FAA-ADS- 28

METALLURGICAL EVALUATION OF FAILED AIRCRAFT STAINLESS STEEL EXHAUST SYSTEM COMPONENTS

TECHNICAL REPORT

JANUARY 1965

by
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Research Center
Brackenridge, Pennsylvania

Under Contract FA NAF-176

for

FEDERAL AVIATION AGENCY
AIRCRAFT DEVELOPMENT SERVICE

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FEDERAL AVIATION AGENCY

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By T. H. McCunn, Allegheny Ludlum Steel Corporation

Summary

A total of twelve samples from small aircraft exhaust systems were investigated metallurgically. Three of the samples, referred to as baseline, were from new, unused systems. These were examined metallographically for general microstructural characteristics and chemically analyzed. The other samples were from systems which had failed while in flight operation. These samples were examined metallographically and analyzed chemically to determine the cause(s) of failure. The investigation was supplemented by visual examination and in some instances identification of the constituents of the oxidation or corrosion products by X-ray means.

The samples were representative of a number of designs and different types of failures which have been encountered. Practically all the materials were AISI Type 321, a titanium-stabilized austenitic stainless steel. Examination of the baseline samples showed microstructures of the base metal, weld and weld heat-affected zone to be normal. Four samples failed because of excessive oxidation or high temperature corrosion due apparently to uneven flow of gases, resulting in local overheating, carburization, and probably more rapid attack by the products of combustion, especially lead compounds. Four other samples from mufflers of similar design and one sample of a different design showed fatigue cracks. The failures were attributed to excessive vibrational and/or thermal stresses in the presence of abrupt changes in section size and likely locations for crack initiation.

INTRODUCTION

Purpose

The investigations of Contract No. FA-NAF-176 were undertaken to determine the cause(s) of failure of small aircraft exhaust systems. Some of the failures result in a serious safety hazard in that cracks in certain locations or parts allow the leakage of exhaust fumes to which occupants of the aircraft may be exposed.

Background

Initially the investigations were to include samples from (1) new, unused systems, (2) new, unused systems which failed after test by vibration only, (3) new, unused systems which failed after being operated on the ground with an aircraft engine in a test bed under simulated flight conditions, and (4) systems which failed while installed in operating aircraft as a result of actual flight. Because of certain delays samples from only new, unused systems and systems which failed in operating aircraft have been received and examined up to this time. The former are referred to as baseline samples.

The exhaust systems are fabricated from a stabilized grade of stainless steel, mostly AISI Type 321 and sometimes AISI Type 347.

Some Characteristics of Stainless Steels

Stainless steels are broadly classified into two groups according to composition. The first group is the AISI 400 series or straight chromium grades which contain chromium as the principal alloy addition. The crystal structure is body-centered cubic and the materials are magnetic. Within this group some of the grades, such as AISI Types 410 and 420, are termed martensitic because they are capable of being heat treated similar to plain carbon or low alloy steels to obtain high strength and hardness. The other straight chromium grades, such as AISI Types 430 and 446, are termed ferritic and are not heat treatable. The martensitic types generally contain less chromium than the ferritic types, but there is some overlap depending on the amount of other elements, especially carbon. The martensitic types can be extended to higher chromium content by increasing the carbon content. Type 440A is an example. The second group is the AISI 300 series or chromium-nickel grades. These steels are austenitic by virtue of the high nickel content. Relatively small amounts of ferrite may be present depending upon the balance of the chromium and nickel contents and other elements such as carbon, molybdenum, etc. The crystal structure of austenite is face-centered cubic. The austenitic steels are nonmagnetic. These steels are not heat treatable but can be cold worked to high strength and hardness levels. The chromium and nickel contents vary somewhat according to specific requirements, but the most common grades, such as AISI Types 301 and 304, contain about 18 percent chromium and 8 percent nickel.

The greater oxidation and corrosion resistance of stainless steels compared to low alloyed steels is due to the presence of chromium. Generally, steels with less than about 11 percent chromium are not considered as stainless steels. The oxidation resistance increases with chromium content, although not linearly. However, as the chromium content increases, the maximum operating temperature for continuous service increases from about 1300°F for the 12 percent chromium steels to 2000°F for 25 percent chromium steels. Similarly, the corrosion resistance to a large number of environments increases with increasing chromium content. The excellent corrosion resistance of the stainless steels is generally attributed to a spontaneously formed thin film on the surface which makes the steels passive. However, stainless steels are more passive under oxidizing service conditions and may be attacked quite rapidly under reducing conditions. The presence of nickel in the austenitic grades increases the resistance of these steels to many kinds of corrosive environments.

Thus, while the oxidation and corrosion resistance of the stainless steels is primarily due to the chromium content, nickel increases the corrosion resistance in certain environments and the addition of molybdenum may further enhance corrosion resistance for special purposes in the more aggressive media. Furthermore, the austenitic chromium-nickel steels have higher strength than the straight chromium steels at elevated temperatures and are somewhat more formable and weldable. Therefore, the austenitic grades have been used for aircraft exhaust systems. However, under conditions which may be present in exhaust systems the austenitic stainless steels may undergo rapid deterioration. This can be further accelerated by design and fabrication and by microstructural changes which occur during exposure of these steels to temperatures at which some parts of an aircraft exhaust system operate.

The austenitic stainless steels are subject to carburization under certain conditions. The carbon combines with the chromium, forming carbides so that the chromium content of the matrix is decreased. The decrease in effective chromium content decreases the oxidation resistance. The oxidation resistance, or high temperature corrosion resistance, is generally considered to be decreased in the presence of lead compounds.

The austenitic stainless steels undergo precipitation of chromium carbides in the grain boundaries upon heating in the temperature range of about 900 to 1500°F. Because of the depletion of chromium near the grain boundaries, the steels are then subject to intergranular attack upon exposure to corrosive environments. In exhaust systems the corrosive substances can be condensates. Susceptibility to intergranular corrosion can be minimized or eliminated by addition of elements such as titanium or columbium which combine with the carbon more readily than chromium. These stabilized grades are AISI Type 321 (titanium addition) and AISI Type 347 (columbium addition). However, under certain conditions as a result of extreme heating or welding followed by exposure at sensitizing temperatures, chromium carbides may form in preference to titanium or columbium carbides and the steels may be susceptible to intergranular attack. A well-known example is knife-line attack near welds.

Austenitic stainless steels are also susceptible to stress corrosion cracking, especially in the presence of liquids containing halide ions. Characteristic of the cracks is that they are transgranular and have many branches. The latter helps to distinguish stress-corrosion cracks from fatigue cracks which are also transgranular.

A number of references is given in Appendix I for those readers interested in more information on the general characteristics of stainless steels. Many of these articles contain references on more specific subjects.

PROCEDURE

A total of twelve samples were received for evaluation. These were identified and described as given in Table I. The samples represented sections from exhaust systems of a number of different designs. Baseline samples had no apparent connection with the samples from systems which had been in service. The relationship of the section received to the entire exhaust system was generally not known at the time the investigation was begun.

Each sample was first visually inspected for condition, location of failure, and any other characteristic which might help in the determination of the cause of failure. Each sample was subjected to simple tests such as a dye penetrant test of the welds of the baseline samples and response to a hand magnet. The samples were then photographed in one or more positions to show the primary characteristics and for future reference.

Each sample was then marked for removal of metallographic specimens and chemical analysis samples. Since no information on the baseline samples other than that given in Table I was available, metallographic specimens were removed for a general examination of the base metal and weld structures in both the longitudinal and transverse directions. For the other samples the metallographic specimens were removed at the

TABLE I

IDENTIFICATION OF SAMPLES FROM AIRCRAFT EXHAUST SYSTEMS

1. Ball Joint Welded at Seam Material AISI 321 - New Baseline Sample. Hanlon and Wilson.

2. Exhaust Pipes, Welded at Seams - Material AISI 321 Steel - New - Baseline Samples. Cessna.

3. Exhaust Pipes (2) - Welded at Seams - Material AISI 347 Steel - New - Baseline Samples. Piper.

5. Cessna 180 Muffler - Bulged with Cracks and Holes - Material AISI 321 Steel. Hanlon and Wilson.

6. Cessna 172 Muffler - Internal Baffle Failure - Material AISI 321 Steel. Hanlon and Wilson.

7. Cessna 150 Muffler - Cracked Rear Stack Inlet - Material AISI 321 Steel.

8. Cessna 150 Muffler - Cracked Stack Inlet - Material AISI 321 Steel.

9. Cessna 150 Muffler - Cracked Between Stack Inlet and End - Material AISI 321 Steel.

10. Cessna 150 Muffler - Cracked Stack Inlet and Tailpipe Support - Material AISI 321 Steel.

11. PA-24-250 Muffler - Internal Baffle Failure - Material May be AISI 347 Steel.

12. PA-22 Muffler - Internal Baffle Failure - Material May be AISI 347 Steel.

14. PA-22-108 Muffler - Crack at Tailpipe Outlet. Material May be AISI 347 Steel.

location of the failure(s) and in some instances away from the failure for comparison of microstructure. Some samples required removal of a number of metallographic specimens because of cracks in more than one location or more than one component of the section. Samples for chemical analysis were taken as near to the location of failure as possible. Since the samples were not flat, the analyses were all determined by wet methods. In order to conserve material analyses were obtained only for carbon, chromium, nickel and titanium or columbium. The samples from the systems which had been in operation were sandblasted and pickled to remove the scale in addition to the usual cleaning methods in preparation for chemical analysis.

The corrosion or oxidation product was scraped from some samples which were particularly attacked for identification of the constituents by means of X-ray analysis.

RESULTS

Chemical analyses of the various samples are given in Table II. All but one of the samples was Type 321.

Since the samples were so different and the results of the metallographic examination varied considerably from sample to sample, the results on each will be presented separately.

Sample No. 1

Sample No. 1 was a ball joint containing a weld as shown in Figure 1. A dye penetrant test of the weld area showed no cracks. Specimens for metallographic examination were taken in both directions from both the base metal and the weld. The microstructures of the base metal and the weld were normal as shown in Figure 2. The base metal contained a few randomly distributed carbides and no grain boundary carbides. The surfaces were somewhat rough, apparently due to anneal and pickle conditions which resulted in some intergranular penetration. The weld metal contained some delta ferrite. There was grain growth in the weld heat-affected zone, but no evidence of continuous carbide precipitation in the grain boundaries in this area.

Sample No. 2

Sample No. 2 consisted of two baseline samples containing welds as shown in Figure 3. The smaller part had apparently been cold worked after welding. The larger part had welds of a very poor appearance but it is not known whether the welds would be left in that condition. Neither showed any evidence of weld cracks upon dye penetrant testing. Specimens

TABLE II

CHEMICAL ANALYSIS OF SAMPLES

SAMPLE NO.	C	CR	NI	TI	CB	TA	REMARKS
1	.045	17.78	10.46	.27	-	-	
2-1	.081	18.79	10.39	.57	-	-	Small tube
2-2	.064	17.65	10.70	.45	-	-	Large tube
3-1	.058	18.65	11.40	-	.82	.045	Sample stamped 347
3-2	.061	17.46	9.48	.41	-	-	Sample with crimp joint
5	.11	17.46	9.29	.53	-	-	Sample from shell away from bulges
6	.39	17.37	9.63	.41	-	-	Sample from internal baffle
7	.062	17.92	10.38	.61	-	-	Sample from shell portion
7	.084	17.42	9.83	.41	-	-	Sample from tube inside shell
8	.060	18.05	10.52	.51	-	-	Sample from shell portion
9	.030	17.83	10.85	.47	-	-	Sample from shell portion
10	.061	17.88	10.68	.60	-	-	Sample from shell portion
11	.45	17.97	10.08	.60	-	-	
12	.57	17.97	10.17	.44	-	-	
14	.059	17.78	9.96	.46	-	-	Sample from outside section

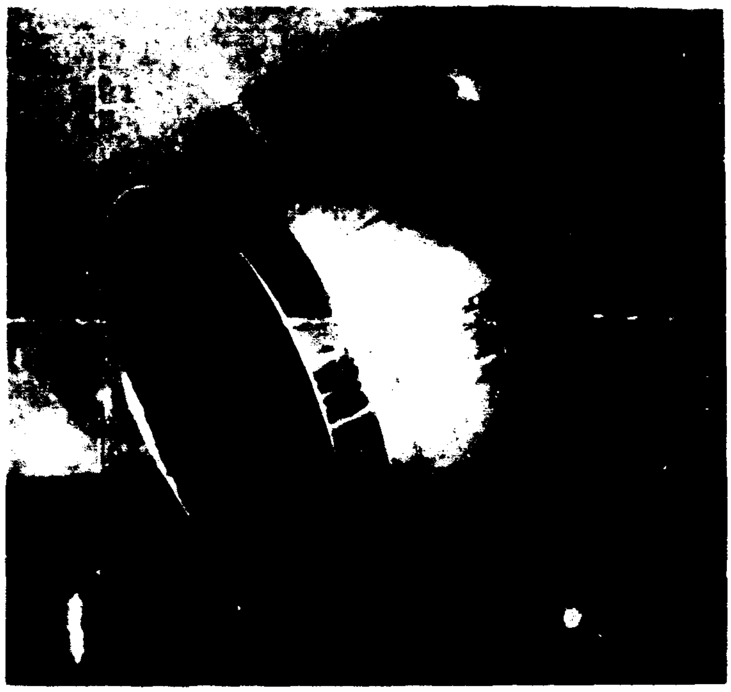

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FIG. 1 SAMPLE NO. 1 - TYPE 321 BASELINE SAMPLE. BALL JOINT WELDED AT SEAM.

A.

BASE METAL AT BOTTOM, HAVING TITANIUM CARBONITRIDES. WELD METAL AT TOP.

AS POLISHED 100X

B.

BASE METAL AT BOTTOM AND WELD METAL AT TOP, SHOWING SOME GRAIN GROWTH IN HEAT-AFFECTED ZONE.

10% OXALIC ACID 100X

FIG. 2 SAMPLE NO. 1, SHOWING NORMAL STRUCTURE

APPROX. 1

FIG. 3 SAMPLE NO. 2 - TWO TYPE 321 BASELINE SAMPLES. EXHAUST PIPES WELDED AT SEAMS.

for metallographic examination were obtained in both directions from both pieces from the weld and from the base metal. The structure at the weld-metal interface of the smaller part is shown in Figure 4 and that of the larger part in the area of the flatter weld in Figure 5. These samples showed the same structural characteristics as Sample No. 1. However, the larger sample in the area of the flatter weld showed a wider area of grain coarsening in the heat-affected zone.

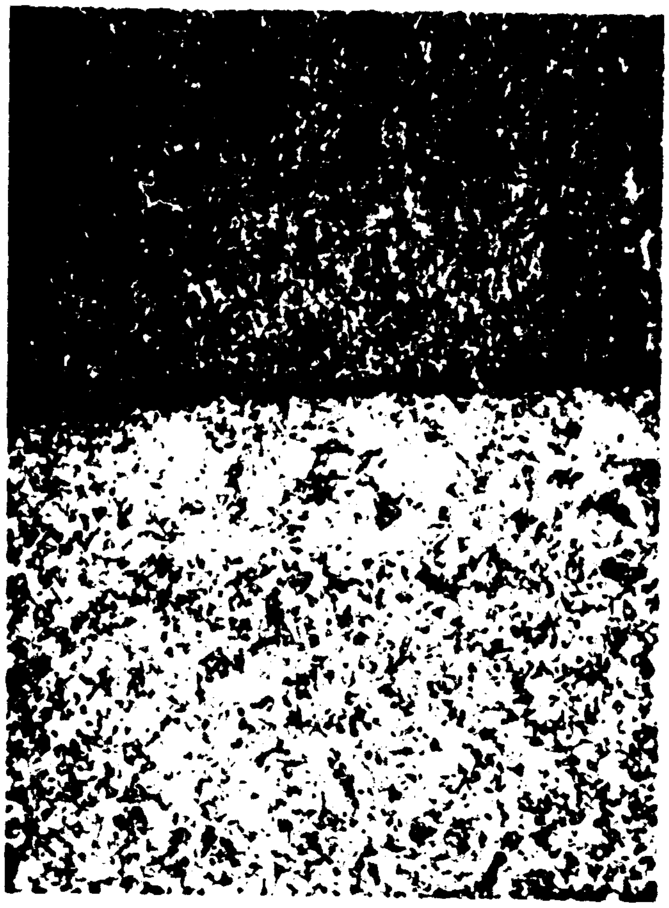
Sample No. 3

Sample No. 3 consisted of two baseline exhaust pipes. While these were supposed to contain welds, no evidence of welds was found. As shown in Figure 6, one part was stamped 347, and chemical analysis showed that this part was Type 347. The other part, containing the crimp, was Type 321. Specimens for metallographic examination were taken in both directions from both parts. The microstructures are shown in Figures 7 and 8. The Type 347 part showed a random distribution of carbides and a few, thin delta ferrite stringers. The Type 321 part showed a random distribution of a few carbides.

Sample No. 5

Sample No. 5 was a section cut from a muffler in which some areas of the shell had bulged and cracked as shown in Figure 9. Some of the studs on the inside (not shown in the photograph) were practically oxidized away. The location of these few studs did not have any particular relationship to the areas of the shell which had bulged and cracked. Going over this part with a hand magnet, it was found that the shell had a slight response, but one stud on the outside and the heavily oxidized studs on the inside of the shell were strongly magnetic.

The strongly magnetic stud on the outside of the shell was cut off and found by chemical analysis to contain 0.53% carbon, 0.98% chromium and 0.078% nickel. The stud was obviously a low alloy ferritic steel. Another stud, nonmagnetic on the outside of the shell and almost completely oxidized on the inside, was cut out for metallographic examination. The structure of the outside stud is shown in Figure 10. The stud was apparently Type 347 as indicated by the presence of columbium carbonitrides. The stud had a large amount of sigma phase in stringers. These stringers were no doubt delta ferrite after processing which transformed to sigma phase during service. A portion of the inside stud still remained beneath the heavy scale. Grain boundaries were revealed by a nital etch. The heavily oxidized studs on the inside of the shell are presumed to be plain carbon or low alloy ferritic steels, similar to one on the outside of the shell which was analyzed chemically.



10% OXALIC ACID 100X

FIG. 4

STRUCTURE OF SMALLER EXHAUST PIPE OF SAMPLE NO. 2, SHOWING WELD, HEAT-AFFECTED ZONE, AND BASE METAL.

10% OXALIC ACID 100X

FIG. 5

STRUCTURE OF LARGER EXHAUST PIPE OF SAMPLE NO. 2 IN AREA OF FLATTER WELD, SHOWING WELD, HEAT-AFFECTED ZONE, AND BASE METAL.

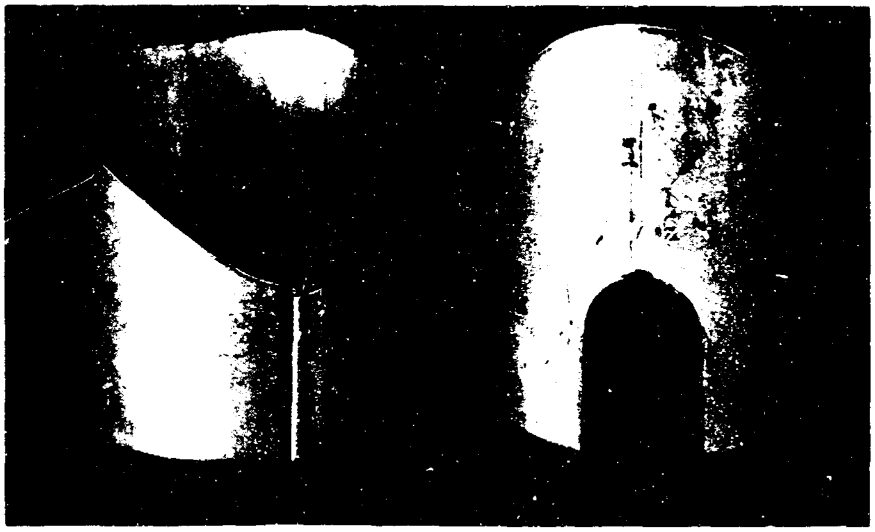


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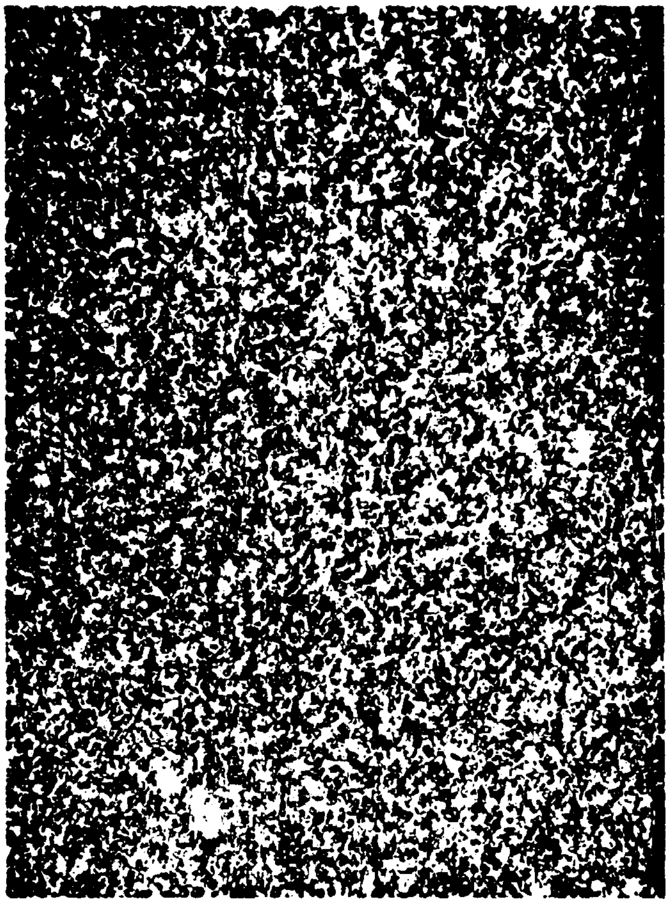
FIG. 6 SAMPLE NO. 3 - BASELINE SAMPLES, THE ONE ON THE LEFT BEING TYPE 321 AND THE RIGHT, TYPE 347.



10% OXALIC ACID 100X

FIG. 7

STRUCTURE OF TYPE 347
BASELINE EXHAUST PIPE,
SAMPLE NO. 3.

10% OXALIC ACID 100X

FIG. 8

STRUCTURE OF TYPE 321
BASELINE EXHAUST PIPE,
SAMPLE NO. 3.

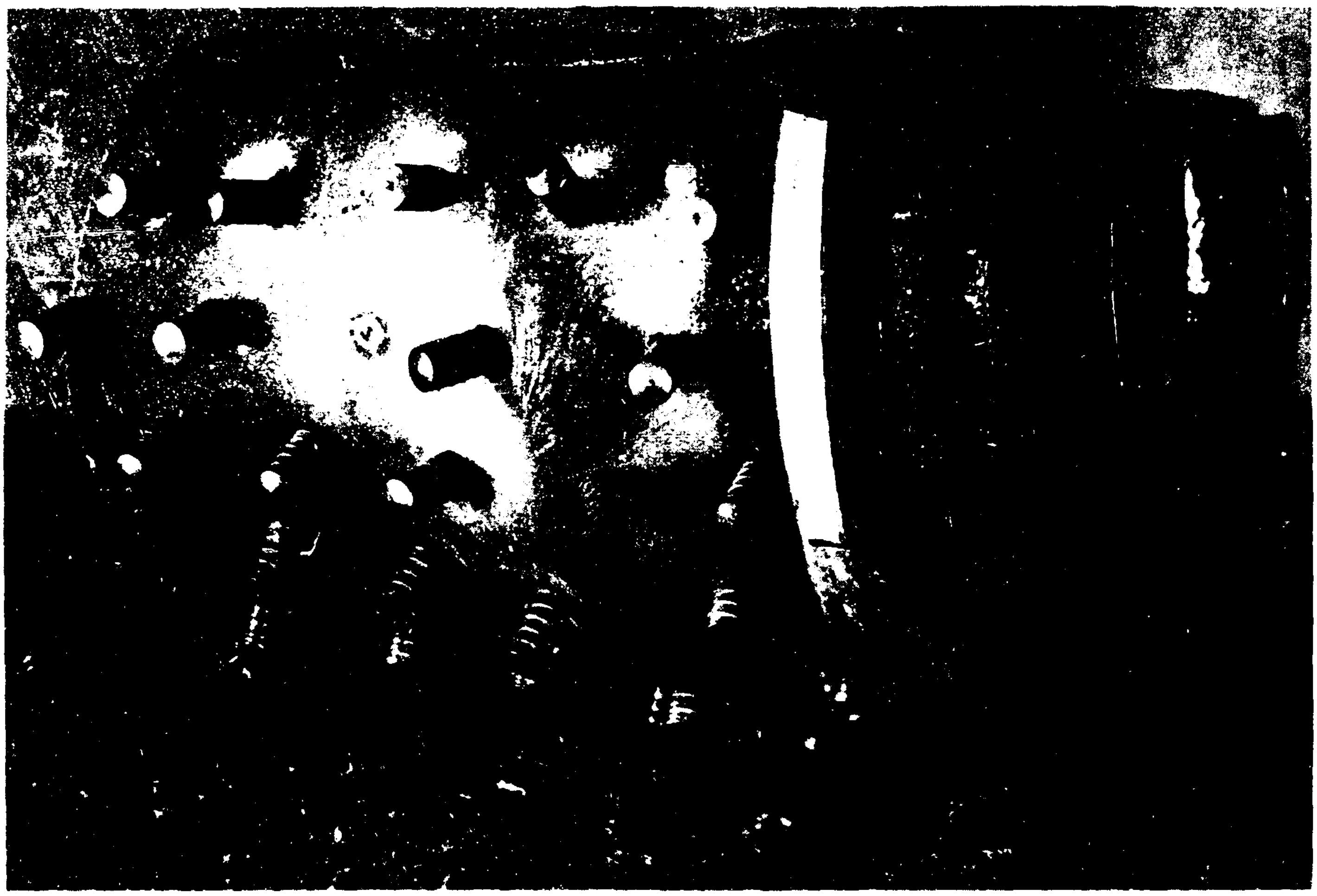


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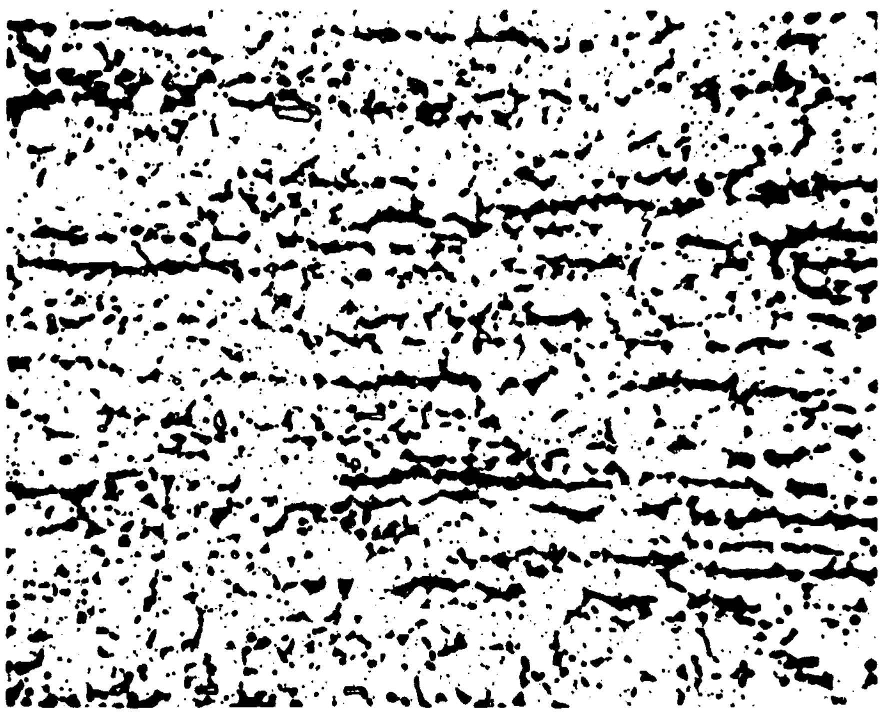
FIG. 9 SAMPLE NO. 5 - SECTION OF MUFFLER SHOWING BULGES AND CRACKS IN SOME AREAS OF SHELL.



10% OXALIC ACID 500X

FIG. 10 STRUCTURE OF STUD FROM TOP OF SHELL, SHOWING STRINGERS OF SIGMA WHICH APPARENTLY TRANSFORMED DURING SERVICE FROM DELTA FERRITE.

Specimens for metallographic examination of the shell were taken from a bulged area, as can be seen in the photograph, and from an area closer to the saw cut where bulging had not occurred. The piece for chemical analysis was also removed from the area which did not bulge. Table II shows that the shell material was Type 321, although the carbon content was somewhat high.

Photomicrographs in the unetched condition in the two areas are shown in Figure 11. The material in the bulged area was more heavily oxidized. In some areas the thickness of the metal remaining in the bulged area was even less than that shown in Figure 11A. Cracks were heavily oxidized so that no information could be obtained with respect to the type of cracking. The structure of the material at the scale-metal interface of the bulged area is shown at higher magnification in Figure 12.

The microstructures at the two locations after etching are shown in Figures 13 to 15. At both locations the structure contained sigma phase, distributed discontinuously in the grain boundaries. In addition, the grain boundaries appear broad. This appears to be due to an etching effect which suggests that the composition of the boundaries is different from that within the grains. Besides the presence of sigma phase, the inside surface of the shell at the bulged area shows carburization to have occurred.

Some corrosion or oxidation product was scraped from the inside of the shell. X-ray analysis showed the presence of α Fe_2O_3, $FeO \cdot Cr_2O_3$ spinel, and Pb (Fe, Mn, Al, $Ti)_{12}$ O_{19}.

A sample was taken from the shell in an area where no bulging occurred for X-ray determination of phases present in the metal. After sandblasting and pickling, the material was slightly magnetic. An X-ray analysis on the outer surface showed SiO_2 α quartz, α Fe and sigma phase. The piece was chemically thinned to .008" thick from its original .028" thickness. Another X-ray analysis showed only the presence of sigma. The piece did not respond to a hand magnet. The SiO_2 α quartz was no doubt sand from the blasting operation which became imbedded in the surface and was not removed by the pickling. The α Fe was a surface condition only which may also have been a result of the sandblasting working the surface. The response of the piece to a magnet after sandblasting and pickling but lack of response after chemical thinning could have been due to surface penetration of the Pb (Fe, Mn, Al, $Ti)_{12}$ O_{19} phase which was not removed during sandblasting and pickling.

Sample No. 6

Sample No. 6 was a section of a muffler in which the internal baffle had failed as shown in Figure 16. Specimens for metallographic examination and

A.

BULGED AREA

AS POLISHED 100X

B.

AWAY FROM BULGED AREA

AS POLISHED 100X

FIG. 11 SAMPLE NO. 5 SHELL CROSS-SECTION, SHOWING EXTENT OF OXIDATION

A.

INSIDE SURFACE

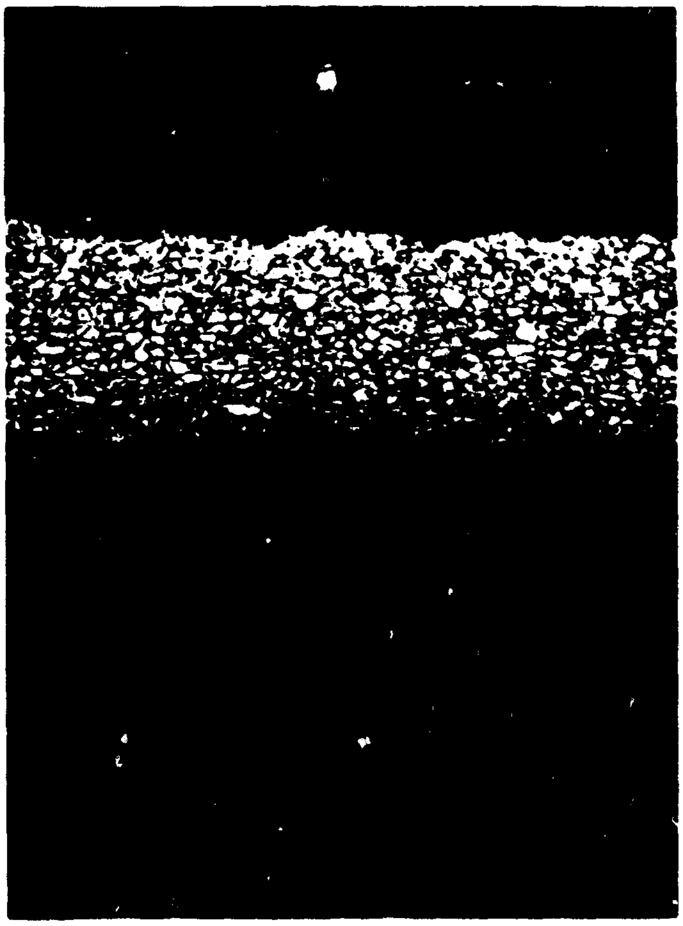
AS POLISHED 500X

B.

OUTSIDE SURFACE

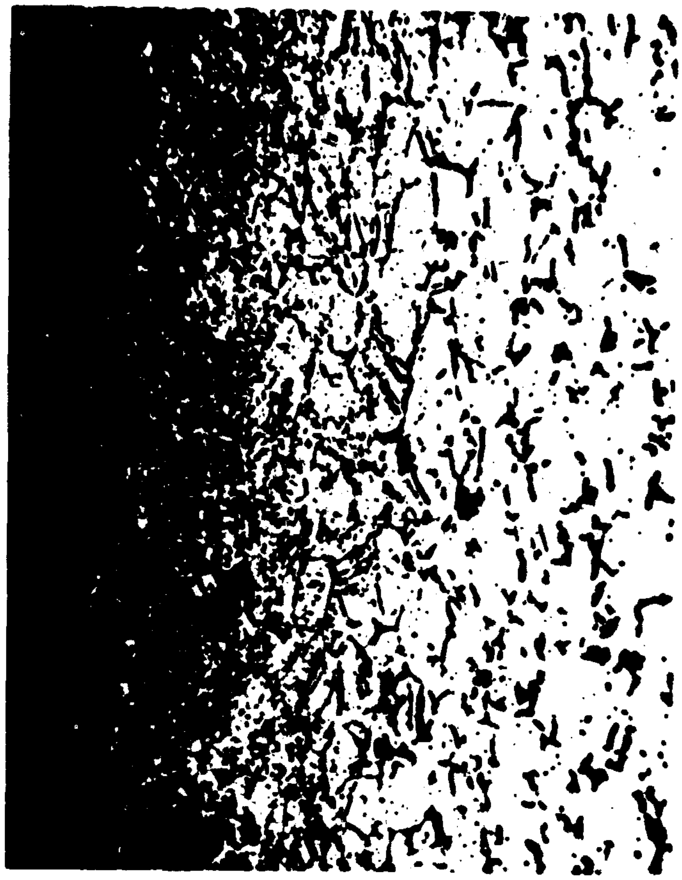
AS POLISHED 500X

FIG. 12 SAMPLE NO. 5 SHELL AT BULGED AREA SHOWING OXIDATION



10% OXALIC ACID 100X

FIG. 13 STRUCTURE OF SAMPLE NO. 5 SHELL IN BULGED AREA



A.

INSIDE SURFACE SHOWING CARBIDES AND SIGMA PHASE

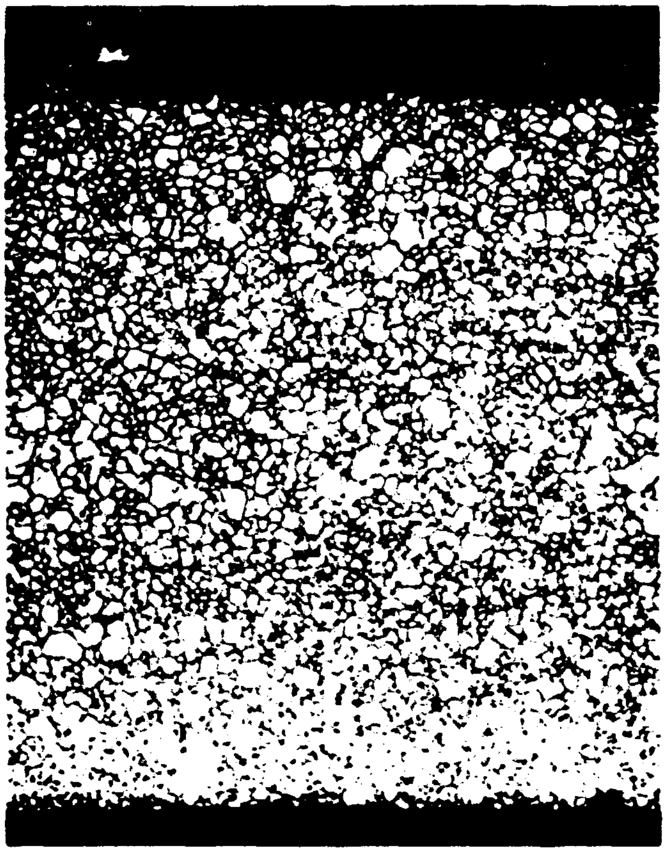
10% OXALIC ACID 500X

B.

OUTSIDE SURFACE SHOWING SIGMA PHASE

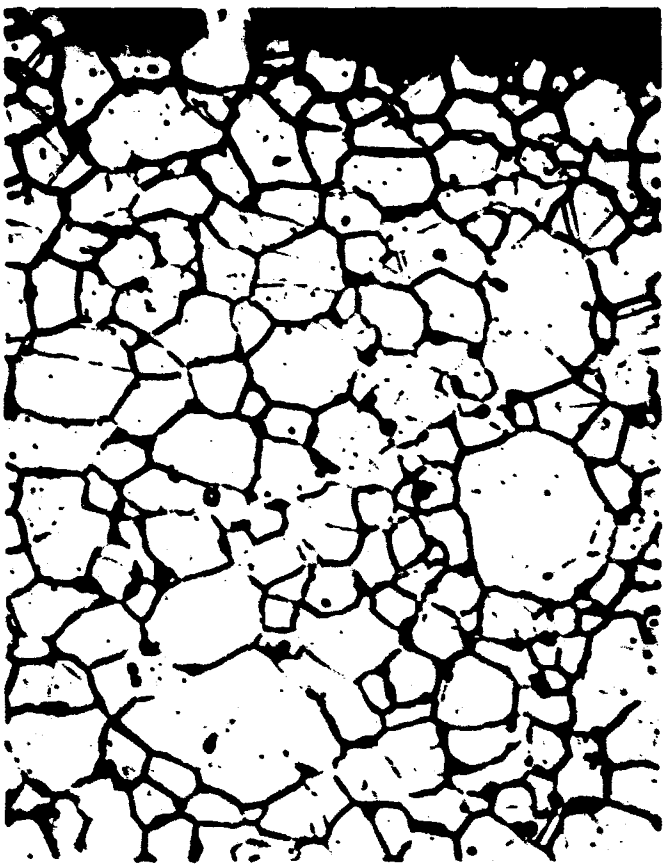
10% OXALIC ACID 500X

FIG. 14 STRUCTURE OF SAMPLE NO. 5 SHELL



A.

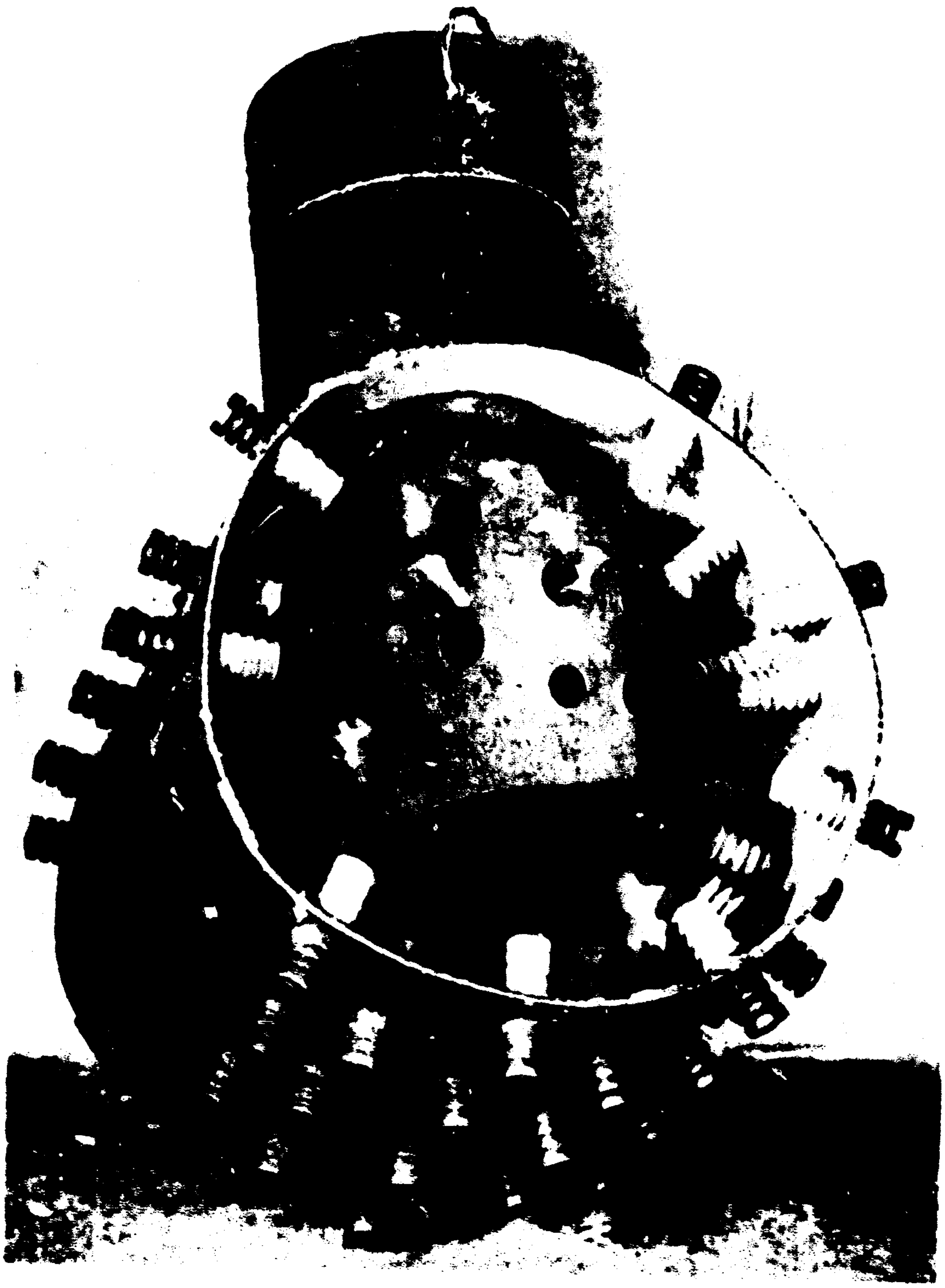
10% OXALIC ACID 100X



B.

10% OXALIC ACID 500X

FIG. 15 STRUCTURE OF SAMPLE NO. 5 SHELL AWAY FROM BULGED AREA, SHOWING SIGMA PHASE IN GRAIN BOUNDARIES



APPROX. 1X

FIG. 16 SAMPLE NO. 6 - SECTION OF MUFFLER SHOWING FAILURE OF INTERNAL BAFFLE chemical analysis were taken from the baffle only. As shown in Table II the material was Type 321 except that the carbon content was very high. This sample for chemical analysis varied in thickness after cleaning from a few mils to about 0.030 inches.

Figure 17 shows that the material was heavily oxidized. Etching revealed a microstructure through the entire cross-section of many carbides and grain boundary sigma similar to the structure shown in Figure 14A at the surface.

Corrosion product was scraped from the baffle. An X-ray analysis showed $FeO \cdot Cr_2O_3$ spinel and $Pb(Fe, Mn, Al, Ti)_{12}O_{19}$.

Sample No. 7

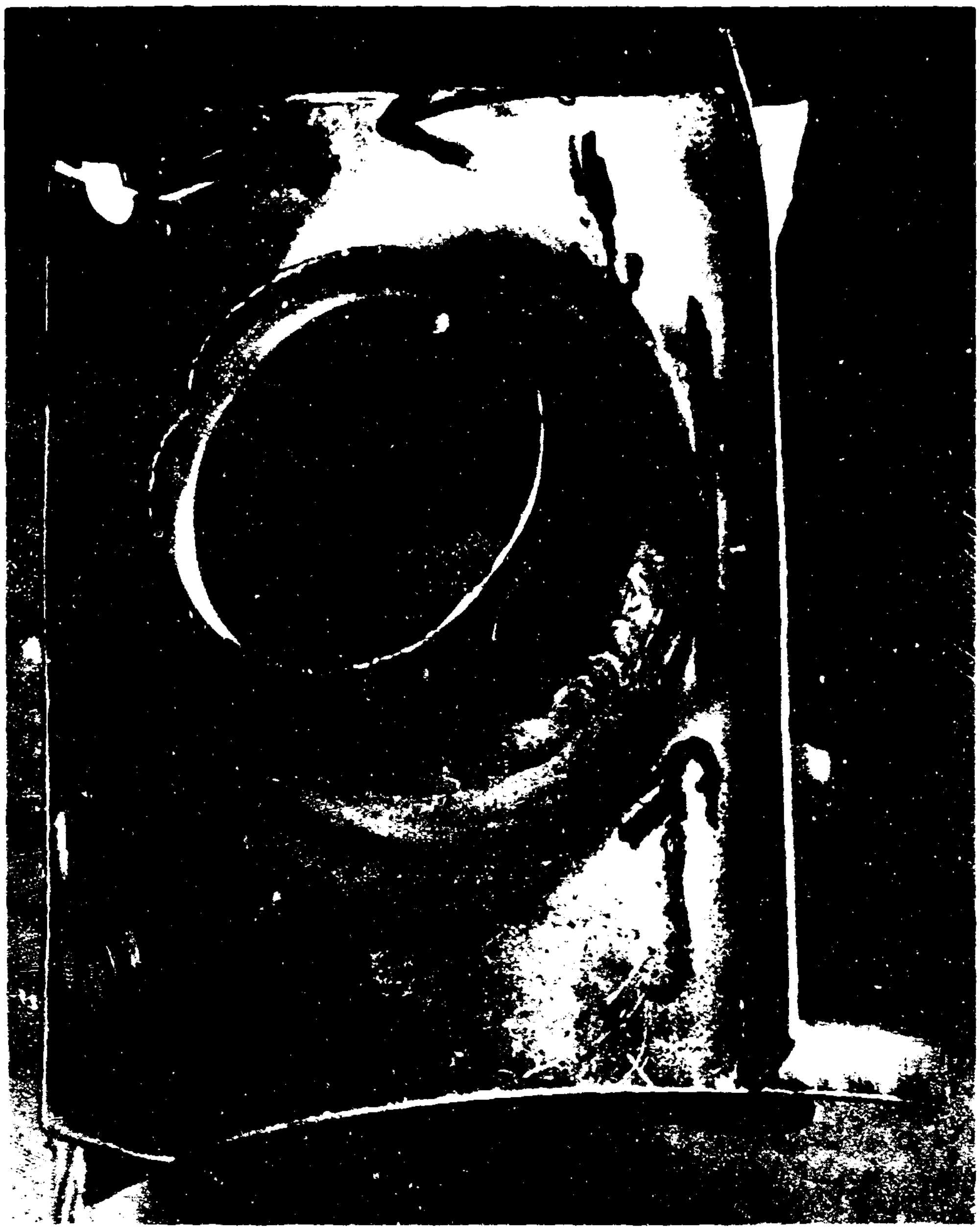
Sample No. 7 was a section of a muffler described as having a cracked rear stack inlet. As Figures 18 and 19 show, there was a crack at one of the holes of the support piece in addition to the crack at the weld which extended into the shell. Material for chemical analysis was taken from both the shell and the portion of the stack or tube inside the shell. The analyses showed both to be Type 321.

One specimen for metallographic examination was taken at the end of the crack through the hole of the support. Figure 20 indicates the crack to be the result of fatigue. The presence of titanium carbonitrides indicates that this support section was Type 321 also. The microstructure was essentially free of finer carbides.

Another specimen was cut through the crack at the weld. The pieces fell apart so that the specimen examined metallographically essentially consisted of a piece of the tubing and the fusion weld. Figure 21 shows where the shell had been joined by welding to the tubing. It is believed that the straight edge is part of the crack through the heat-affected zone. Note that the amount of delta ferrite along this edge of crack surface is somewhat less than that in the weld, thus suggesting that this is the heat-affected zone. The straightness and the transgranular course of the crack in addition to little evidence of deformation indicate failure by fatigue. While not shown by a photomicrograph, the tube had a normal microstructure where it was not exposed to the hot gases. The portion of the tube within the shell showed a continuous grain boundary precipitate, starting somewhat beyond the heat-affected zone. Within the heat-affected zone, the grain size was large due to the fusion welding, but there was no grain boundary precipitate. The difference here is believed to be due to the temperatures attained during operation rather than to effects of the fusion welding. The crack between the weld and the support also appeared to be caused by fatigue as it was relatively straight and transgranular. The crack was for the most part in the heat-affected zone.

AS POLISHED 100X

FIG. 17 SAMPLE NO. 6 - INTERNAL BAFFLE, SHOWING HEAVY OXIDATION



APPROX. 1X

FIG. 18 SAMPLE NO. 7 - SECTION OF MUFFLER SHOWING CRACK THROUGH MOUNTING HOLE AND AT FUSION WELD BETWEEN TUBE AND SUPPORT PIECE

APPROX. 1X

FIG. 19 SAMPLE NO. 7 - ANOTHER VIEW OF THIS SAMPLE SHOWING CRACKING OF SHELL AT FUSION WELD. THE CRACK IN THE SHELL ABOVE THE TUBE IS PART OF THE SAME CRACK AT THE WELD.

10% OXALIC ACID 100X

FIG. 20

SAMPLE NO. 7 - SHOWING END OF CRACK THROUGH HOLE IN SUPPORT PIECE

10% OXALIC ACID 250X

FIG. 21

SAMPLE NO. 7 - SHOWING FUSION WELD WHERE SHELL WAS JOINED TO THE TUBE. A SMALL PORTION OF THE TUBE IS ON THE LEFT

Another specimen was taken at the end of the crack in the shell which can be seen in Figure 19 just above the tube. The crack is shown in Figure 22. It also appears to be a fatigue crack. The microstructure shows a continuous grain boundary precipitate similar to that observed in the portion of the tube which was inside the shell and exposed to the hot gases.

Sample No. 8

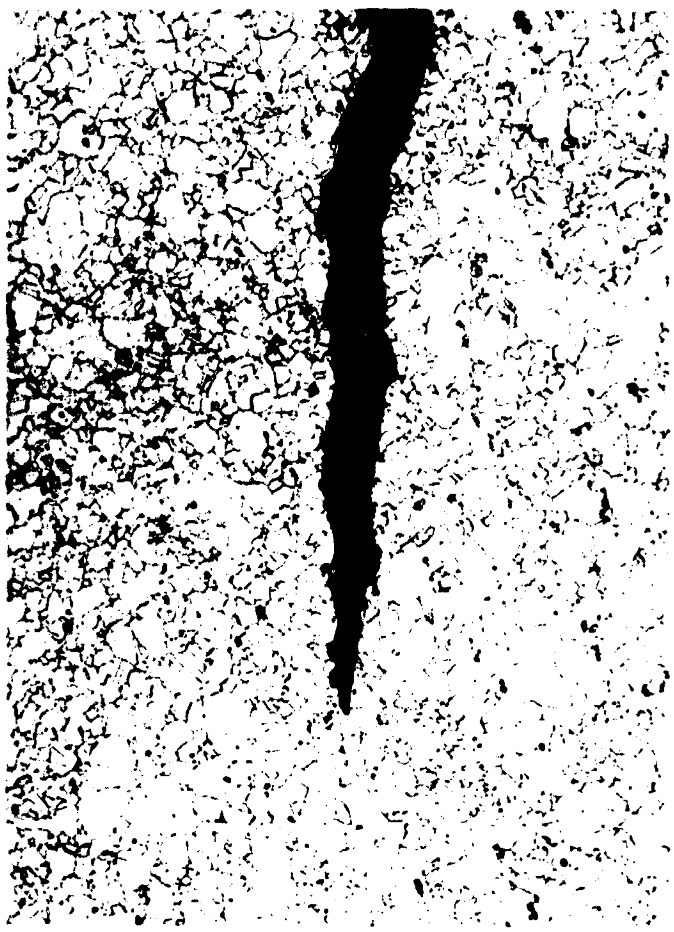
Sample No. 8 was a section of a muffler having a cracked stack inlet. As Figure 23 shows, this part also had a crack through one of the holes in the support piece. Figure 24 shows the crack at the weld of the shell portion. Viewing from the back and using the tube as a reference, the crack in the shell extended towards twelve o'clock and the other end towards four o'clock. The inside of the shell had a deposit of carbon which practically brushed off. The piece for chemical analysis was taken from the shell. The material was Type 321.

A specimen for metallographic examination was taken at the end of the crack extending in the shell at four o'clock from the tube. Figure 25 shows the end of the crack and another location of the crack where it seems to have been changing direction. The crack appears to be a fatigue failure. A specimen taken to show the cross-section of the shell confirmed that the microstructure of the shell of this muffler, unlike that of Sample No. 7, did not have a grain boundary precipitate, indicating that this muffler operated at a lower temperature or for a shorter time than that from which Sample No. 7 was taken.

Sample No. 9

Sample No. 9 was a section from another muffler similar in design to Sample Nos. 7 and 8. Figure 26 shows a crack in the shell portion. There was also a crack through one of the holes of the support piece. The piece for chemical analysis was taken from the shell portion. The material was Type 321.

A specimen for metallographic examination was taken at the end of the crack in the shell. An adjacent specimen was taken to view the cross-section. Figure 27 shows the end of the crack. While this crack had a few branches, it still appears to be a fatigue failure. As Figure 28 shows, the microstructure contained sigma phase and carbides. This material also had a few stringers of delta ferrite which had transformed to sigma phase. The indication is that this muffler operated at higher temperatures or for a longer time than Sample Nos. 7 or 8.



10% OXALIC ACID 100X

FIG. 22 SAMPLE NO. 7 - SHOWING END OF CRACK IN SHELL WHICH CAN BE SEEN IN FIGURE 19 JUST ABOVE THE TUBE.

APPROX. 1X

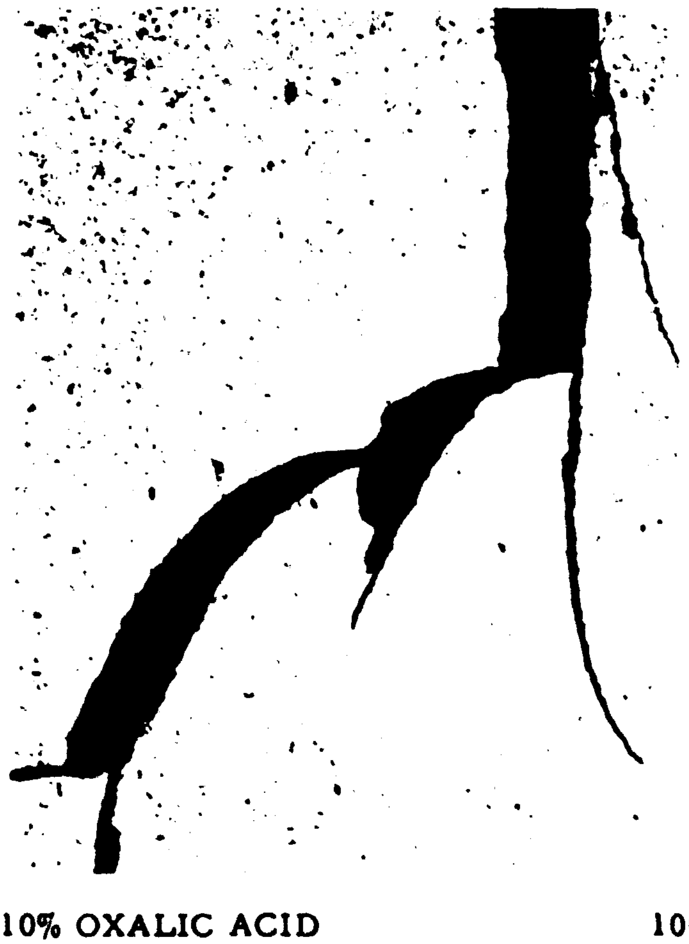
FIG. 23 SAMPLE NO. 8 - SECTION OF MUFFLER SHOWING CRACK THROUGH HOLE IN SUPPORT PIECE AND CRACK IN SHELL

APPROX. 1X

FIG. 24 SAMPLE NO. 8 - VIEW SHOWING CRACK IN SHELL AT FUSION WELD

A.

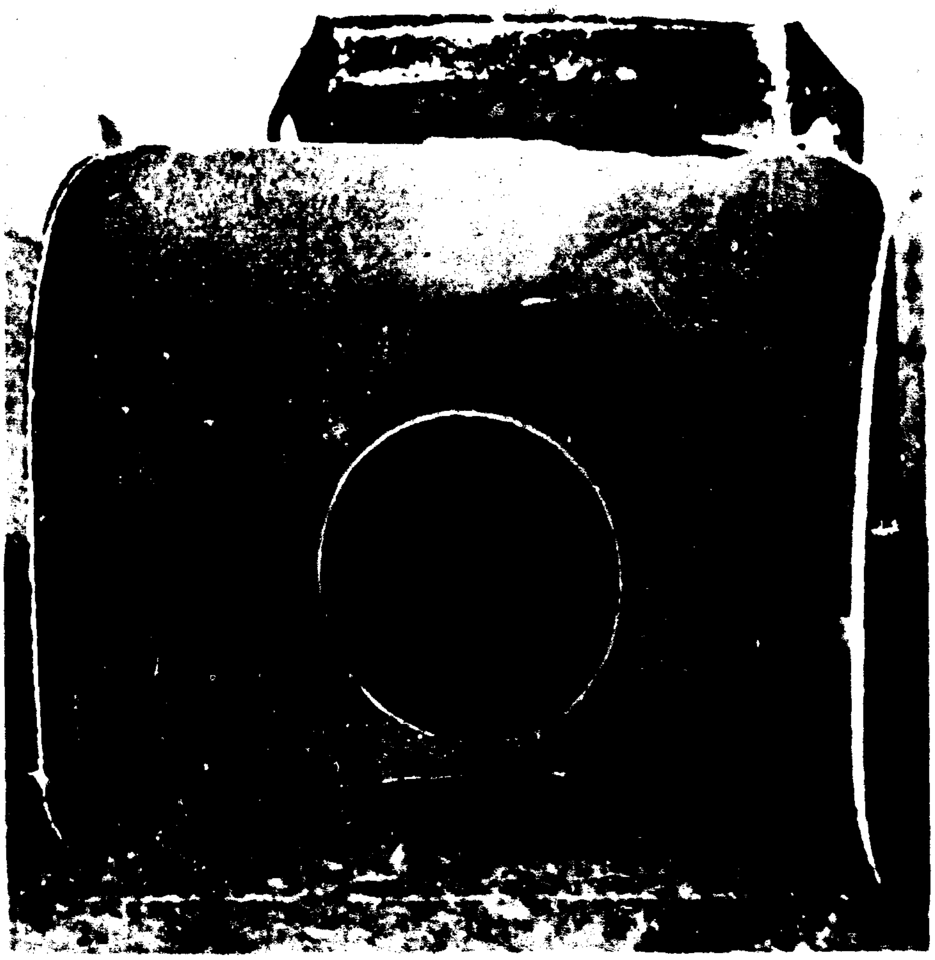
10% OXALIC ACID 100X



B.

10% OXALIC ACID 100X

FIG. 25 SAMPLE NO. 8 - SHOWING (A) END AND (B) ANOTHER LOCATION OF CRACK IN SHELL



APPROX. 1X

FIG. 26 SAMPLE NO. 9 - SECTION OF MUFFLER SHOWING CRACK IN SHELL PORTION

FIG. 27

SAMPLE NO. 9 - SHOWING END OF CRACK IN SHELL

10% OXALIC ACID 100X

FIG. 28

SAMPLE NO. 9 - SHOWING STRUCTURE OF SHELL

10% OXALIC ACID 250X

Sample No. 10

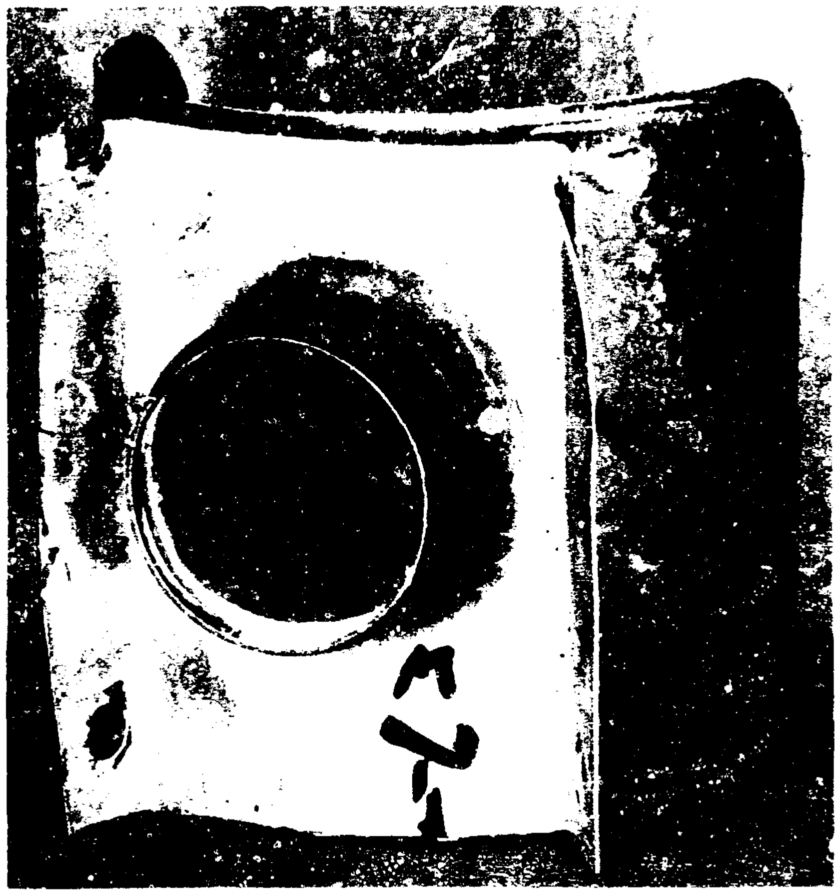
Sample No. 10 was a portion of another muffler similar in design to Sample Nos. 7, 8 and 9. As Figure 29 shows, this part had a crack through one of the holes of the support piece and a crack at the fusion weld in the support piece. The crack extended into the shell portion as shown in Figure 30. The piece for chemical analysis was taken from the shell. The material was Type 321.

Since a specimen for metallographic examination to view the end of the crack was difficult to obtain because of the curved surfaces, a specimen was taken through the weld perpendicular to the plane of the crack in the shell. This specimen included portions of the tube, the support piece, and the shell. After the sample was polished, the crack through the shell extended all the way through the cross-section in the plane being viewed. This is shown in Figure 31 by the relative displacement of the two pieces.

Examination of this specimen showed a myriad of microstructures. First of all, the microstructures of the weld, the tube where it was outside the shell, and the support piece appeared normal. Similar to Sample No. 7, the structure of the portion of the tube within the shell had a continuous grain boundary network of carbides starting beyond the heat-affected zone, apparently because of different temperatures attained during operation. In the shell portion at the crack the microstructure showed a continuous grain boundary precipitate near the surfaces, but not near midthickness. The microstructure in Figure 31B shows this characteristic at the outside surface of the shell. Note that the surface shows some attack and that another short crack had started. There was a similar crack to a shallower depth on the outside surface but on the other side of the main crack. These cracks are transgranular and appear to be fatigue cracks. The microstructure of the shell in the heat-affected zone showed the usual large grain size but the grain boundary precipitate did not appear until near the unaffected base metal.

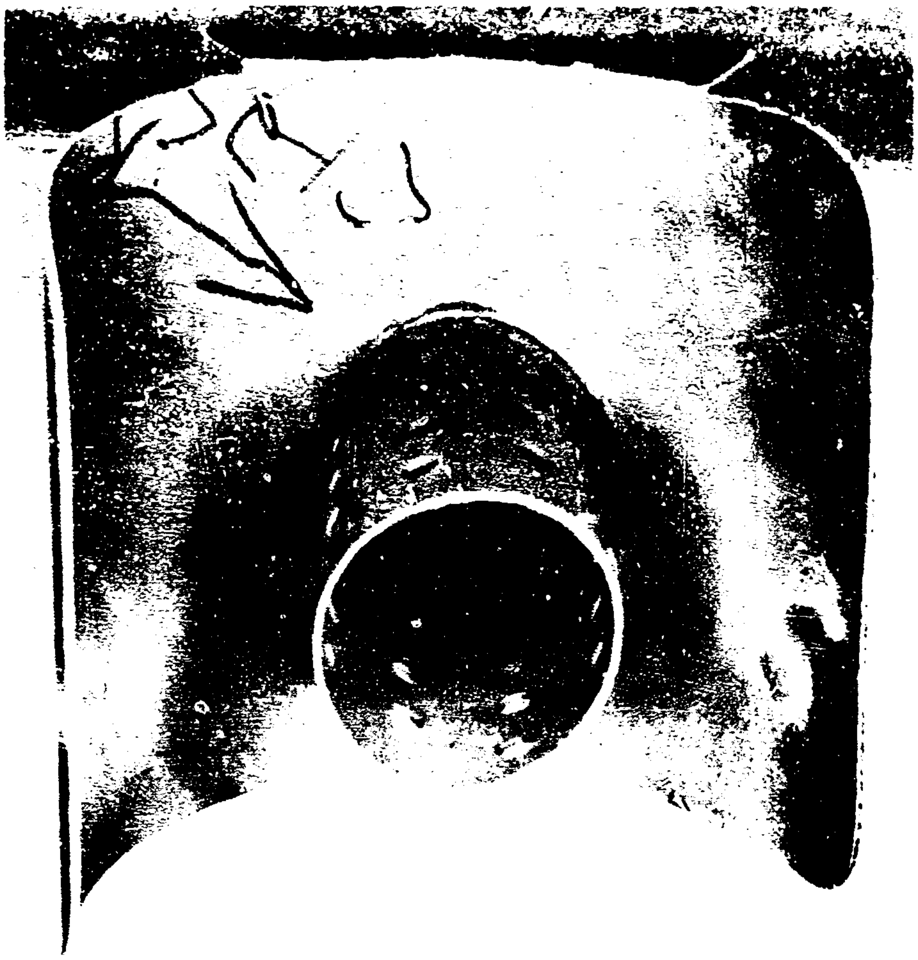
Sample No. 11

Sample No. 11 was an internal baffle failure. Figure 32 shows the baffle which was heavily oxidized and distorted and contained cracks especially at the holes. A piece for chemical analysis was obtained. The material was Type 321, but the carbon content was high as shown in Table II.



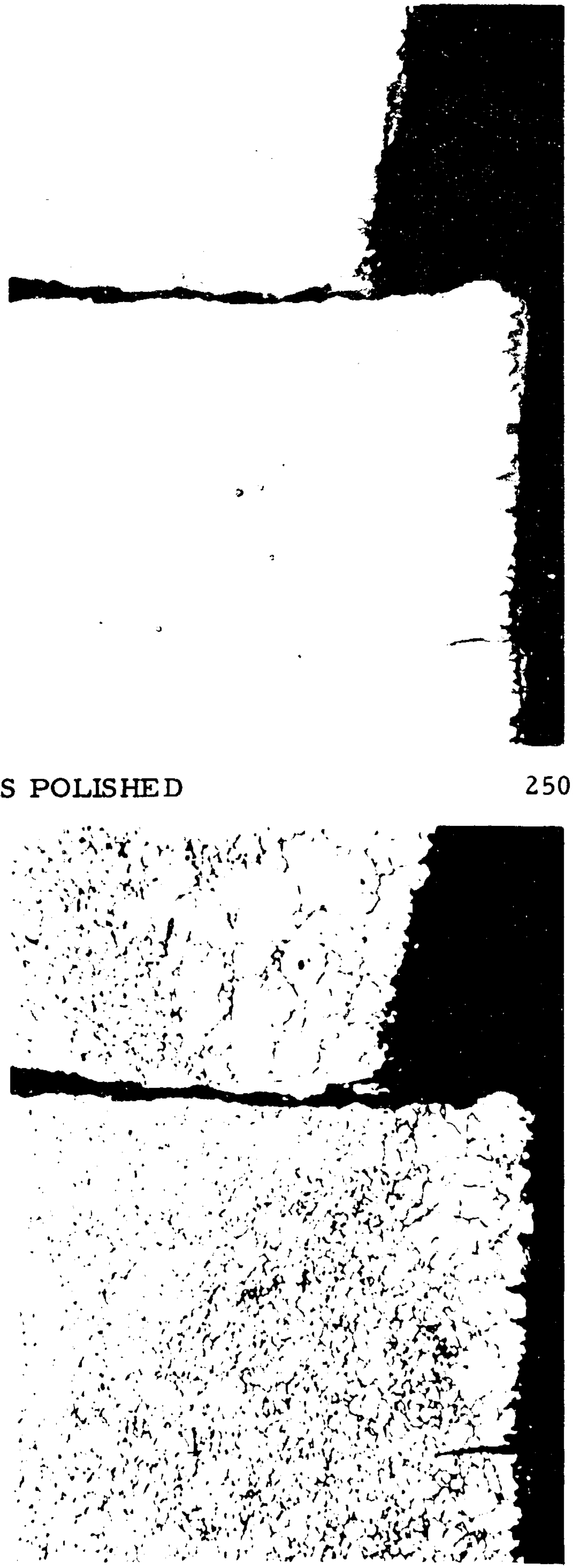
APPROX. 1X

FIG. 29 SAMPLE NO. 10 - SECTION OF MUFFLER SHOWING CRACK THROUGH HOLE OF SUPPORT PIECE (LOWER LEFT) AND CRACK AT FUSION WELD



APPROX. 1X

FIG. 30 SAMPLE NO. 10 - VIEW SHOWING CRACK IN SHELL



A.

AS POLISHED 250X

B.

10% OXALIC ACID 250X

FIG. 31 SAMPLE NO. 10 - SHOWING CRACK IN SHELL

APPROX. 1X

FIG. 32 SAMPLE NO. 11 - INTERNAL BAFFLE FAILURE

Specimens for metallographic examination were taken in areas of various amounts of distortion. Figure 33 shows heavy oxidation and a tendency towards intergranular oxidation at the metal-heavy scale interface. Thicknesses of the specimens varied considerably due to the amount of oxidation involved. Figure 34 shows the microstructure at one surface. The structure contains many carbides and sigma phase. The sigma phase was present throughout the cross-section of all specimens examined. The carbides were present at both surfaces of all specimens. Where material was thinned considerably many carbides were present throughout the cross-section.

Some oxidation product was scraped from the baffle. X-ray analysis showed Pb (Fe, Mn, Al, Ti)$_{12}$ O$_{19}$ and a possible trace of $FeO \cdot Cr_2O_3$ spinel.

Sample No. 12

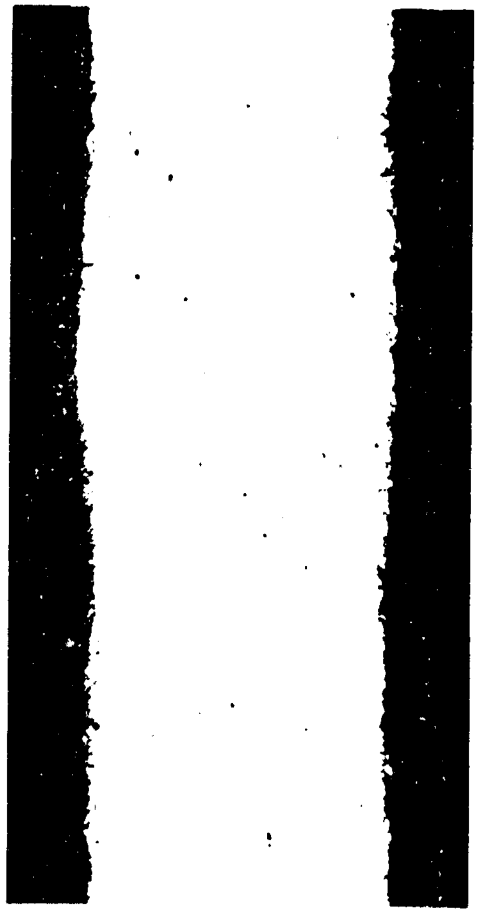
Sample No. 12 was also an internal baffle which had failed. Figure 35 shows, like Sample No. 11, that the baffle was distorted and contained cracks especially at the holes. Chemical analysis showed the material to be Type 321, but the carbon content was high.

Specimens for metallographic examination were taken at only one location. Figure 36 shows the heavy oxidation. In addition, the inside surface showed deeper penetration at various locations along the surface. Figures 37 and 38 show that the carburization was more prevalent on the outside surface. Figure 38 shows the presence of sigma phase in the grain boundaries. The sigma phase was present throughout the cross-section.

Some oxidation product was scraped from the baffle and X-ray analysis showed the presence of α Fe_2O_3, $FeO \cdot Cr_2O_3$ spinel, and Pb (Fe, Mn, Al, Ti)$_{12}$ O$_{19}$.

Sample No. 14

Sample No. 14 was a section of a muffler which had cracked at the tailpipe outlet as shown in Figure 39. This part had a collar around the stack opening spot-welded on the back. The lip of the collar can be seen inside the tube and a section of the collar can be seen where the crack is open. The collar was joined to the cracked part by two concentric rings of spot welds. The crack tended to circumvent the spot welds in the outer concentric ring. A piece for chemical analysis was cut from the part which cracked. The material was Type 321.



AS POLISHED 100X

FIG. 33

SAMPLE NO. 11 - SHOWING HEAVY OXIDATION OF BAFFLE

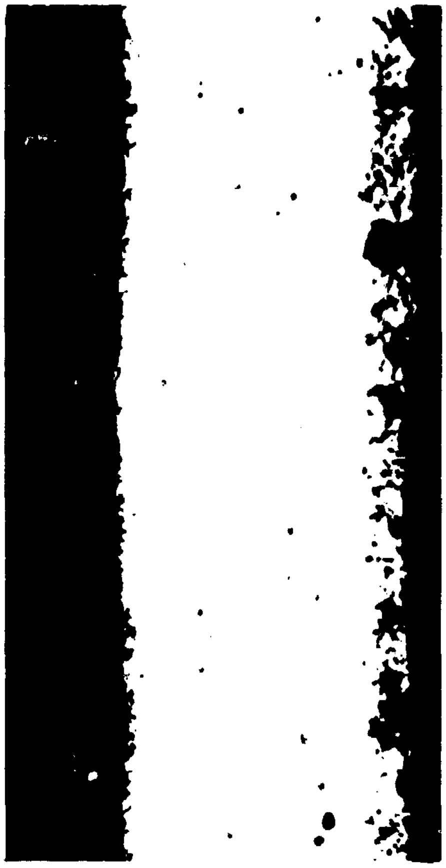
10% OXALIC ACID 500X

FIG. 34

SAMPLE NO. 11 - SHOWING CARBIDES AT INSIDE SURFACE OF BAFFLE (TOP) AND SIGMA PHASE IN GRAIN BOUNDARIES

APPROX. 1X

FIG. 35 SAMPLE NO. 12 - INTERNAL BAFFLE FAILURE



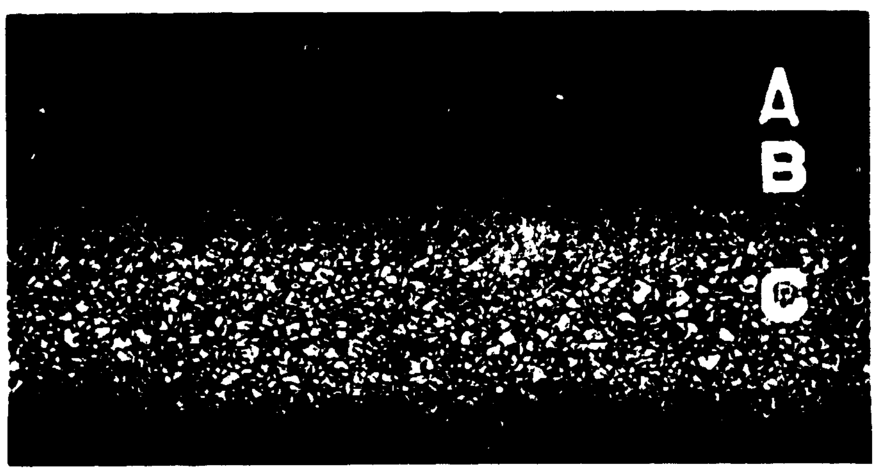
A.

AS POLISHED 100X

B.

AS POLISHED 500X

FIG. 36 SAMPLE NO. 12 - SHOWING (A) OXIDATION AT SURFACES AND (B) DEEPER PENETRATION AT VARIOUS LOCATIONS ON INSIDE SURFACE



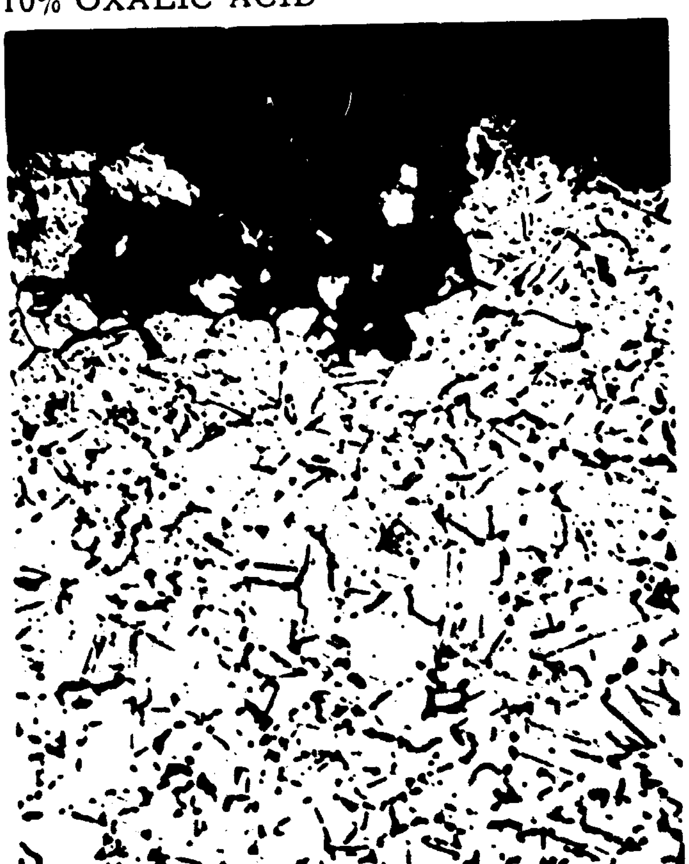
10% OXALIC ACID 100X

FIG. 37 SAMPLE NO. 12 - SHOWING HEAVIER CARBURIZATION ON OUTSIDE SURFACE OF BAFFLE

A - SCALE
B - HEAVY CARBURIZED LAYER
C - METAL

A.

10% OXALIC ACID 500X



B.

10% OXALIC ACID 500X

FIG. 38 SAMPLE NO. 12 - SHOWING (A) SIGMA PHASE AND CARBIDES AT THE OUTSIDE SURFACE AND (B) SIGMA PHASE WITH MUCH LESS CARBURIZATION AT THE INSIDE SURFACE

APPROX. 1X

FIG. 39 SAMPLE NO. 14 - SECTION OF MUFFLER WITH CRACK AT TAILPIPE OUTLET

Two specimens for metallographic examination were taken through the spot welds, one specimen being from the side that cracked and the other being on the opposite side of the stack. The grain size of the piece which cracked was larger than that of the collar. The two specimens allowed examination of four spot welds. All four of these showed the weld nugget to be located more in the collar than in the cracked piece. The microstructures of the spot welds and base metal appeared normal in the specimen taken on the opposite side of the crack. The microstructures of the two materials are shown in Figure 40 at a section between the two spot welds.

Figure 41 shows a spot weld and that the course of the crack in the base metal is somewhat removed from the spot weld. In this location both the cracked material and the collar had a grain boundary precipitate as shown in Figure 42. The precipitate was present throughout the structure of this specimen. Figure 43 shows part of the spot weld which was nearer the fusion weld. Apparently the heat during fusion welding resulted in the grain growth of the spot weld and the base metal. The presence of the grain boundary precipitate in this location and not on the opposite side of the tube indicates that the material operated at a higher temperature on the side containing the crack.

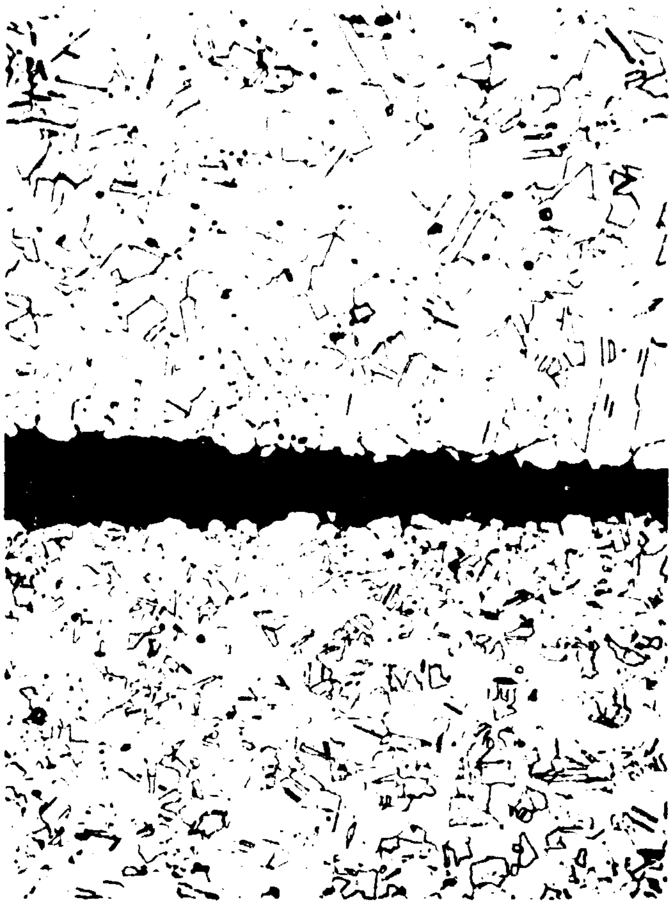
Another specimen for metallographic examination was taken along the crack where it had branched so that both sides of the crack could be viewed. Figure 44 shows this crack which appears to be the result of fatigue.

ANALYSIS

While the sections of exhaust systems submitted for examination varied in design and the results of the metallographic examination showed a variety of microstructures, the samples can be conveniently grouped with respect to general microstructural characteristics and to probable cause(s) of failure.

Baseline Samples

In general the microstructures of the baseline samples were normal although the different materials varied with respect to grain size and surface condition of the base metal and characteristics of the weld heat-affected zone due apparently to welding procedure. Perhaps the investigation of the baseline samples should have been carried further. However, without any information other than that given in Table I and with no apparent connection between the baseline samples and the other samples submitted, it was not obvious that further investigations were required or necessary. It is noted that the characteristics of the



10% OXALIC ACID 250X

FIG. 40

SAMPLE NO. 14 - SHOWING STRUCTURE AT A LOCATION ON SIDE OF TAILPIPE OPPOSITE TO THAT WHICH CRACKED

10% OXALIC ACID 100X

FIG. 41

SAMPLE NO. 14 - SHOWING SPOT WELD AND COURSE OF CRACK IN BASE METAL

10% OXALIC ACID 250X

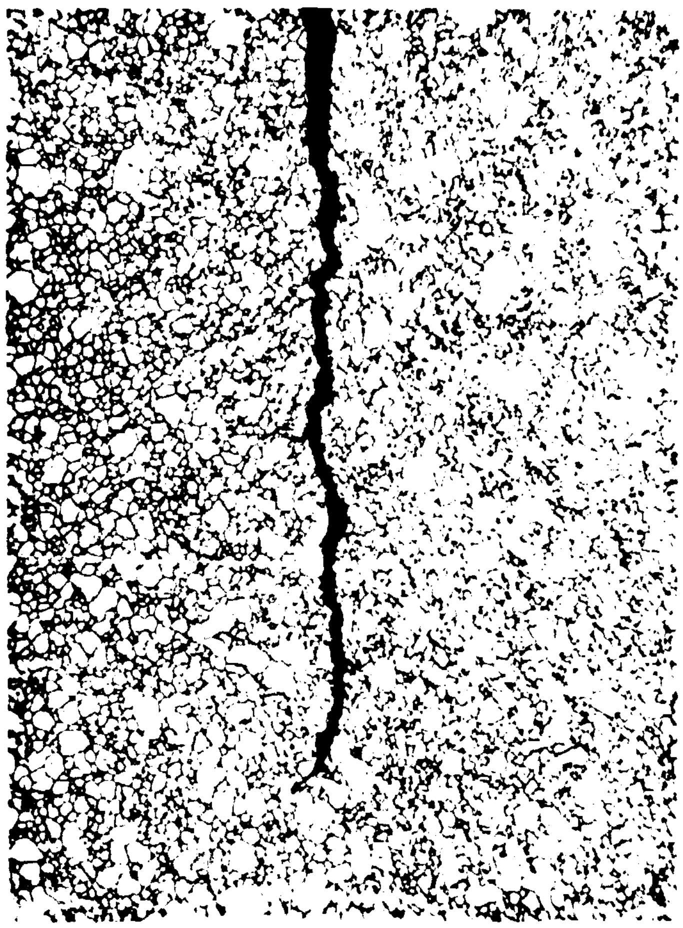
FIG. 42

SAMPLE NO. 14 - SHOWING GRAIN BOUNDARY PRECIPITATE AT A LOCATION NEAR THE SPOT WELD AND THE CRACK.

10% OXALIC ACID 100X

FIG. 43

SAMPLE NO. 14 - SHOWING THE STRUCTURE OF A PORTION OF THE SPOT WELD AND THE BASE METAL NEAR THE FUSION WELD. THE GRAIN SIZE IS LARGER THAN AT OTHER LOCATIONS EXAMINED. THE STRUCTURE SHOWS A GRAIN BOUNDARY PRECIPITATE.



10% OXALIC ACID 100X

FIG. 44 SAMPLE NO. 14 - SHOWING A BRANCH OFF THE MAIN CRACK occurrence of grain growth and the lack of continuous grain boundary carbides in the weld heat-affected zones of the baseline samples were similar to those observed in the examination of the samples which had been in operation, provided that the temperature of operation did not result in carbide precipitation.

Heavily Oxidized Samples

The samples showing heavy oxidation were Nos. 5, 6, 11 and 12. Sample No. 5 was the shell which showed bulging and cracks in some areas and Nos. 6, 11 and 12 were baffles which were distorted and showed cracks, especially at holes, in some areas. Characteristics common to all four samples were as follows:

1. In the areas of distortion and cracks, the materials had been thinned considerably from the occurrence of severe oxidation.

2. Determination by X-ray analysis of the constituents in the oxidation products showed the compound Pb (Fe, Mn, Al, Ti)$_{12}$ O$_{19}$ (magnetoplumbite) to be present.

3. The structure of the metal contained sigma phase, distributed discontinuously in the grain boundaries, throughout the cross-section. With respect to Sample No. 5 sigma phase was present in the structure at locations where bulging had not occurred as well as at bulges. With respect to Sample No. 11 sigma phase was present in the structure at a location of less distortion and thinning as well as a location of severest distortion and thinning.

4. The structure of the metal contained many carbides generally near the surface, but throughout the cross-section in one specimen taken from an area which was very thin. The material was carburized. The lack of many carbides in the section of Sample No. 5 which did not bulge suggests that carburization occurred only in the areas of severest oxidation.

The above findings and the visual examination of the samples indicate that severe oxidation occurred in some locations and this was then followed by distortion and cracking at these areas because of loss in thickness of metal. The rate of oxidation increases with increasing temperature and oxidation would be expected to be more severe in the presence of lead compounds, carburization and possibly sigma phase. However, the fact that oxidation was more severe in certain locations indicates that uneven flow of the exhaust gases existed through the exhaust system. The uneven flow of gases may have manifested itself only in local overheating, but at these areas of higher temperature carburization and attack by lead compounds would be more severe.

First of all, it is doubtful that sigma phase contributed to more rapid oxidation in certain locations because sigma was found to be present in areas of no distortion (for example, Sample No. 5) or less distortion (baffles). The presence of sigma phase indicates that the temperature during normal operation could have been as high as 1650° F.

There was no evidence of grain growth, thus indicating that temperature was not extremely high for long periods of time. However, this does not preclude that the temperature could have been in the neighborhood of at least 1900° F intermittently at some locations. The best evidence which indicates local overheating in the areas of failure is the presence of carburization. This is particularly true for Sample No. 5 in which carburization was observed only in the area of the bulges. Other evidence which supports local overheating to have occurred at the bulged areas of Sample No. 5 was the observation that these areas had considerably more oxide on the outside surface than the areas which did not bulge.

Higher temperatures in the areas of failure indicate uneven flow of gases through the exhaust system. With uneven flow of gases the presence of lead compounds could be more detrimental because of more rapid fluxing away of the normal scale and constant exposure to the lead compounds. The most direct evidence of uneven flow of gases, thereby possibly resulting in overheating, was again Sample No. 5. A baffle was located such that the flow of gases upon entering the shell was obviously directed towards the shell. It was this area of the shell which thinned and bulged.

It is concluded that the failures of these parts were not due to any material deficiencies, but rather to overheating in the areas of failure. The severe oxidation occurring in these areas resulted from a combination of the higher temperature, carburization and attack by the products of combustion, particularly lead compounds. The overheating in the areas of failure suggests an uneven flow of gases through the exhaust system and therefore design changes to eliminate or minimize this condition. If these conditions cannot be changed by design, then a more resistant material is required. Type 310 (25 percent chromium-20 percent nickel) or Incoloy (21 percent chromium-34 percent nickel) with Incoloy preferred, are suggested as possible selections for these parts which are exposed to the high temperatures and products of combustion.

Cessna 150 Mufflers

Sample Nos. 7, 8, 9 and 10 were all indicated as being parts from Cessna 150 mufflers. The parts were of similar design and in general showed similar failures. Since the examination of these parts, it was learned that the muffler consisted of two stacks. One-half of the assembly was forwarded for examination.

Visual and metallographic examinations revealed the following characteristics of the four parts:

1. All parts showed a crack through at least one of the support holes. Examination of one of these cracks showed it to be the result of fatigue.

2. All parts showed a crack between the support and shell. The cracks extended into the shell away from the weld in all four parts, but only two of the four parts showed the crack to be through the support piece. Examination of these cracks showed all to be caused by fatigue.

3. The welds between the support and shell showed poor penetration in some locations, leaving defects such as notches and undercuts.

4. Microstructures of the shell material varied. The shell of one part showed no precipitation in the grain boundaries. The shell of another part showed a continuous grain boundary precipitate. The shell of another showed a discontinuous grain boundary precipitate of a larger particle size. Another showed precipitation in the grain boundaries along the surface to various depths.

5. The microstructures of the support pieces showed no precipitation. Lack of scaling of the support pieces also indicate that this section did not operate at a high temperature.

6. The microstructure of the stack showed no precipitation on the support side of the assembly and continuous grain boundary precipitation on the shell side where the stack was exposed to the hot gases.

7. Microstructures of the welds and weld heat-affected zones were normal. Precipitation in the shell, if present, and in the stack started beyond the weld heat-affected zone.

In summary, all the cracks appeared to be fatigue failures with no evidence that corrosion or oxidation was instrumental in starting the cracks.

Since all the cracks were in essentially similar locations, but the microstructures of the shells varied, it is believed that the structure did not contribute to the failures. Rather, the indication is that the design of the muffler contributed to the failures. The fact that the cracks around the stack occurred in the weld heat-affected zone is believed to be due to the change in section size rather than any weakness resulting from the microstructural characteristics. Also, the rather poor condition of the weld between the support piece and the shell would provide ideal locations for initiation of fatigue cracks.

Since the operating conditions are not known, it is difficult to determine the source of the stresses which led to the fatigue failures. However, there are two possibilities. First, the support piece was apparently rigidly mounted and it appears that there would be vibrational stresses between the support piece and the shell. Second, the shell operated at a higher temperature than the support piece. This would result in thermal stresses in both the support piece and the shell, especially in the area between the two stacks.

In summary, it is felt that examination of these mufflers indicates a need for change in design to minimize or eliminate (a) sources of crack initiation in the part itself, and (b) vibrational and thermal stresses due to the method of assembly and mounting.

Sample No. 14

Sample No. 14 was the only part submitted of its particular design and failure characteristics. It is not possible to determine the exact location of the initiation of the crack of this part. As shown by the metallographic examination of specimens from this part, the side (with reference to the tube) on which the crack occurred was subjected to a higher temperature than the opposite side. There was no evidence that the crack may have started at a poor spot weld nor any evidence that the crack may have started at a location affected in some way by corrosion or oxidation. However, these possibilities cannot be ruled out. Again, the change in section size at a spot weld would provide a site for initiation of a crack in presence of vibration. Stresses set up by the temperature differences would add to any residual stresses due to welding and vibrational stresses. These are all possibilities, and suggest a change in design to minimize or eliminate temperature differentials during operation, residual stresses from method of assembly, and vibrational stresses from method of mounting.

CONCLUSIONS

The conclusions should be considered tentative at this time because (a) sufficient information was not known with regard to service conditions, (b) failures had progressed too far in some instances to determine the source and (c) the amount of handling and its effects on the condition of the samples before receipt were not known. From the results of a metallographic examination of the general structure of baseline samples and of the failed areas of samples which had been in operating aircraft, supplemented by chemical analyses, visual examination and X-ray identification of oxidation products, the following conclusions are made.

1. All materials were AISI Type 321 except for one baseline sample although some parts were indicated as possibly being AISI Type 347.

2. The general microstructures of the baseline samples were normal although differences in grain size and surface condition of the base metal were evident. As it was expected, welds contained delta ferrite and weld heat-affected zones showed grain growth to have occurred during welding.

3. Four samples, either baffles or shells exposed to high temperatures and the products of combustion, showed various degrees of distortion, oxidation and cracking. Locations of most severe distortion and cracking showed substantial thinning of the metal. The severe attack was probably a combination of local overheating, carburization and contamination by products of combustion, especially lead compounds, as a result of uneven flow of the gases. If changes in design cannot eliminate or minimize uneven flow and local overheating, then a more resistant material to oxidation and high temperature corrosion, such as Incoloy (21 percent chromium-34 percent nickel), is required.

4. Four samples from mufflers of similar design and failure characteristics showed all cracks to be caused by fatigue. There was no evidence that the materials, although showing various microstructures within and among the four parts due to different operating temperatures, or any corrosion effects were responsible for the failures. The failures are attributed to excessive vibrational and thermal stresses in the presence of abrupt changes in section size and likely sources of crack initiation at the weld-base metal interface. Changes in design in methods of assembly and mounting are indicated.

5. A tailpipe support failed by fatigue. Examination showed that one side (with reference to the pipe) operated at a higher temperature than the other. Again, the failure appears to have been due to excessive vibrational and thermal stresses rather than a deficiency of the material or corrosion effects.

APPENDIX I

GENERAL REFERENCES ON STAINLESS STEELS

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