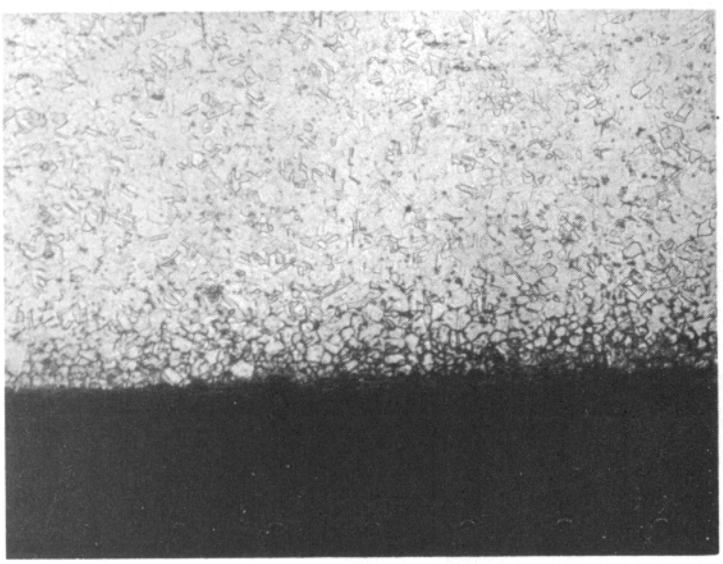

Figure 13

Sample No. 3 - Specimen No. 3

General structure around crack.

Magnification: 250X
Etchant: 10% Oxalic acid

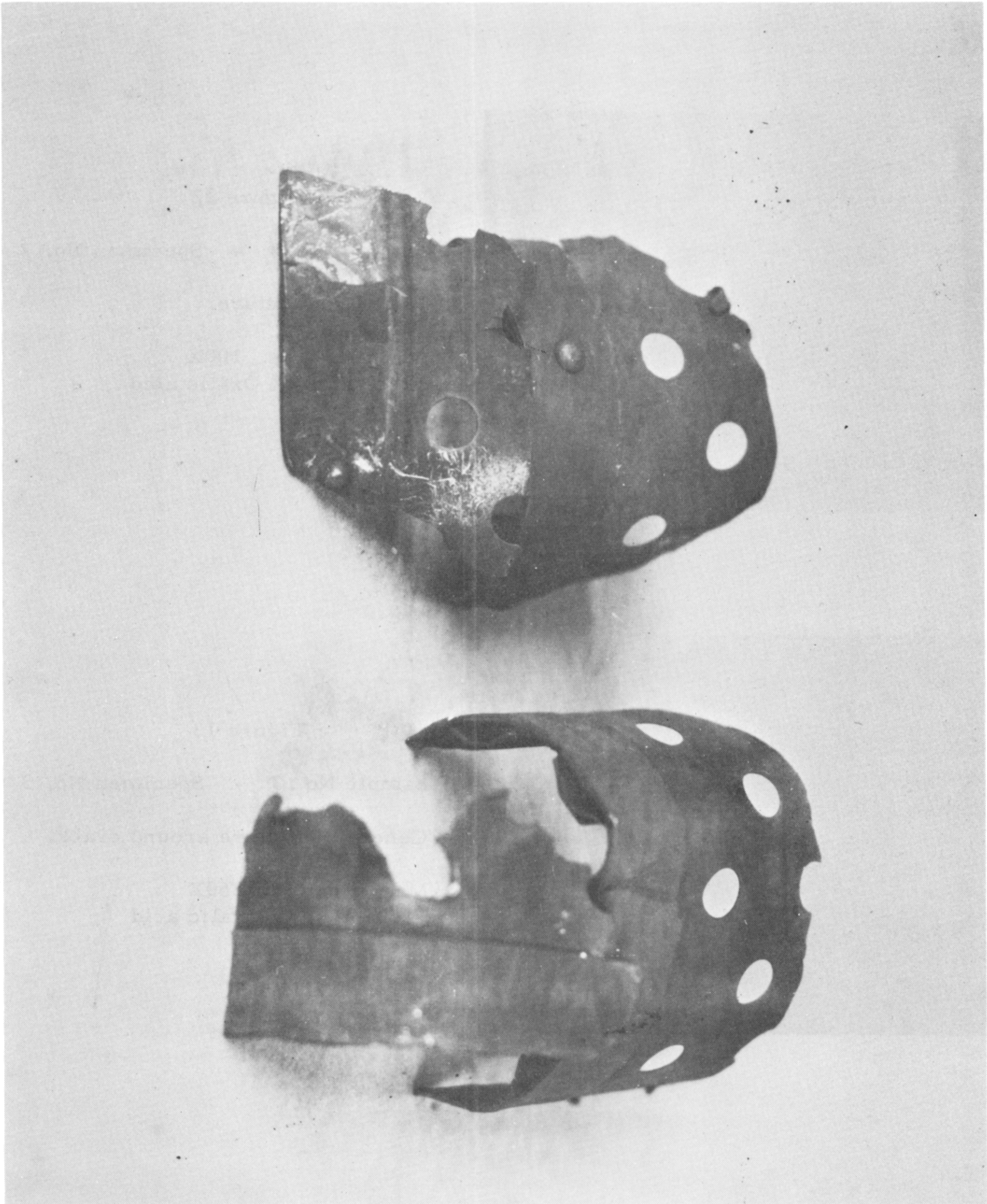

Figure 14. Sample No. 4 - Muffler Baffle, 160 Test Hours

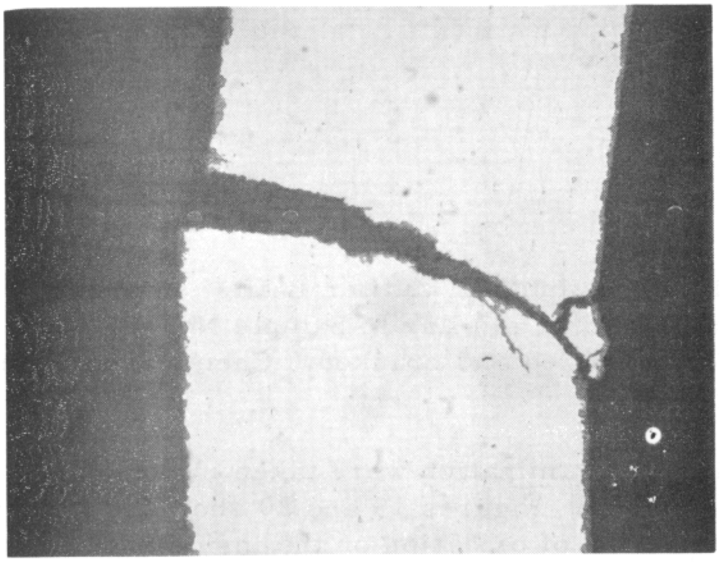

Figure 15

Sample No. 4 - Specimen No. 1

Showing end crack in shell and columbium carbides.
As polished.

Magnification: 100X

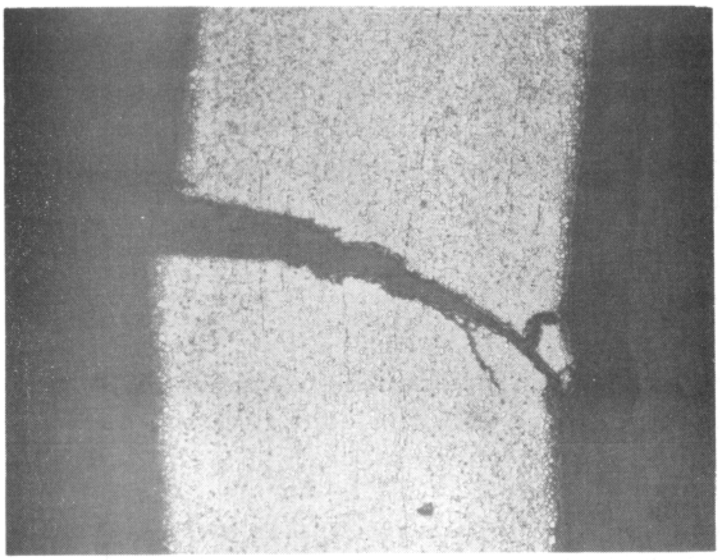

Figure 16

Sample No. 4 - Specimen No. 1

Showing structure of shell.

Magnification: 100X
Etchant: 10% Oxalic acid

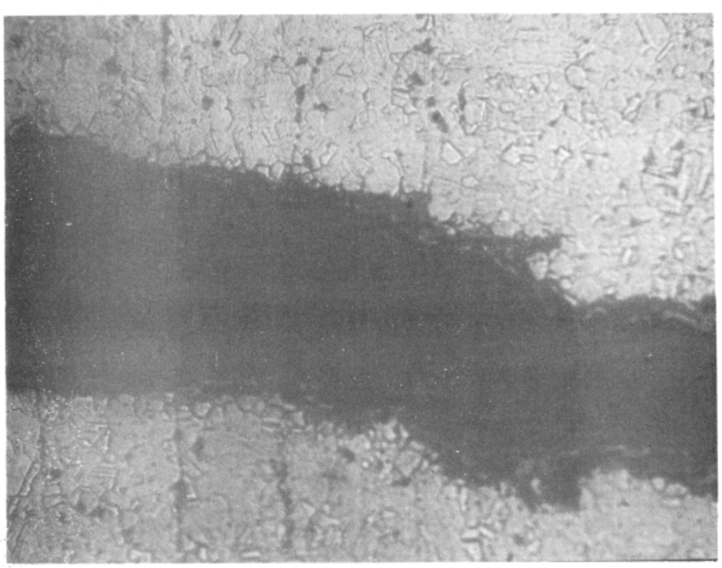

Figure 17

Sample No. 4 - Specimen No. 1

Showing grain structure around crack.

Magnification: 500X
Etchant: 10% Oxalic acid

Sample No. 5

Sample No. 5 (see Figure 18) is another Muffler Baffle. The test conditions and former configuration were similar to Sample No. 4. This sample as-received was twisted, oxidized and cracked. Chemical analysis indicated the material to be AISI 347.

Specimens for metallographic examination were taken in both the longitudinal and transverse directions. Figures 19 and 20 show the general structure and comparative penetration of oxidation on the inside and outside surfaces. The structure revealed grain growth on the outside and inside portion and a finer structure in the middle. This condition is probably due to the higher operating temperatures experienced at these edges.

The second metallographic specimen was taken in a transverse direction at the end of a crack through one of the baffle holes, (see Figure 21). Examination of the grain structure showed intergranular corrosion (see Figures 22 and 23).

Sample No. 6

Sample No. 6 was described as a Joint, Muffler-to-Manifold. It appeared quite similar to Samples No. 2 and 3 in configuration as shown in Figures 24 and 25.

Visual examination showed some oxidation internally and externally along with some distortion and bulging near the intake tube. It is also noted that one of the two rivets holding the internal baffle to the joint was completely sheared off and the metal was cracked adjacent to the other rivet.

Pieces for chemical analysis were cut from the end of the intake tube and the shell. The material was Type 347.

Figure 26 shows the general structure of the sample and the deeper penetration of oxidation in the inside surface.

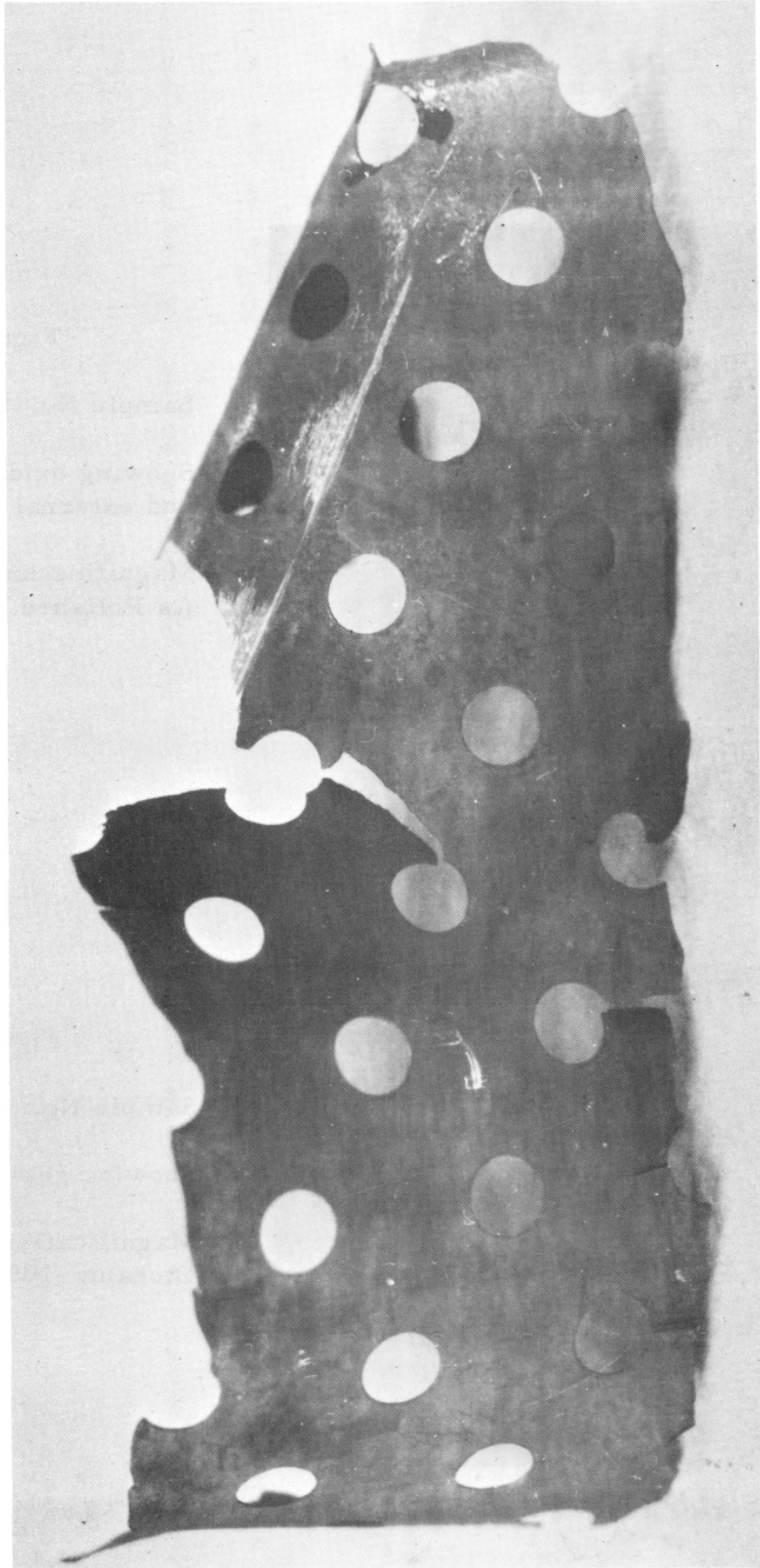

Figure 18. Sample No. 5 - Muffler Baffle, 160 Test Hours

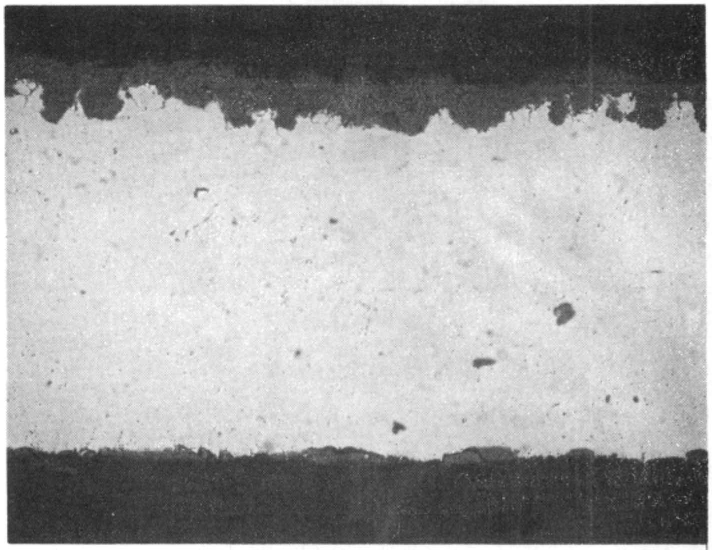

Figure 19

Sample No. 5 - Specimen No. 1

Showing oxidation on both internal and external surfaces.

Magnification: 100X
As Polished

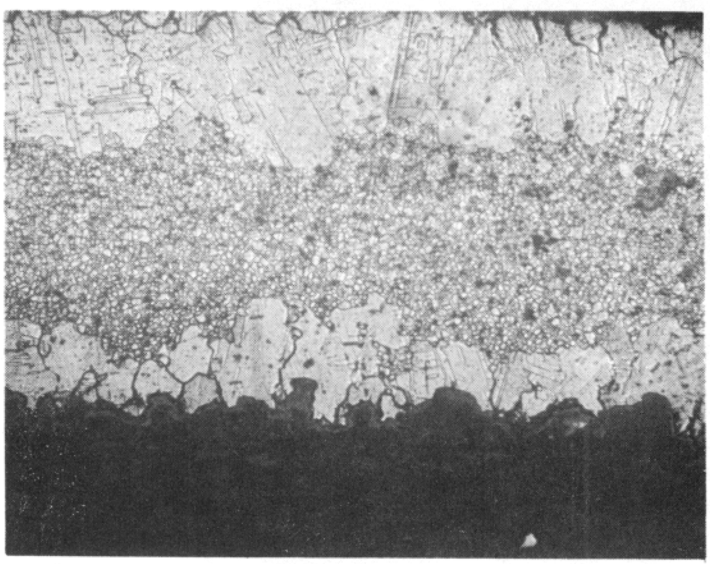

Figure 20

Sample No. 5 - Specimen No. 1

Showing grain growth.

Magnification: 100X
Etchant: 10% Oxalic acid

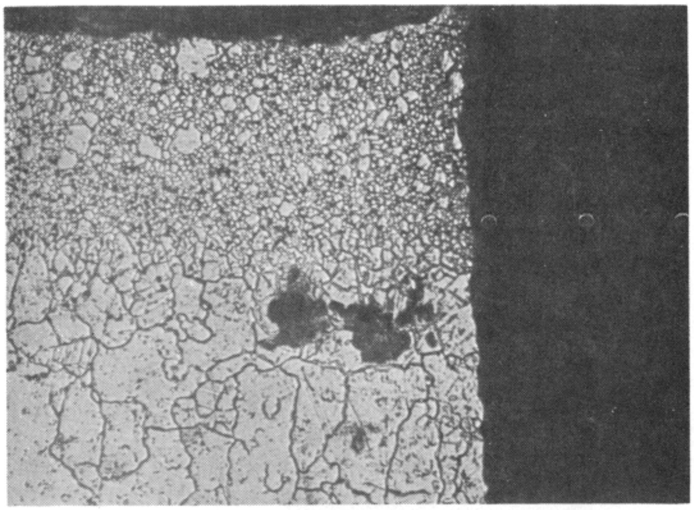

Figure 21

Sample No. 5 - Specimen No. 2

General structure.

Magnification: 100X
Etchant: 10% Oxalic acid

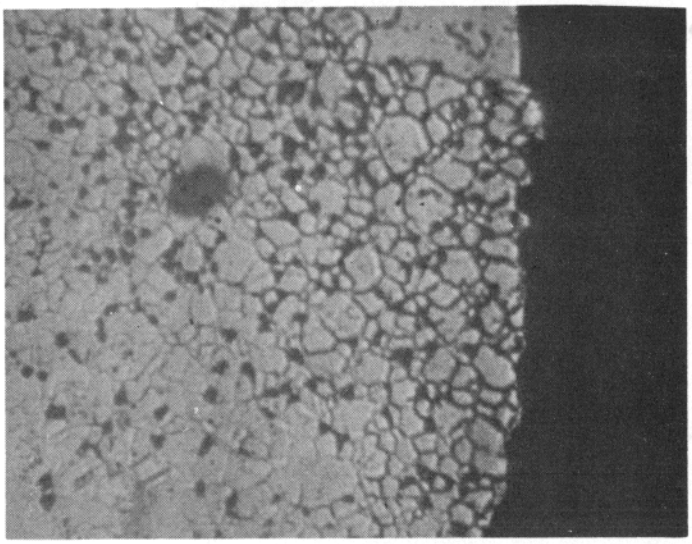

Figure 22

Sample No. 5 - Specimen No. 2

Showing carbide precipitation along grain boundaries.

Magnification: 500X
Etchant: 10% Oxalic acid

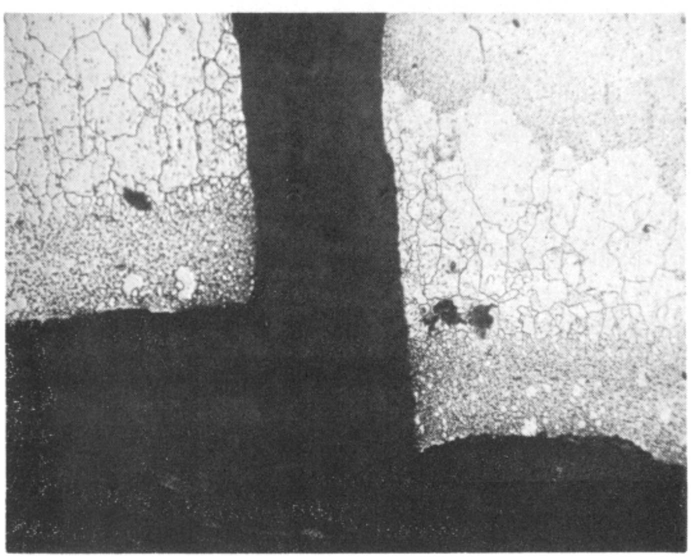

Figure 23

Sample No. 5 - Specimen No. 2

Showing general microstructural appearance of crack.

Magnification: 50X
Etchant: 10% Oxalic acid

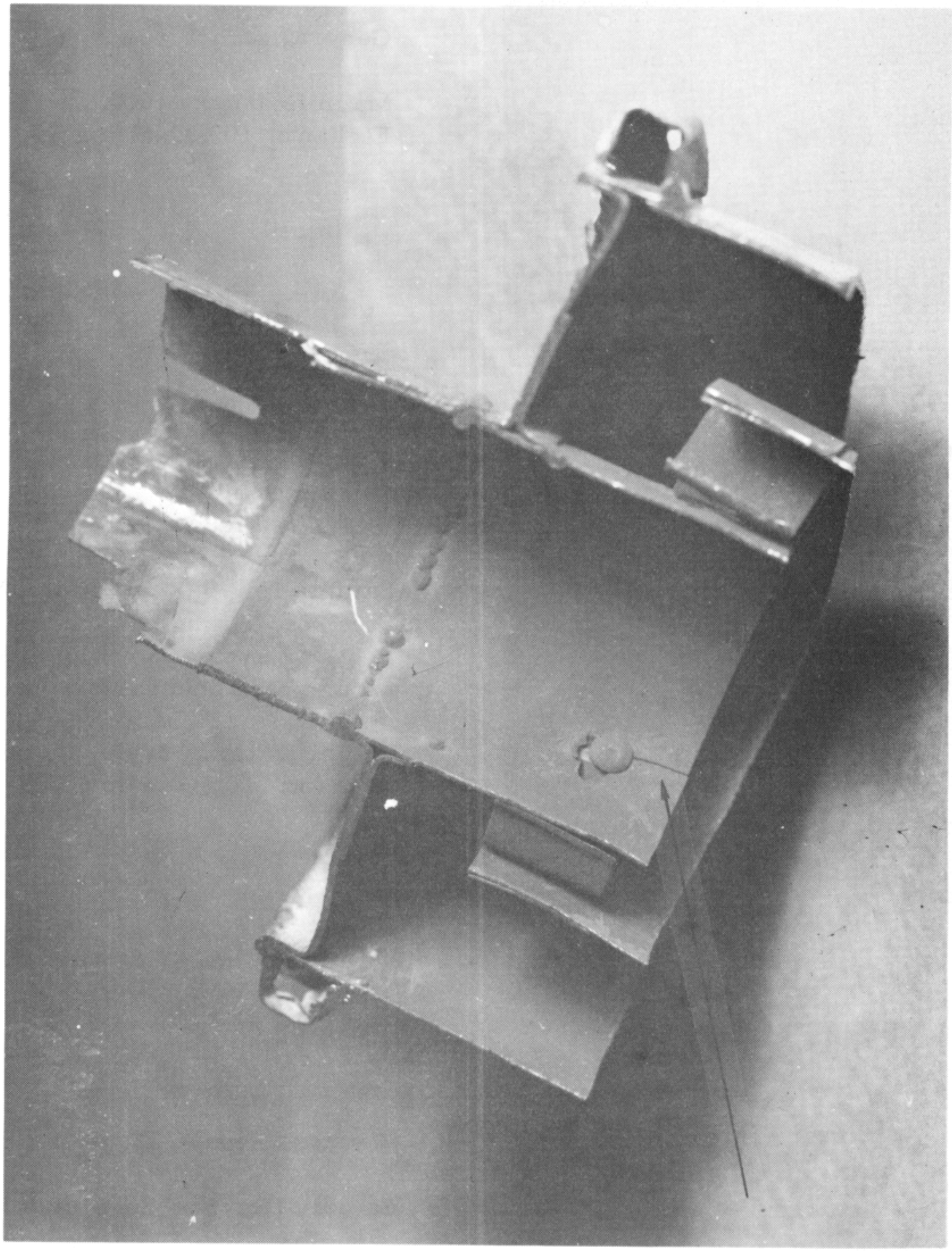

Figure 24. Sample No. 6 - Joint, Muffler to Manifold, inside, 490 Test Hours

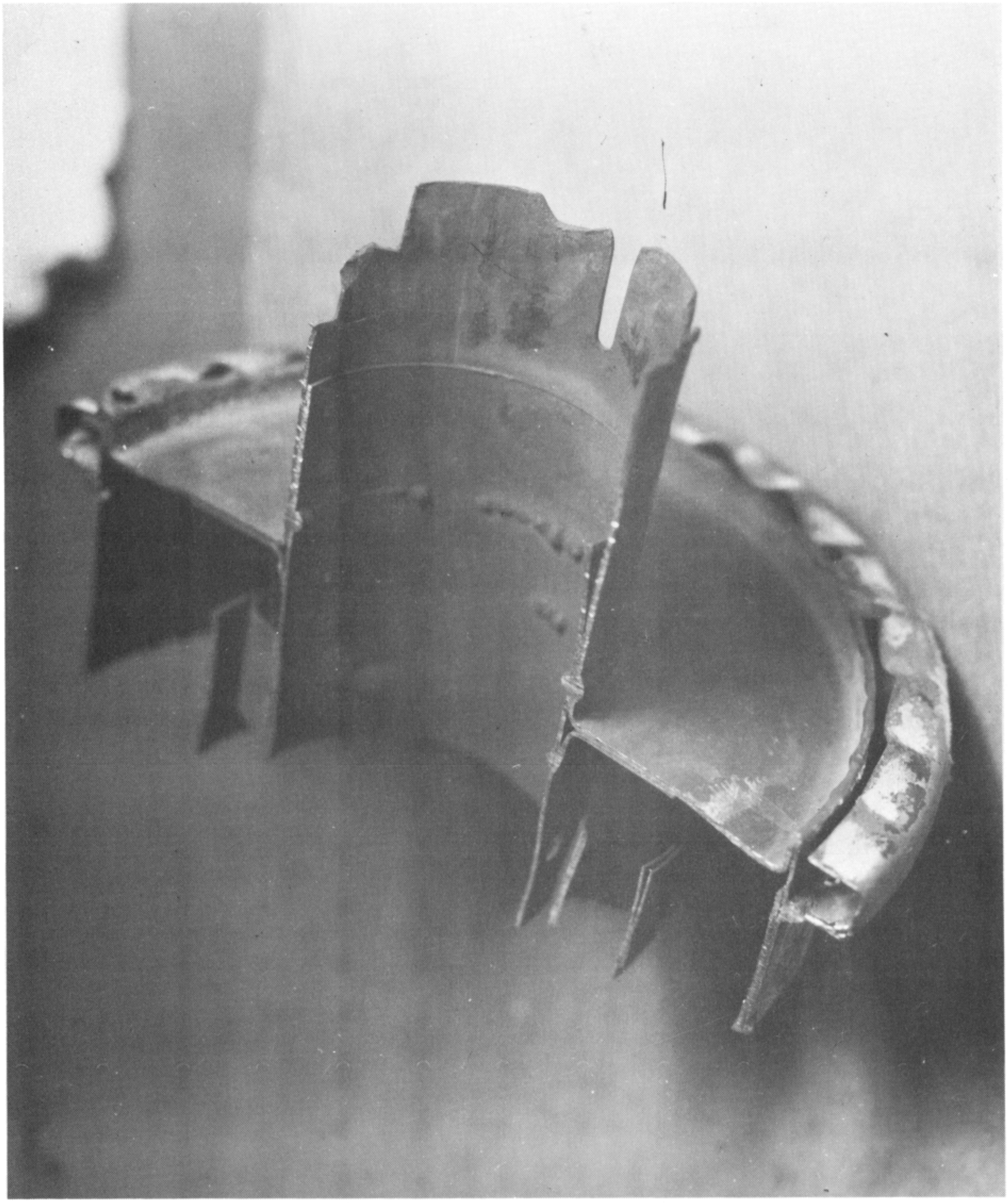

Figure 25. Sample No. 6 - Joint, Muffler to Manifold, outside, 490 Test Hours

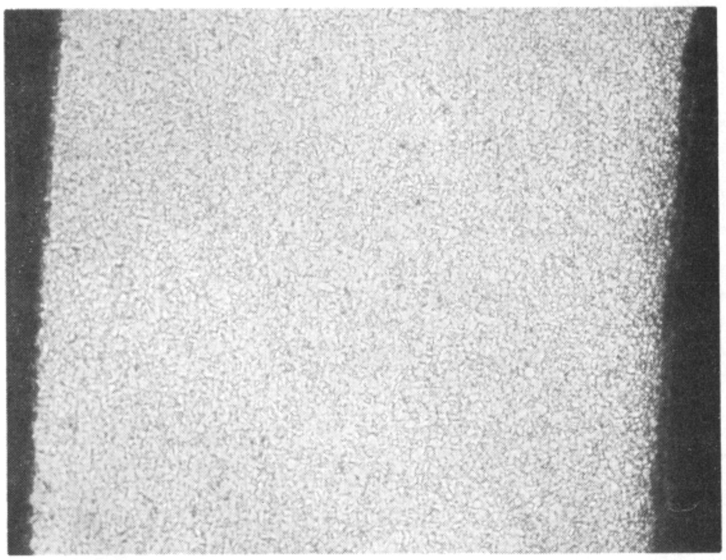

Figure 26

Sample No. 6 - Specimen No. 1

General structure and deeper penetration of oxidation in the inside surface.
(Inside surface on left)

Magnification: 100X
Etchant: 10% Oxalic acid

Sample No. 7

Sample No. 7 was described as a Muffler End Plate similar in design to Sample Nos. 2, 3, and 6. It was test run for 448 hours. Figure 27 shows that 3 of the 4 rivets joining the baffle to the end plate intake tube were completely sheared and the fourth, while still intact, was cracked and weakened by lost material. Specimens for chemical analyses were cut from the outer shell, the intake tube and the internal baffle. The material was Type 347.

Figure 28 shows one of the welded joints in Sample No. 7. The weld material, heat affected zone and base metal are typical. The general structure of the sample is shown in Figure 29.

Sample No. 8

Sample No. 8 was a Stack Joint containing a weld as shown in Figure 30. The sample was lightly oxidized and reported to have been test run for 112 hours. The crack originated at the outside edge of the tube near the weld, continued in a straight line until it reached the curved portion of the sample and then extended in a direction normal to the original path.

A specimen for chemical analysis was taken along the lower edge of the sample. The sample was AISI 321.

Metallographic specimens were cut near the end of the crack and from the top edge of the tube. Examination of the structure (see Figure 30) showed that some carburization had occurred on the inside surface.

The metallographic examination of the cross section of the crack revealed heavy oxidation on the surfaces on either side of the crack (see Figures 32 and 33). This is a strong indication of the progressive nature of the crack since oxidation occurred on the fracture surface as the crack progressed. The fact that there is no thinning of the metal at the fracture also suggests that it is a type of fatigue crack. Figure 34 shows the structure close to the tip of the crack. The slip bands are typical of a condition created at the tip of a fatigue crack.

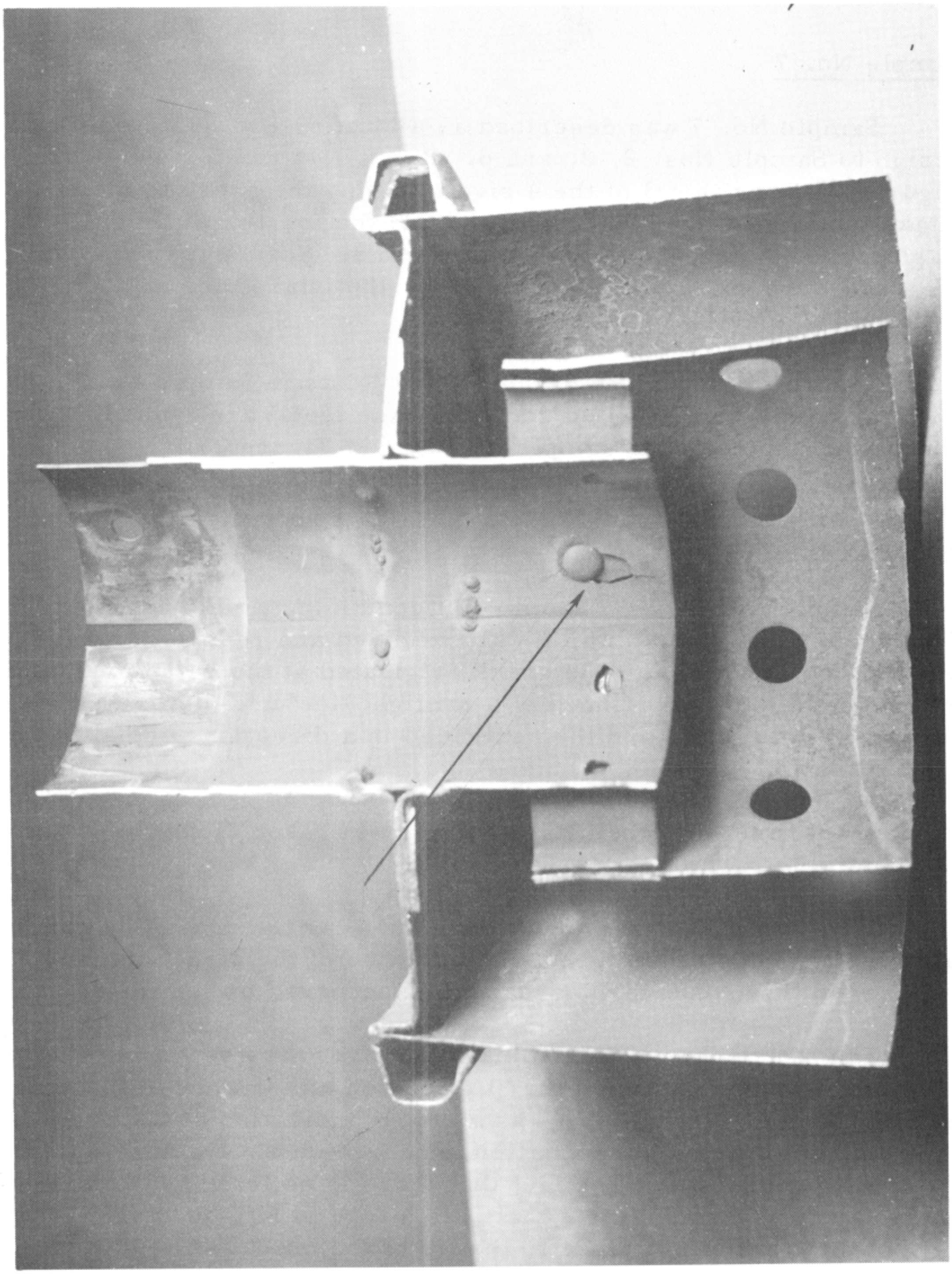

Figure 27. Sample No. 7 - Muffler End Plate, 448 Test Hours

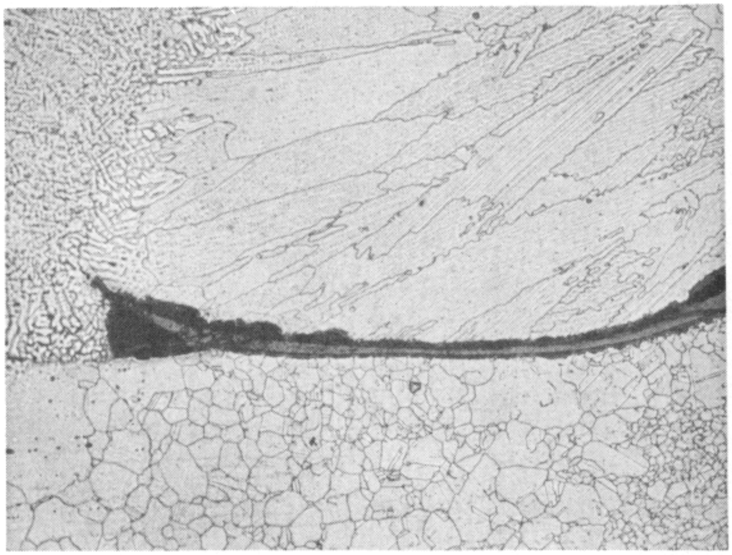

Figure 28

Sample No. 7 - Specimen No. 1

Weld joint.

Magnification: 100X
Etchant: 10% Oxalic acid

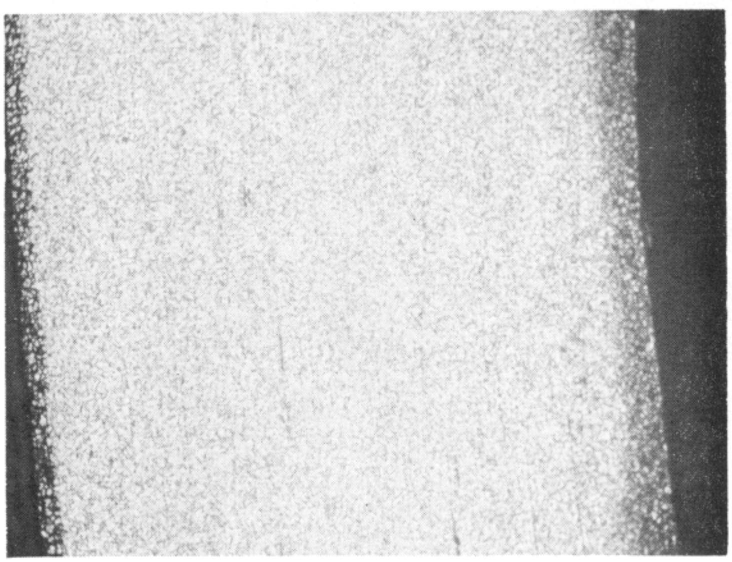

Figure 29

Sample No. 7 - Specimen No. 2

General structure.

Magnification: 100X
Etchant: 10% Oxalic acid

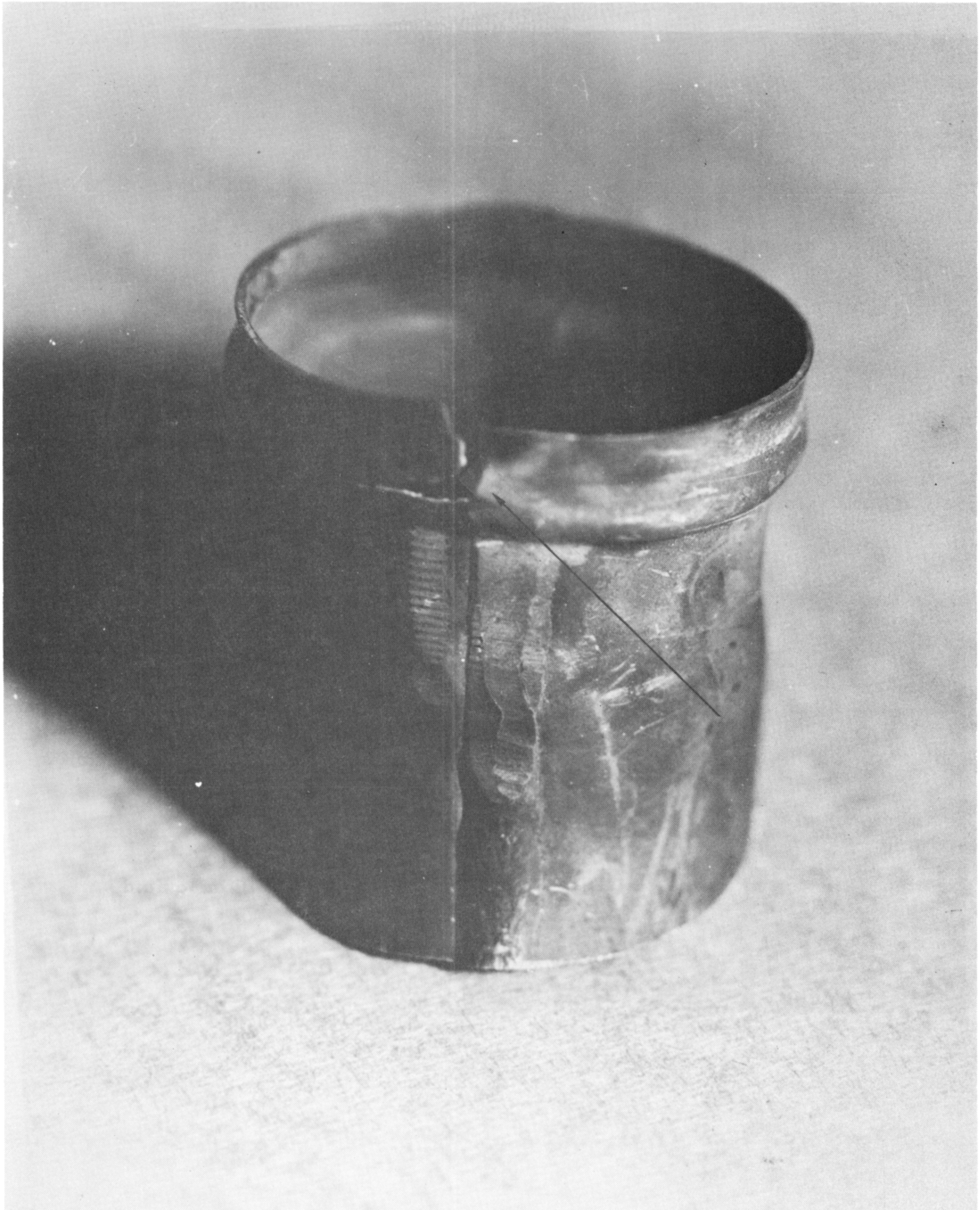

Figure 30. Sample No. 8 - Stack Joint, 112 Test Hours

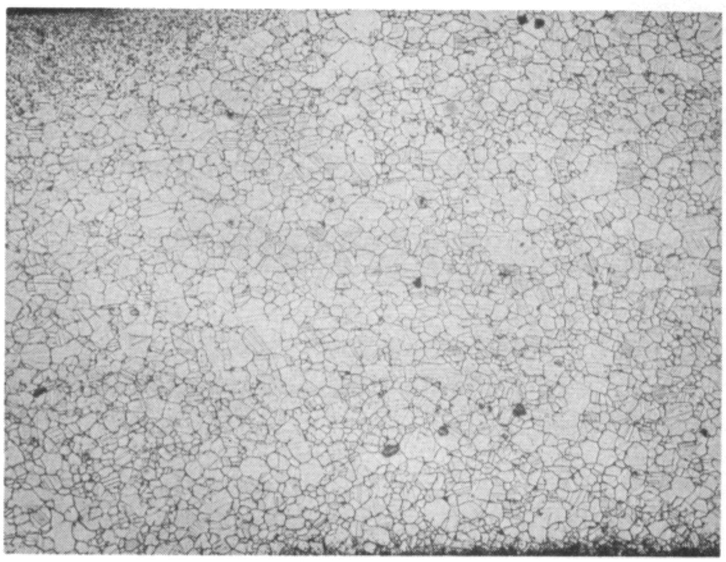

Figure 31

Sample No. 8 - Specimen No. 1

Tube cross-section showing general structure and carburization. (Inside surface in center)

Magnification: 100X
Etchant: 10% Oxalic acid

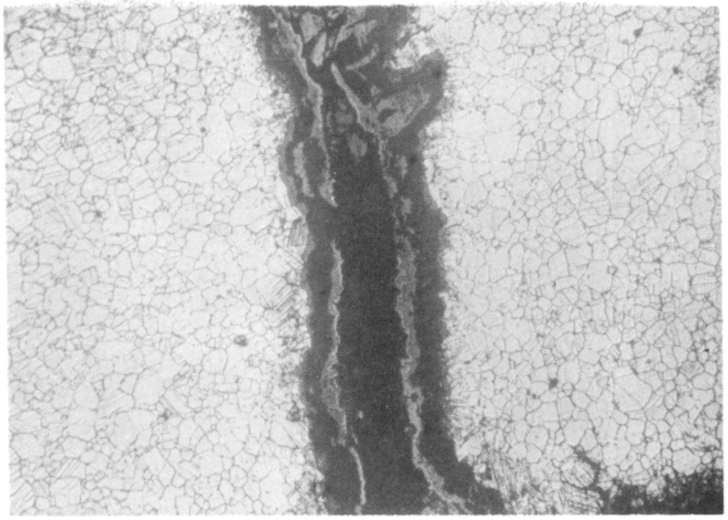

Figure 32

Sample No. 8 - Specimen No. 1

Showing oxidation on crack surface.

Magnification: 100X
Etchant: 10% Oxalic acid

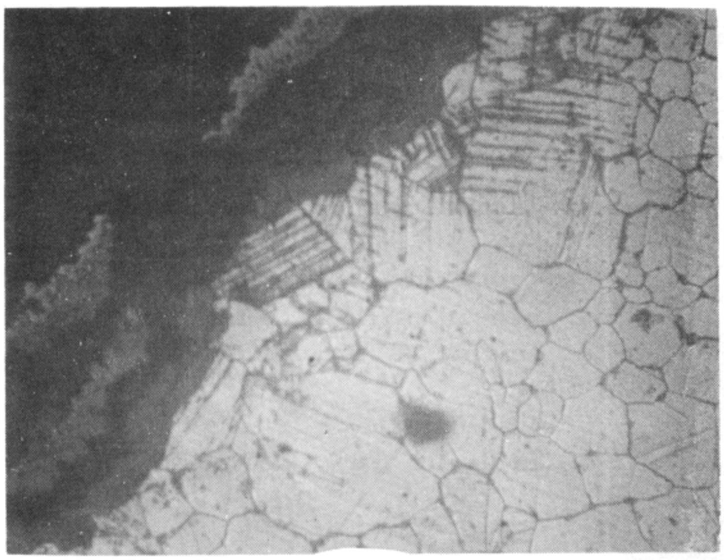

Figure 33

Sample No. 8 - Specimen No. 1

Showing oxidation at higher magnification.

Magnification: 500X
Etchant: 10% Oxalic acid

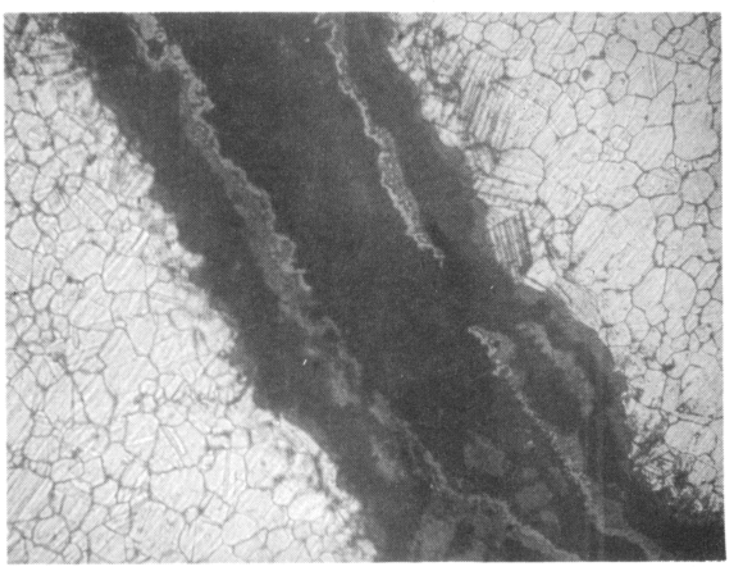

Figure 34

Sample No. 8 - Specimen No. 1

End of crack. Note slip bands adjacent to edge of crack.

Magnification: 250X
Etchant: 10% Oxalic acid

Sample No. 9

Sample No. 9 was described as a Muffler Wall, Heat Exchanger Surface. The sample was heavily oxidized on both the inside and outside surfaces. Figures 35 and 36 show the part in the as-received condition. There was a crack in the shell above the tube. Specimens for chemical analyses were cut from the shell, the tube and the support piece. All were Type 321. The sample was test run for 555 hours.

Metallographic specimens were cut at the end of the crack and at the opposite end of the shell. Examination of the polished surface showed a thick layer of oxidation on the inside surface. Figures 37 and 38 show the heavy oxidation. The outside surface showed deeper penetration at various locations along the surface. It is considered significant that the oxidation corrosion penetrates in some areas in a sharp pointed manner. Thus, creating points of stress concentration from which fatigue cracks can originate.

The microstructure at the two locations after etching are shown in Figures 39 and 40. The structure around the crack contained sigma phase distributed discontinuously in the grain boundaries, and severe oxidation.

Sample No. 10-11

Sample No. 10-11 was identified as a failed Muffler Diffuser Cone. Figure 41 shows a crack occurred around one of the support rods completely separating a section of the top cone. All of the three cones were heavily oxidized internally. The bottom two cones, which were still intact, were slightly oxidized, while the failed cone showed little, if any, evidence of oxidation on the outside surface.

Specimens for chemical analyses were cut from all three cones and from one of the support rods. All specimens were AISI 321.

Figures 42 and 43 show the difference in thickness of oxidation on the different cones. Examination of the microstructure, (Figures 44 and 45), revealed a substantial amount of sigma phase in the grain boundaries and some within the grains.

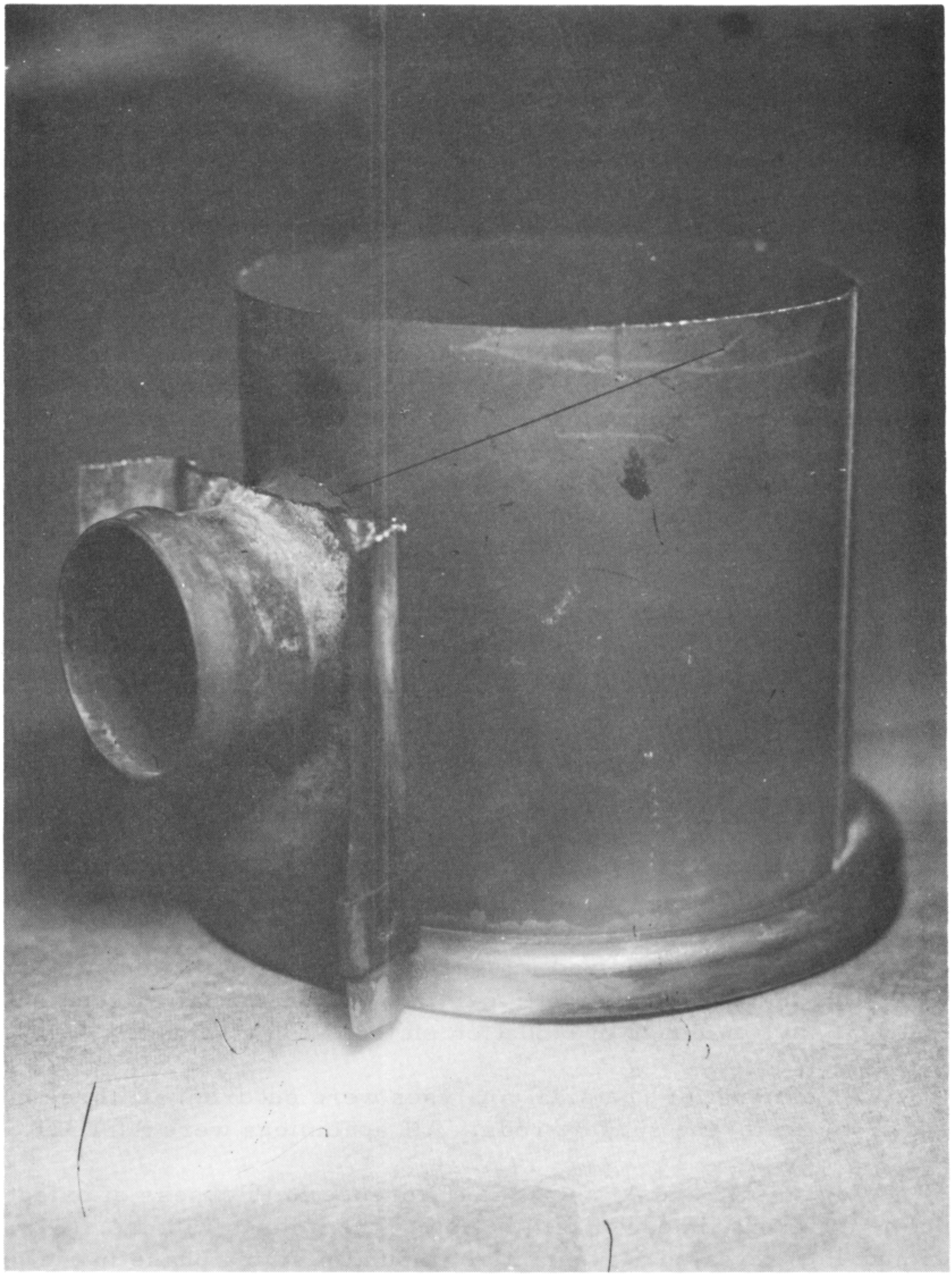

Figure 35. Sample No. 9 - Muffler Wall, Heat Exchanger Surface, 555 Test Hours

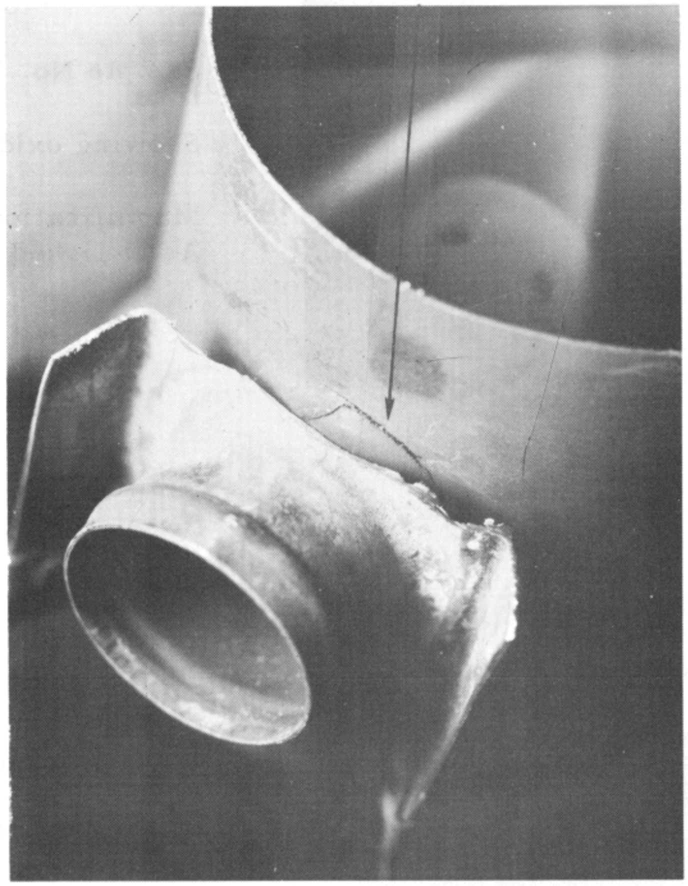

Figure 36. Sample No. 9 - Muffler Wall, Heat Exchanger Surface, View of crack, 555 Test Hours

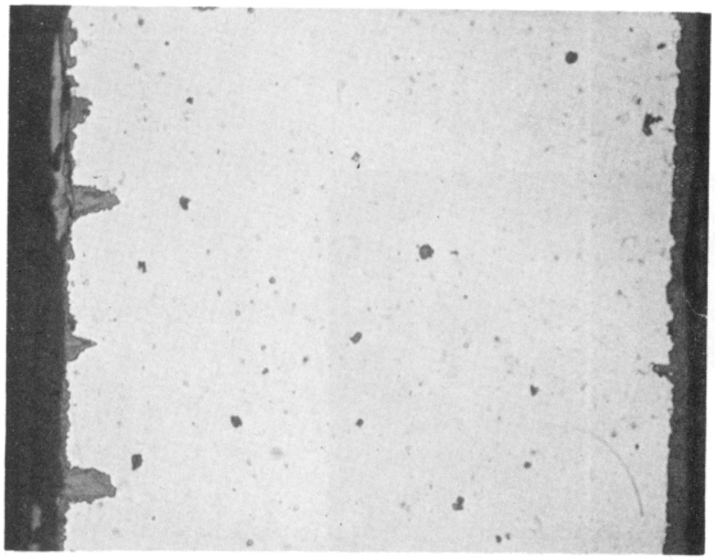

Figure 37

Sample No. 9 - Specimen No. 1

Showing oxidation at surfaces.

Magnification: 100X
As Polished

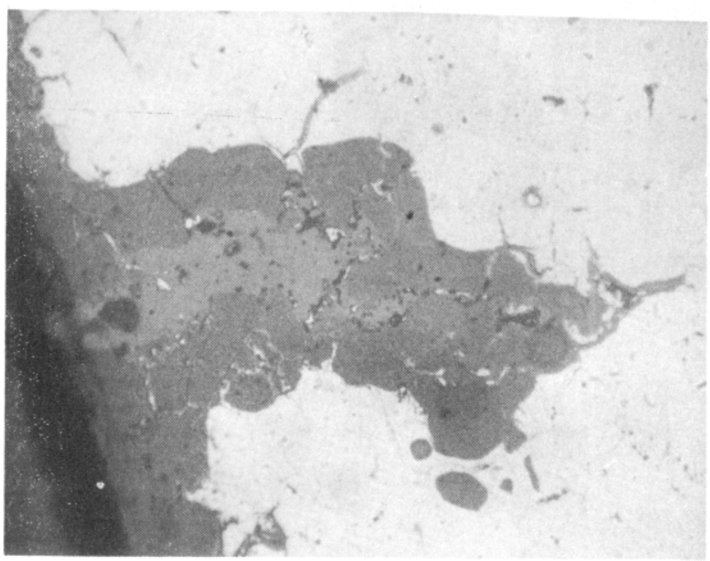

Figure 38

Sample No. 9 - Specimen No. 1

Deeper penetration at various locations on outside surfaces.

Magnification: 500X
As Polished

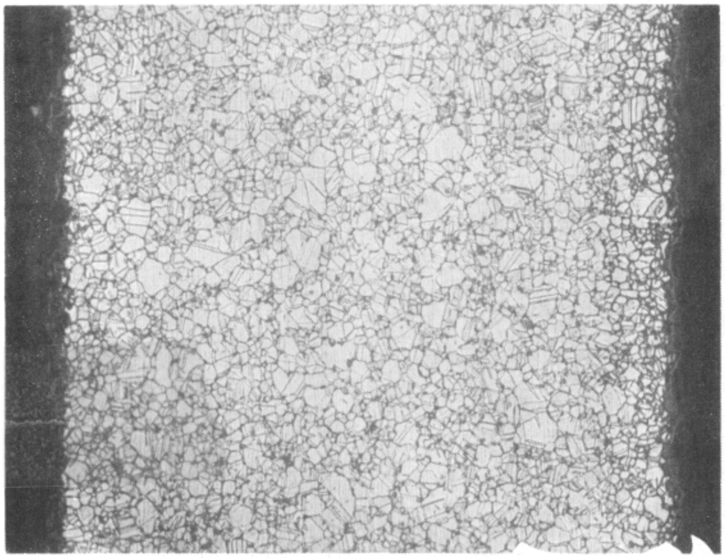

Figure 39

Sample No. 9 - Specimen No. 1

Showing general structure.

Magnification: 100X
Etchant: 10% Oxalic acid

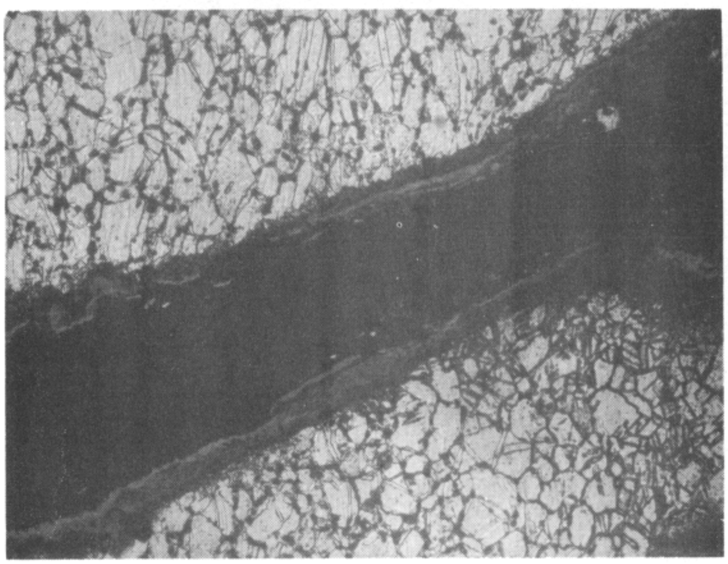

Figure 40

Sample No. 9 - Specimen No. 1

Showing structure about crack and sigma phase in the grain boundaries.

Magnification: 250X
Etchant: 10% Oxalic acid

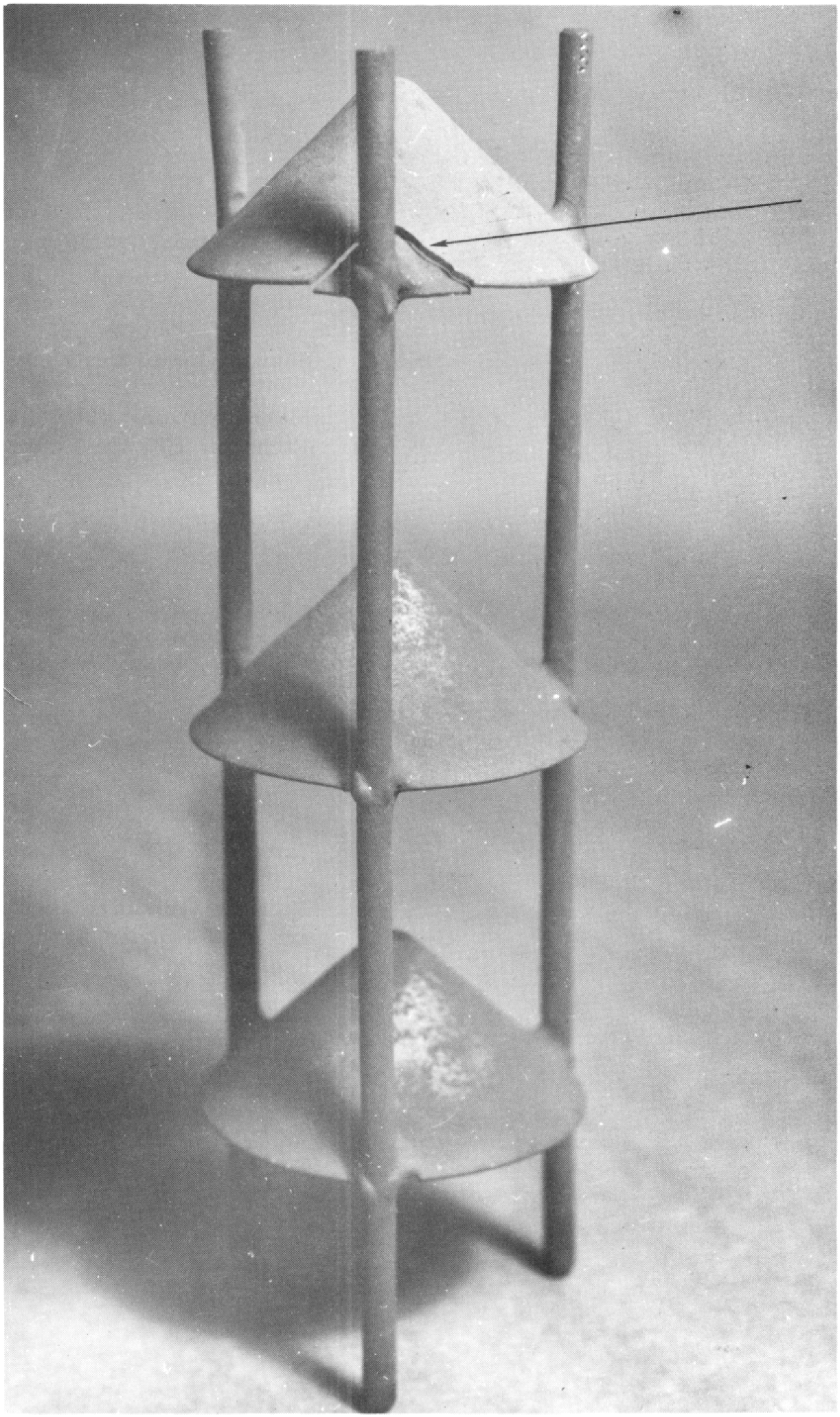

Figure 41. Sample No. 10-11 - Muffler Diffuser Cone, 600 Test Hours

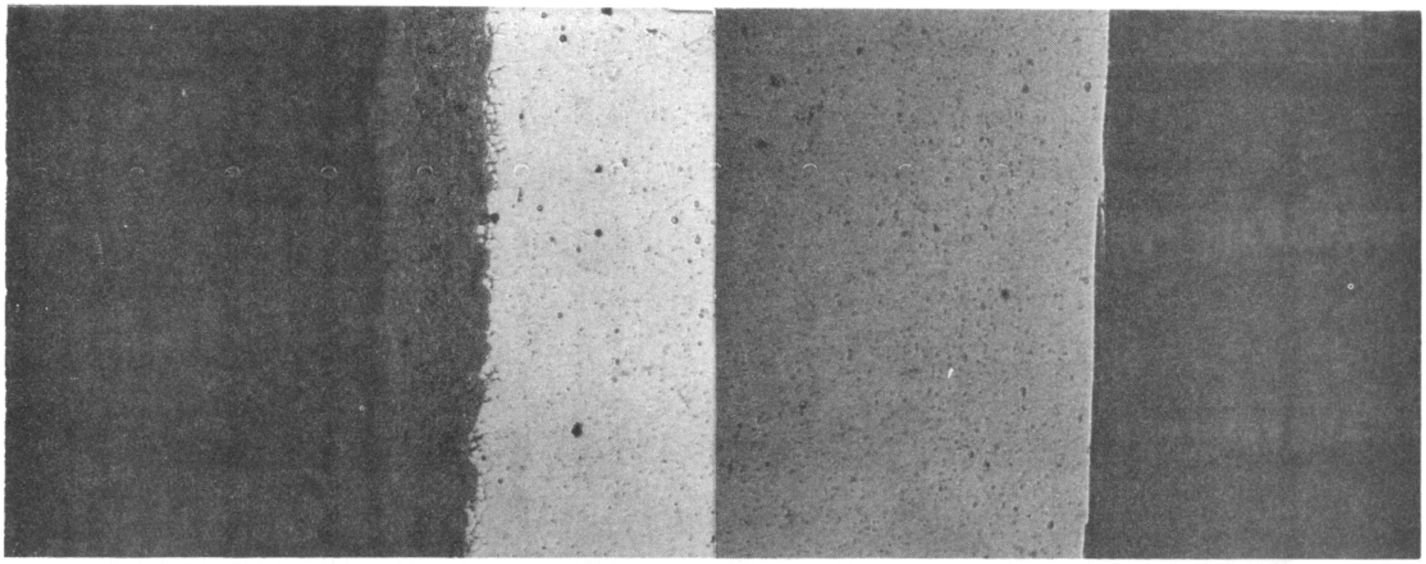

Figure 42. Showing extent of Oxidation on Top Cone of Sample No. 10-11.
Magnification: 100X As Polished

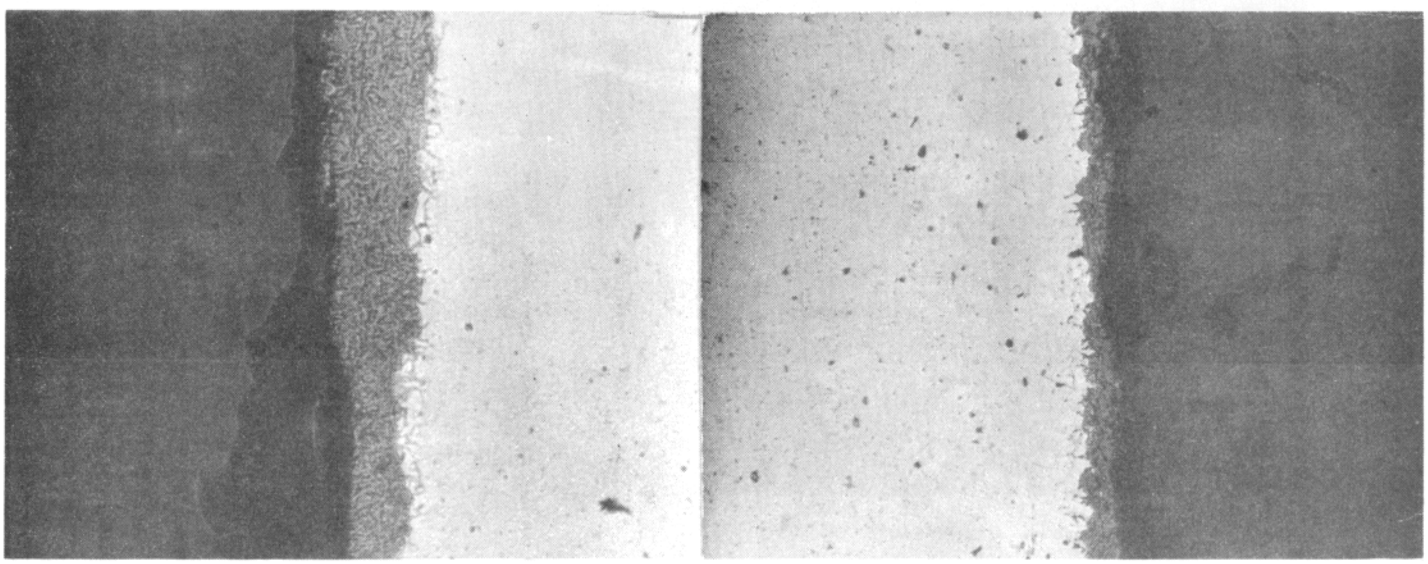

Figure 43. Showing extent of oxidation on Middle Cone of Sample No. 10-11.
Magnification: 100X As Polished

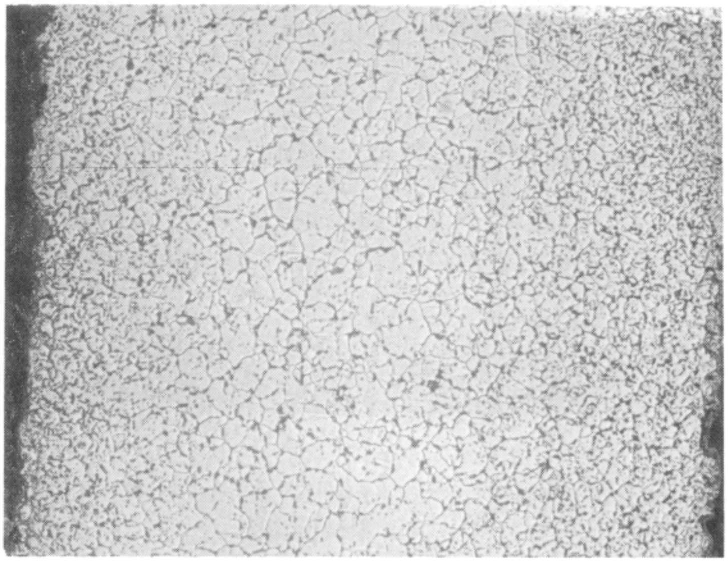

Figure 44

Sample No. 10-11
Specimen No. 1

Showing general structure.

Magnification: 100X
Etchant: 10% Oxalic acid

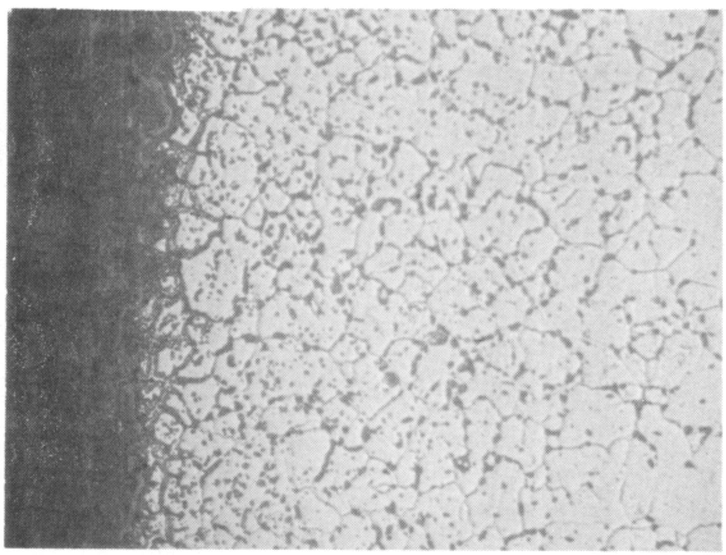

Figure 45

Sample No. 10-11
Specimen No. 1

Showing sigma phase and intergranular corrosion.

Magnification: 250X
Etchant: 10% Oxalic acid

Sample No. 12-13

Sample No. 12-13 was identified as a Muffler Wall. There was no observed failure. Visual examination showed evidence of some internal oxidation and very little external oxidation. The studs were heavily oxidized. Chemical analyses showed the entire sample to be Type 321. The sample, which was test run for 600 hours, is shown as-received in Figure 46.

Metallurgical samples were cut from the muffler wall and a stud was cut in half to view the structures of both the inside and outside. The unetched cross sections are shown in Figure 47. The general structure of the wall, as shown in Figure 49, was normal. Examination of the stud showed intergranular corrosion and some sigma phase also in the grain boundaries (see Figure 48).

Sample No. 14-15

Sample No. 14-15 was another Muffler Diffuser Cone similar to Sample No. 10-11. These samples were one of the two furnished that were fabricated from Incoloy Alloy 800. They were test run for 600 hours. The part was free from failure and visual examination revealed no evidence of oxidation. Specimens for chemical analyses were cut from the top cone and the support rod. The analysis confirmed that the cones were Incoloy Alloy 800. However, the support rod was AISI 321. Figure 50 shows the sample as-received.

Metallurgical specimens were cut from all of the three cones (Incoloy Alloy 800). The microphotographs of the samples in the unetched condition showed very little oxidation. Many titanium cyano-nitrides were evident as shown in Figures 51 and 52. Figures 53 and 54 show the general structure of one of the cones from Sample No. 14-15.

Sample No. 16-17

Sample No. 16-17 was a section cut from a Muffler Wall. The sample was identical in configuration to Sample No. 12-13. The description did not specify the amount of test hours. It was determined to be 600. Chemical analyses showed the sample to be Incoloy Alloy 800 with the exception of the studs which were Type 321. As in Sample No. 14-15, there was a conspicuous absence of oxidation except on the studs. Figure 55 shows the sample as-received.

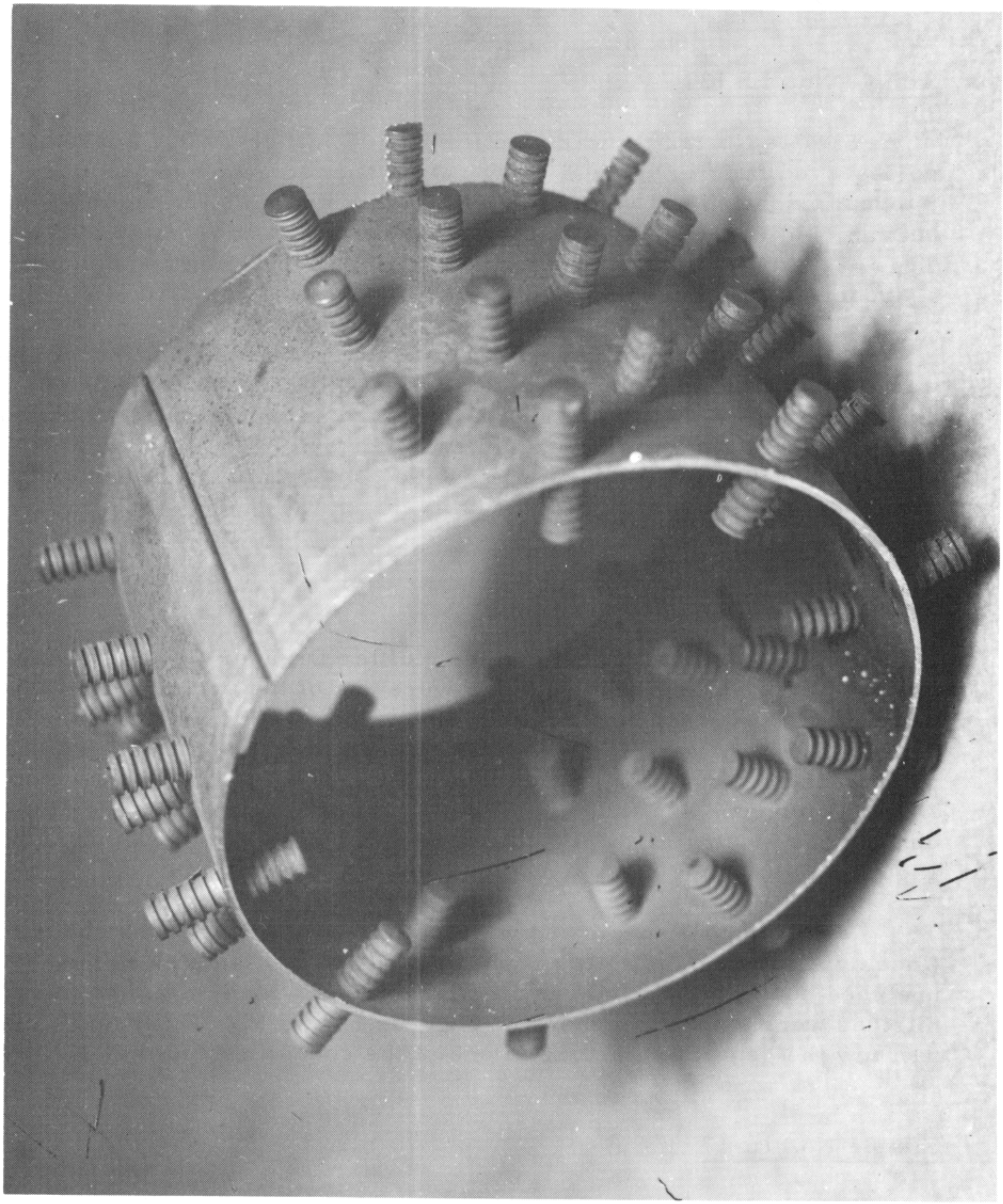

Figure 46. Sample No. 12-13 - Muffler Wall, 600 Test Hours

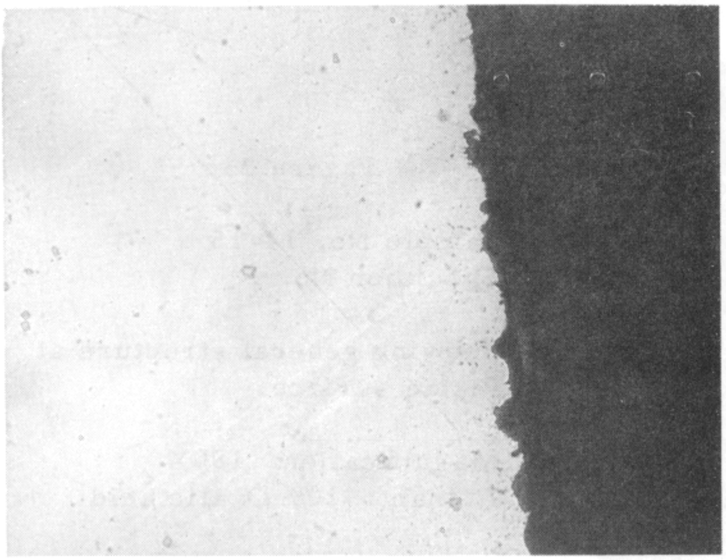

Figure 51

Sample No. 14-15
Specimen No. 1

Inside surface showing oxidation and titanium cyanonitrides.

Magnification: 100X
As Polished

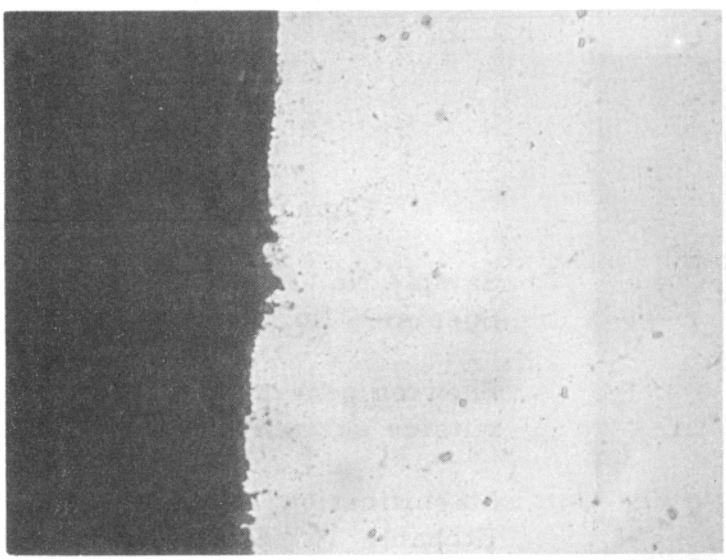

Figure 52

Sample No. 14-15
Specimen No. 1

Outside surface showing oxidation and titanium cyanonitrides.

Magnification: 100X
As Polished

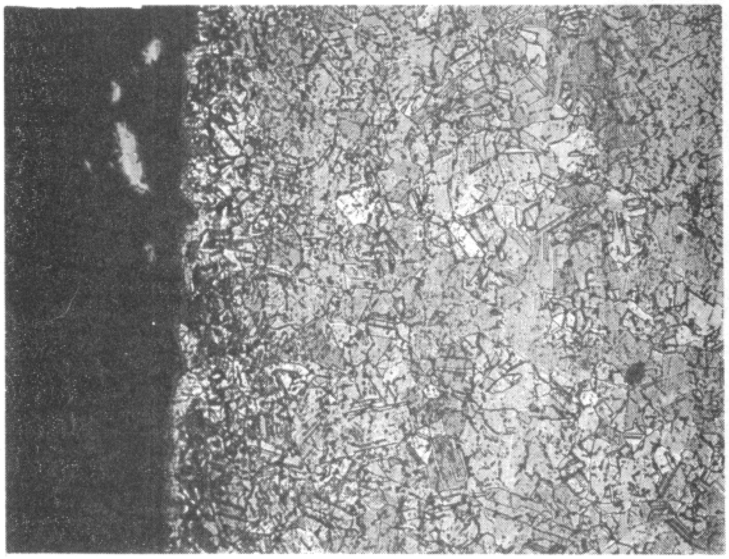

Figure 53

Sample No. 14-15
Specimen No. 1

Showing general structure at inside surface.

Magnification: 100X
Etchant: 10% Oxalic acid

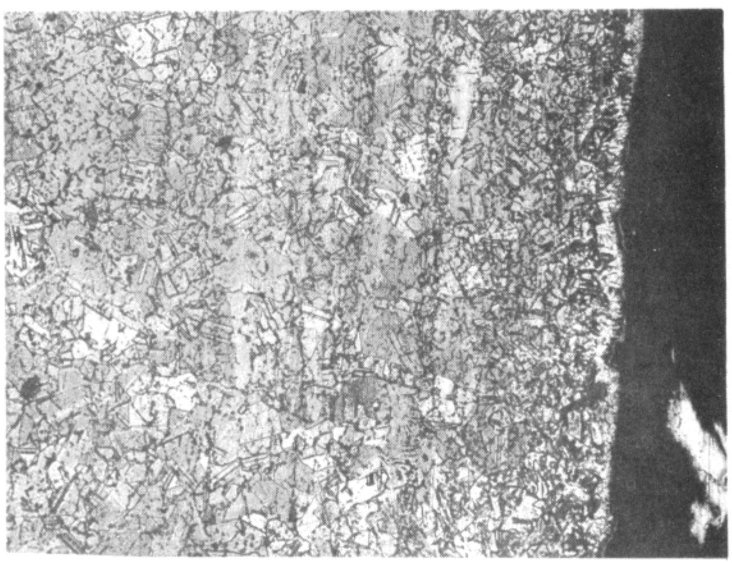

Figure 54

Sample No. 14-15
Specimen No. 1

Showing general structure at outside surface.

Magnification: 100X
Etchant: 10% Oxalic acid

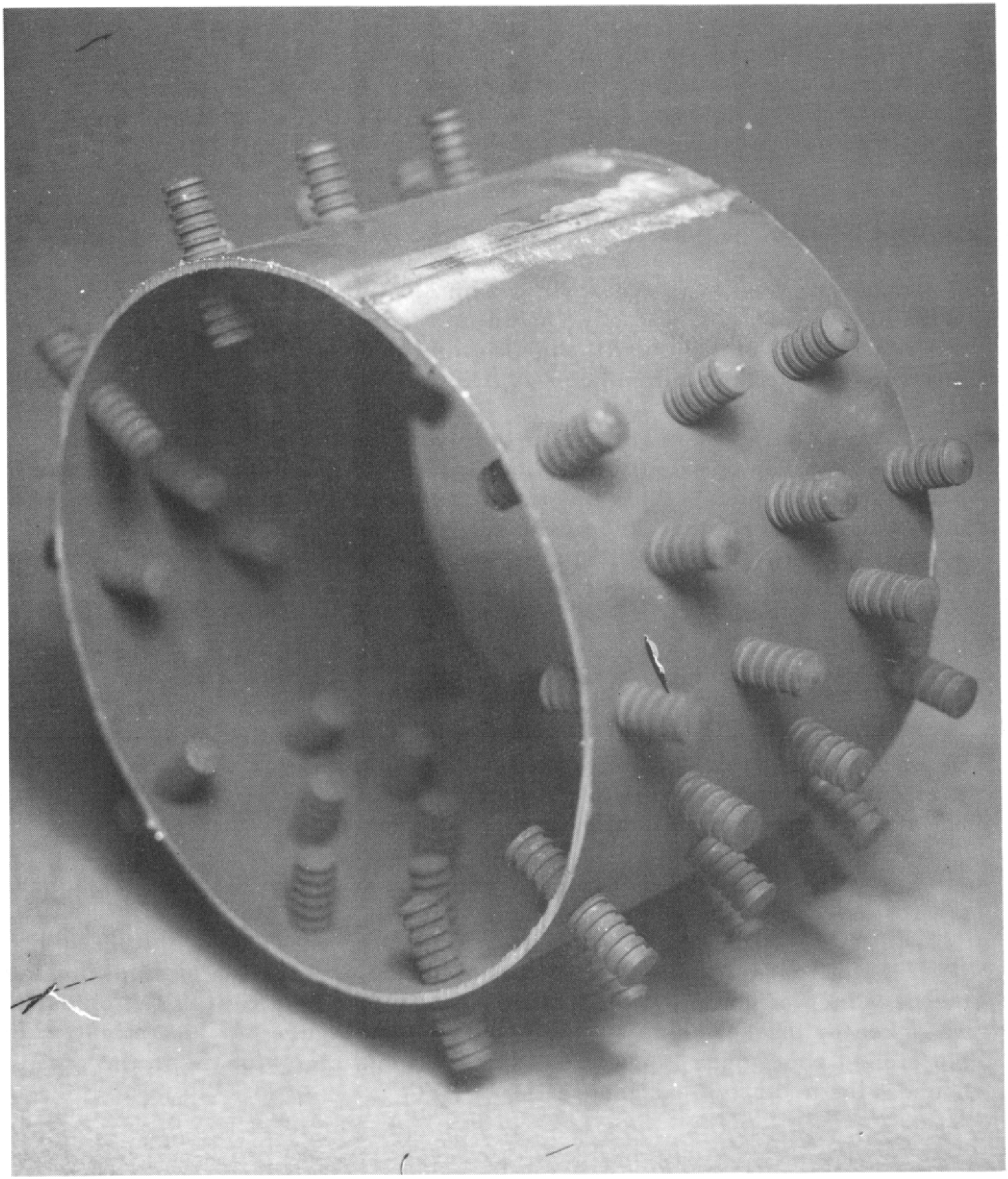

Figure 55. Sample No. 16-17 - Incoloy 800 Muffler Wall, 600 Test Hours

Metallurgical specimens were taken from the wall and the stud. Figures 56 and 57 compare the extent of oxidation on the inside edge of the AISI 321 stud and the Incoloy Alloy 800 wall. The general structure and titanium cyanonitrides are shown in Figures 58 and 59.

Sample No. 18

Sample No. 18, Figure 60, was a Muffler Baffle similar in design to Samples No. 1, 4, and 5. The sample was test run for 490 hours and showed no sign of failure although the oxidation was thick. Chemical analyses showed the samples to be AISI 347.

Metallographic examination in the unetched condition revealed a deep penetration of oxidation on both the inside and outside surfaces and columbium carbides. This condition is shown in Figure 61. Figure 62 shows the general structure of the sample. Intergranular corrosion is evident on the internal and external surfaces and there is a great amount of sigma phase present in the grain boundaries.

Sample No. 19

Sample No. 19, Figure 63, was a part of a Muffler Wall. The thickness was given as .02 inch and it was test run for 490 hours. This particular muffler was not of the same configuration as Sample No. 12-13, but a comparison of general condition was desired.

A specimen for chemical analyses was cut from the sample along the lower edge of the base. The material was Type 321.

Metallographic investigation showed the penetration of oxidation and the presence of columbium carbides. As in previous cases, the oxidation was greater on the inside surface as shown in Figure 64. Examination of the etched specimens (Figure 65) showed some sigma phase in the grain boundaries and a typical general structure.

Sample No. 20

Sample No. 20 was a Muffler Wall .03 inch thick and test run for 600 test hours, as shown in Figure 66. This muffler wall was of a different configuration when compared to Samples No. 9, 12-13, 16-17, and 19. Chemical analyses showed the material to be Type 321.

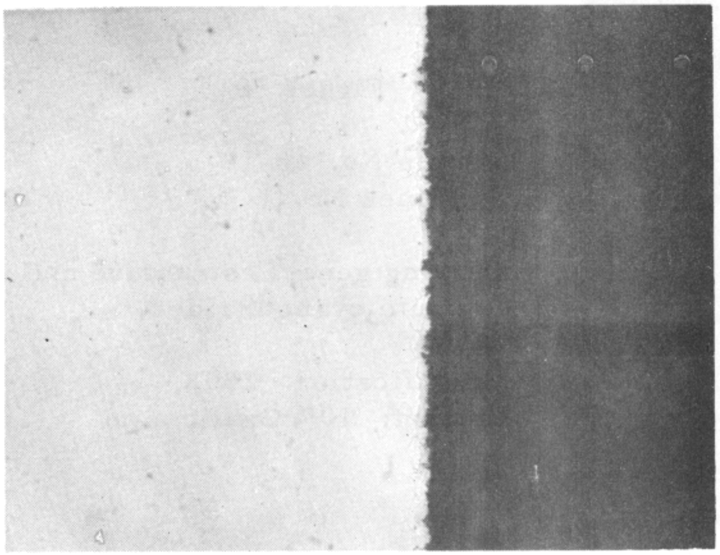

Figure 56

Sample No. 16-17
Specimen No. 1

Showing extent of oxidation on the inside surface of the Incoloy Alloy 800 muffler wall.

Magnification: 100X
As Polished

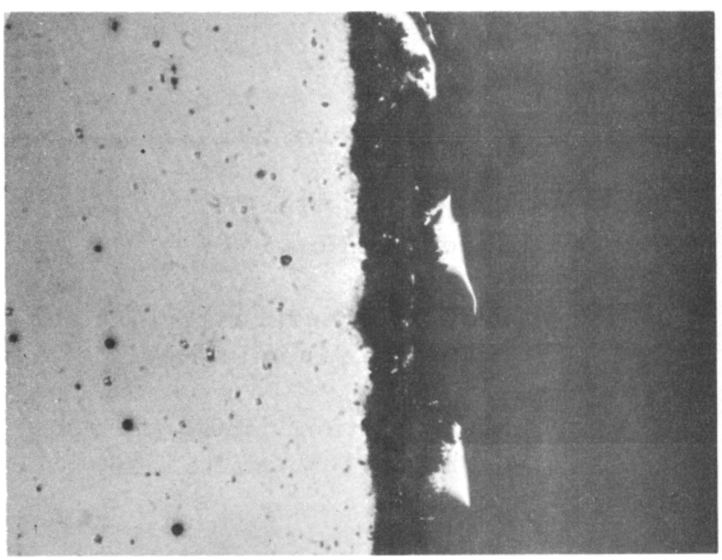

Figure 57

Sample No. 16-17
Specimen No. 1

Showing extent of oxidation on the inside surface of AISI 321 stud.

Magnification: 100X
As Polished

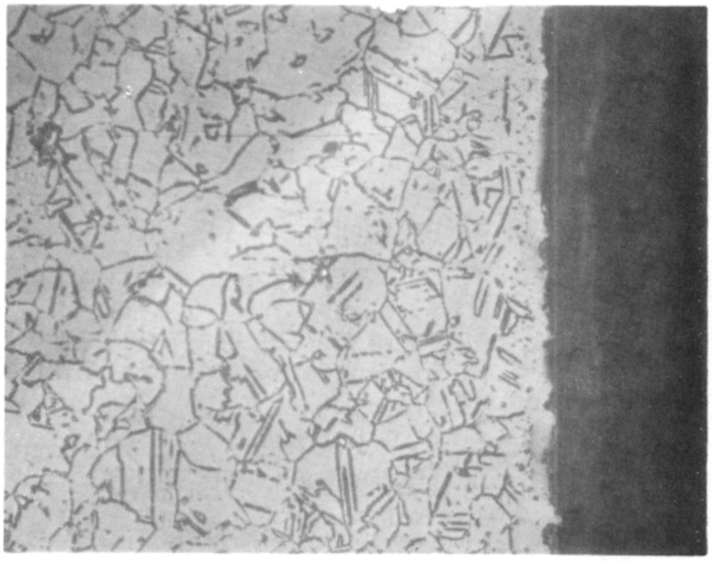

Figure 58

Sample No. 16-17
Specimen No. 1

Showing general structure and titanium cyanonitrides.

Magnification: 250X
Etchant: 10% Oxalic acid

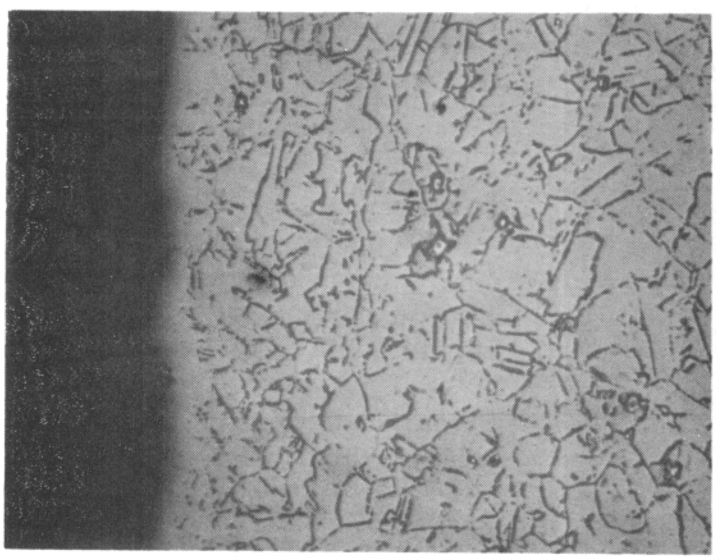

Figure 59

Sample No. 16-17
Specimen No. 1

Showing general structure and titanium cyanonitrides.

Magnification: 250X
Etchant: 10% Oxalic acid

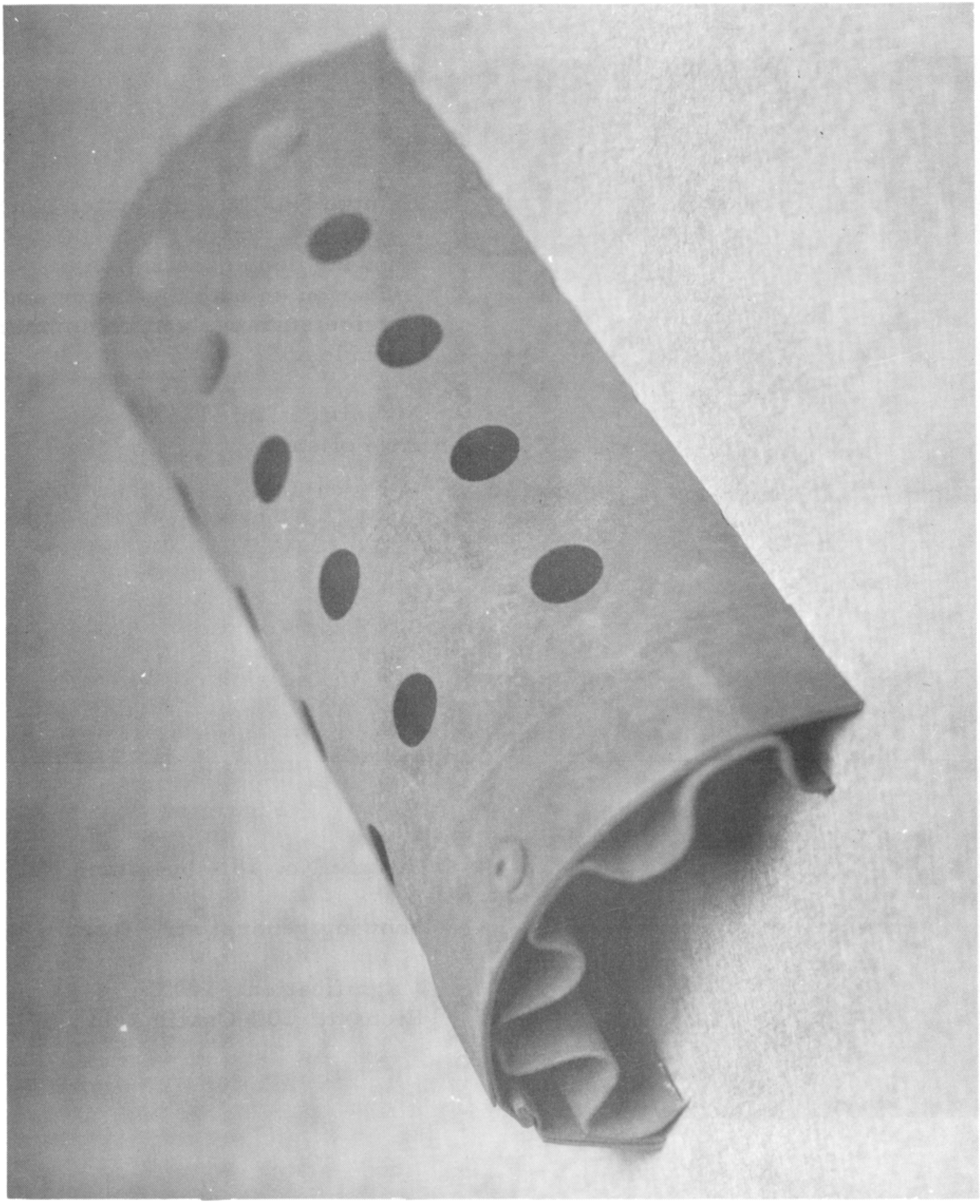

Figure 60. Sample No. 18 - Muffler Baffle, 490 Test Hours

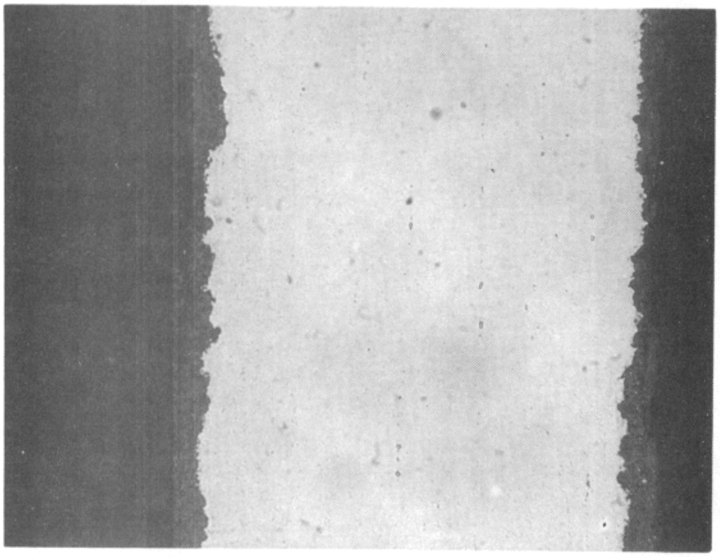

Figure 61

Sample No. 18 - Specimen No. 1

Showing deep penetration of oxidation on both the inside and outside surfaces and columbium carbides.

Magnification: 125X
As Polished

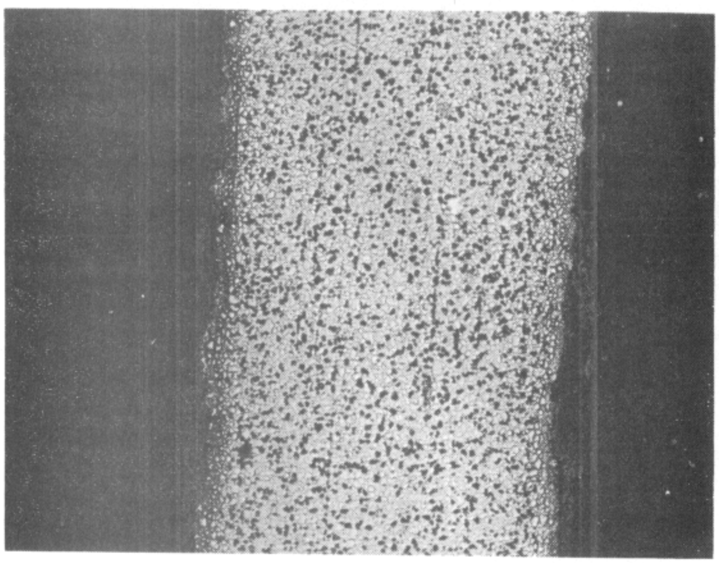

Figure 62

Sample No. 18 - Specimen No. 1

Showing general structure.

Magnification: 100X
Etchant: 10% Oxalic acid

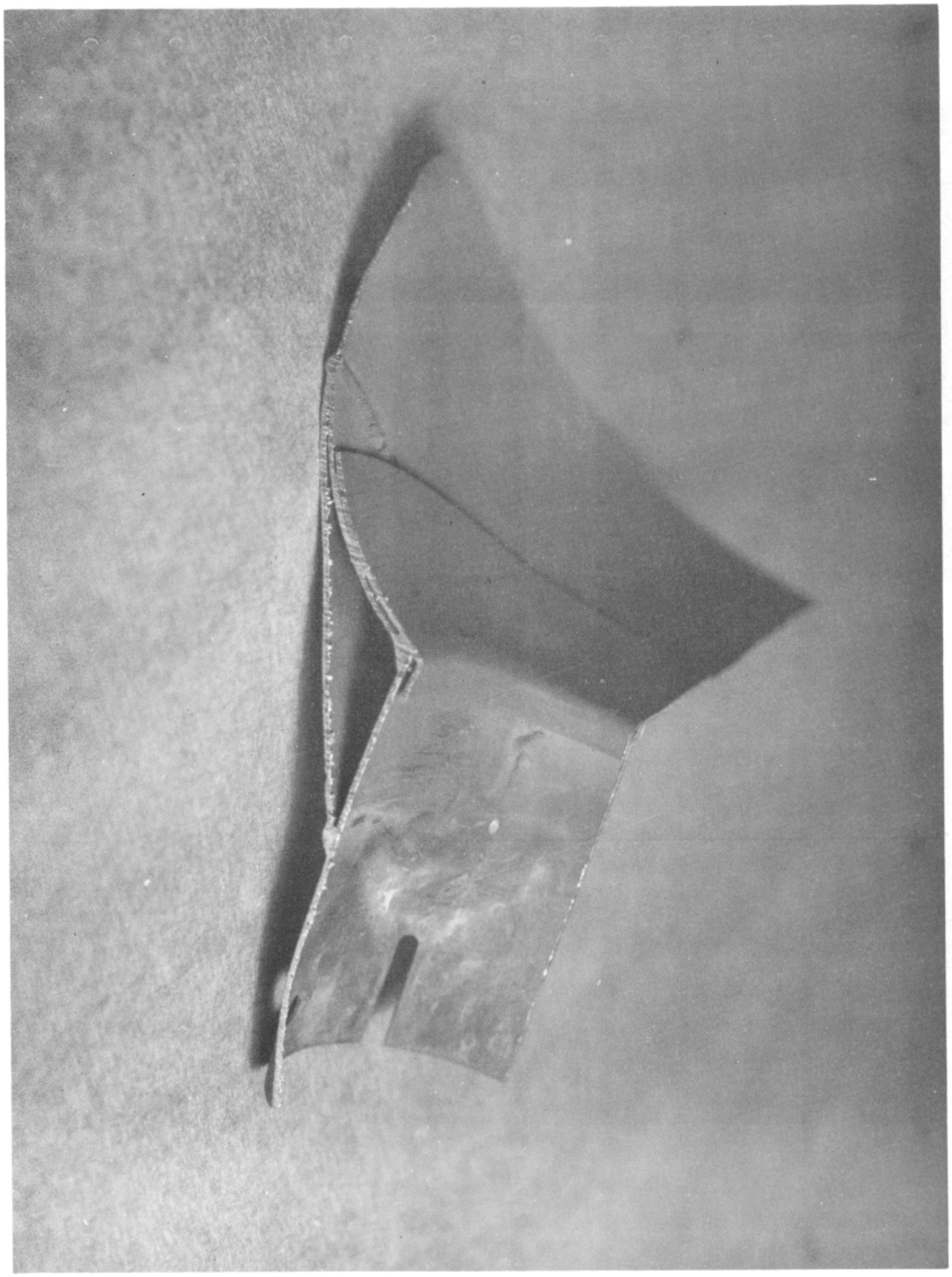

Figure 63. Sample No. 19 - Muffler Wall, 490 Test Hours

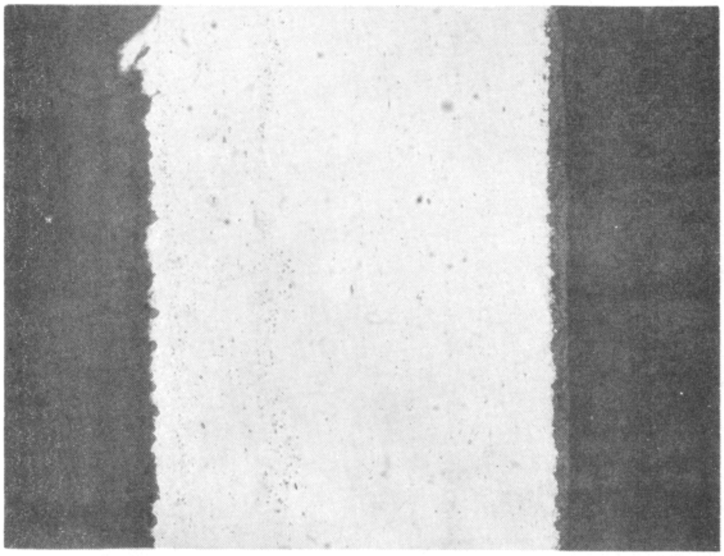

Figure 64

Sample No. 19 - Specimen No. 1

Showing penetration of oxidation.

Magnification: 100X
As Polished

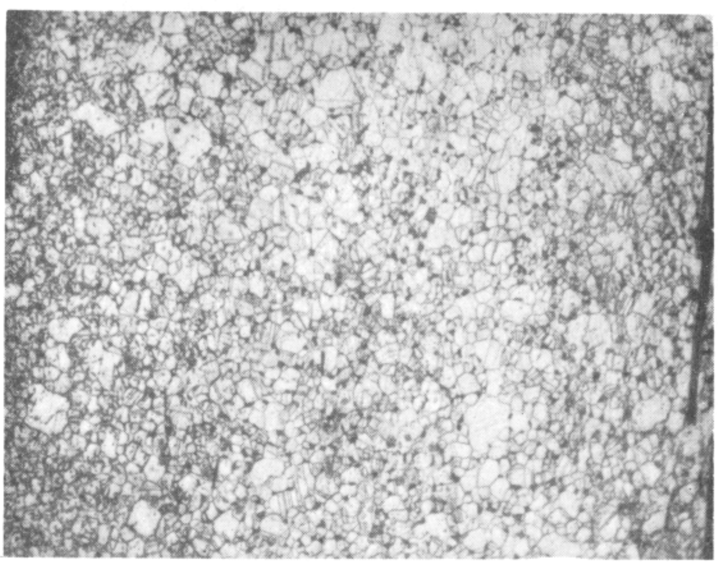

Figure 65

Sample No. 19 - Specimen No. 1

Showing general structure.

Magnification: 100X
Etchant: 10% Oxalic acid

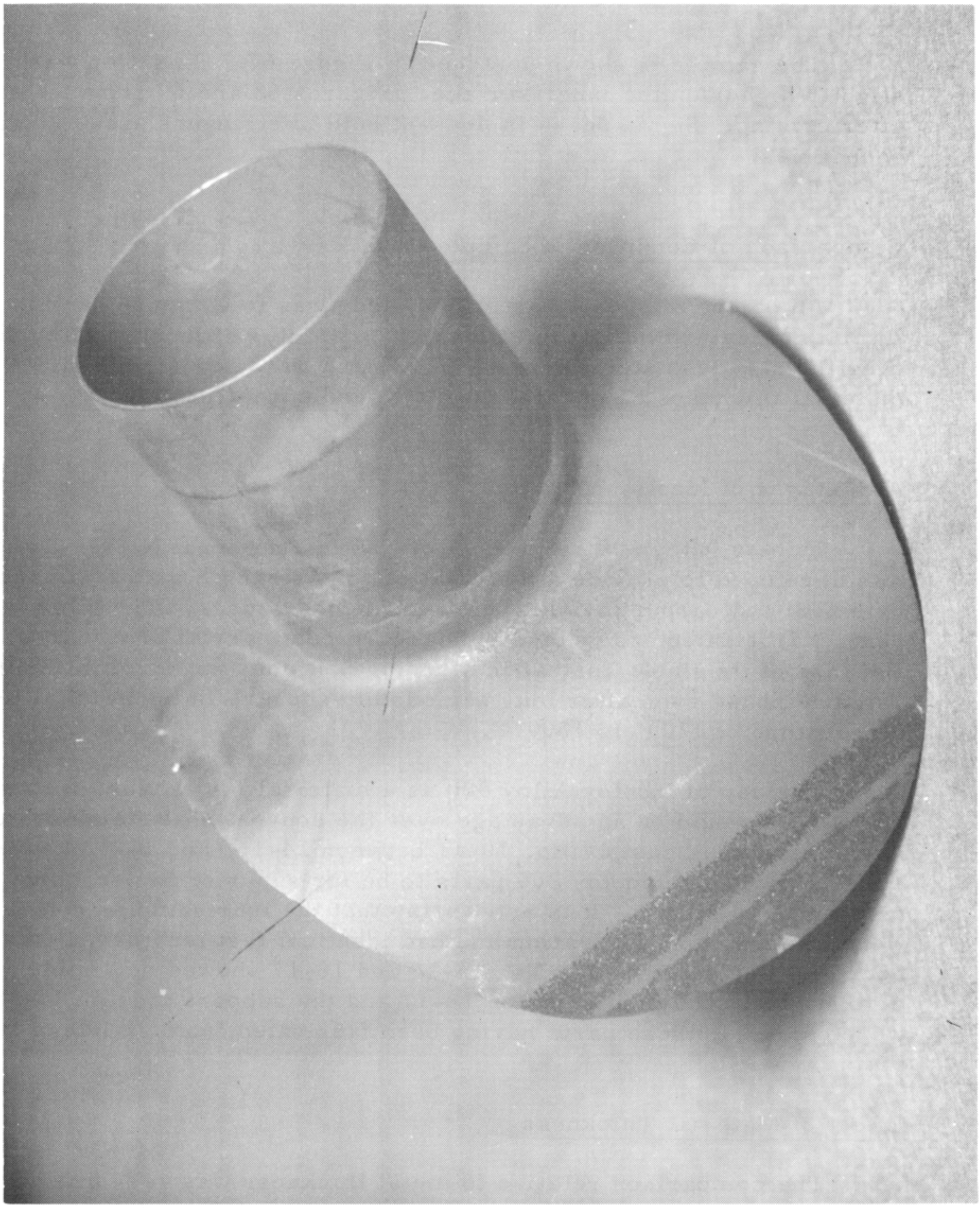

Figure 66. Sample No. 20 - Muffler Wall, 600 Test Hours

The sample is shown unetched in Figure 67. Oxidation was slightly higher on the inner surface. Figures 68 and 69 show the sample after etching. Sigma phase is present both in stringers and in the grain boundaries.

Comparison of Condition of Samples

An objective of this part of the study was to compare certain samples to determine (1) the advantages, if any, of Incoloy Alloy 800 over the stainless steels types AISI 321 and 347, and (2) the effect of material thickness on general condition and durability.

Advantages of Incoloy Alloy 800

Incoloy Alloy 800, a product of The International Nickel Company, was developed to provide a material of good strength with resistance to oxidation and carburization at elevated temperatures. The alloy is readily fabricated and welded by standard commercial procedures. Because of its stable austenitic structure, it does not form the brittle "sigma" phase even after long periods of exposure in the critical temperature range of 1200° to 1600°F.

The use of Incoloy Alloy 800 as a material for exhaust system application would be an advantage over the conventional stainless steels. A comparison of Sample No. 10-11 between 14-15, and 12-13 between 16-17 showed the Incoloy 800 parts to be far superior in corrosive or oxidation resistance. It is noteworthy that the four samples compared were similar in configuration and had identical test lengths. In the 600 hour test period, Samples No. 14-15 and 16-17 showed negligible amounts of oxidation. Only the studs on 16-17 and the support rods on 14-15 were oxidized, these parts having been fabricated from stainless steel.

Effect of Material Thickness

The comparison relative to metal thickness was very difficult inasmuch as the parts to be compared were of a different configuration and because of the significant difference in test times. The samples compared are identified in Table III giving a general description and test data.

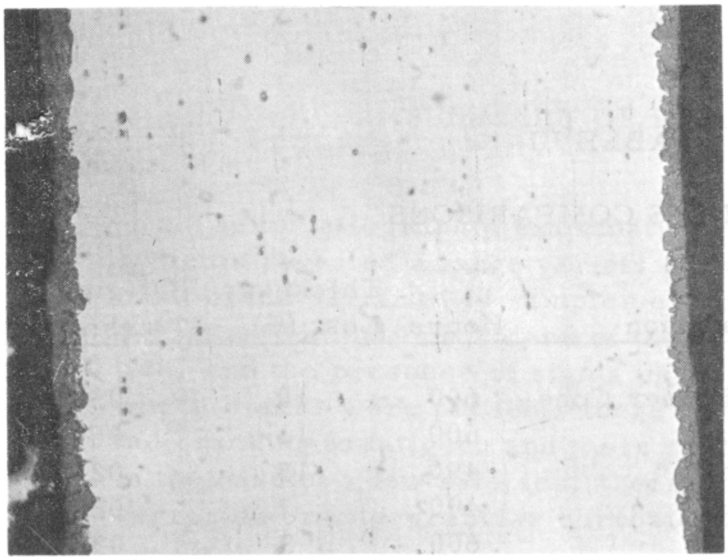

Figure 67

Sample No. 20 - Specimen No. 1

Showing penetration of oxidation and carbides.

Magnification: 100X
As Polished

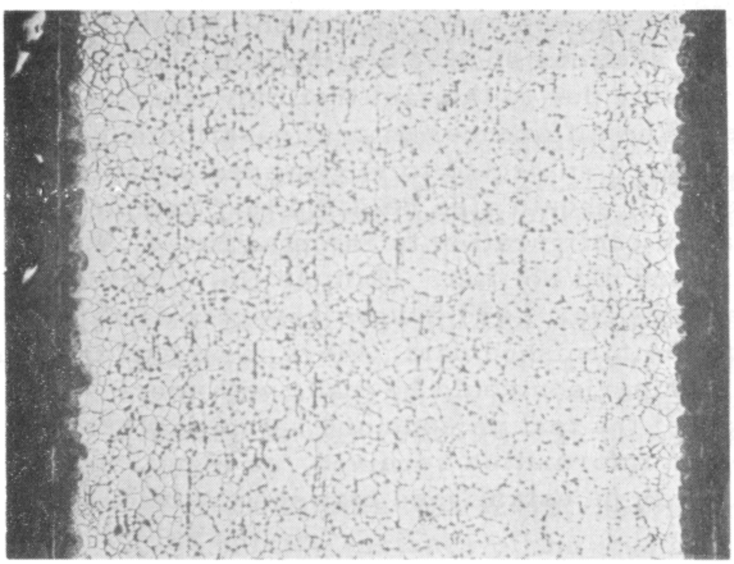

Figure 68

Sample No. 20 - Specimen No. 1

Showing general structure.

Magnification: 100X
Etchant: 10% Oxalic acid

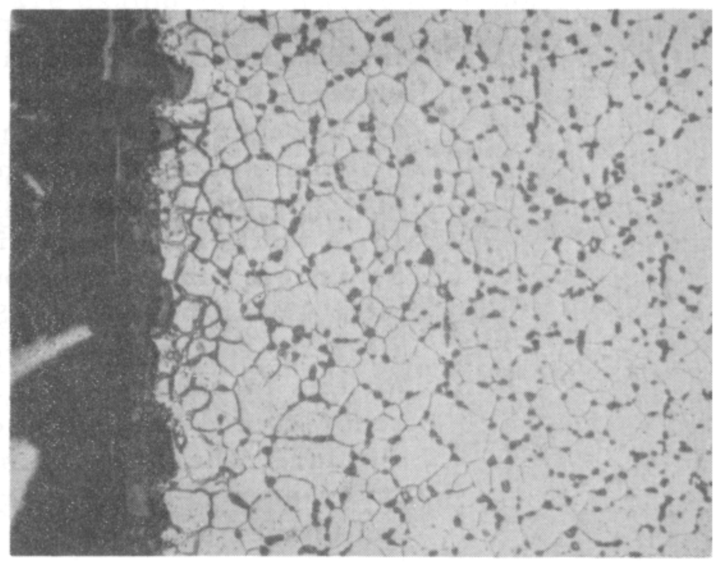

Figure 69

Sample No. 20 - Specimen No. 1

Showing intergranular corrosion, and sigma phase.

Magnification: 250X
Etchant: 10% Oxalic acid

Test Stand Failures	Corresponding Operating Aircraft Failures
3. Some internal oxidation and very little external oxidation on muffler wall. Studs are heavily oxidized on both sides, but significantly more on inside.	3. Ferritic steel studs were practically oxidized away. No comment made on oxidation of 347 studs. Muffler wall was heavily oxidized and inside area showed carburization.
4. No bulged areas.	4. Large bulged area in muffler wall.
<u>Sample No. 16-17</u>	No corresponding sample made of Incoloy 800 was evaluated.
1. Muffler wall was Incoloy 800 alloy and studs were Type 321 steel.	
2. The 800 alloy showed very little evidence of oxidation whereas the 321 studs showed considerable oxidation.	

CONCLUSIONS

It is concluded that:

1. Parts indicated as 321, 347, and Incoloy 800 were verified as such by chemical analyses.

2. There was no evidence that the severe oxidation or cracking resulted from any abnormality in the materials.

3. The condition of many of the samples indicates that nonuniform heating existed in the system.

4. The presence of delta ferrite, sigma phase and carburization was determined.

5. Cracking can be attributed to fatigue, and in particular to corrosion fatigue.

6. The Incoloy 800 parts exhibited superior oxidation and erosion resistance to that of the stainless steels.

7. In general, the types of failures experienced on the test stand samples were similar to those experienced on the corresponding operating aircraft samples reported in Technical Report FAA-ADS-28.