Dr. J. Convey

IR 63-73

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EXAMINATION OF FAILED ENGINE EXHAUST ASSEMBLIES FOR CS2F AIRCRAFT

by

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PHYSICAL METALLURGY DIVISION

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W.P. Campbell* and R.D. McDonald*

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SUMMARY OF RESULTS

A metallurgical examination of five exhaust assemblies was carried out to determine the cause of failure. Four of the failures were associated with fillet welds, and one failure was unrelated to welding. All failures were due to metal fatigue. Failures associated with welds were concluded to have been initiated at the geometrical notch at the toe of each fillet. No obvious notch or defect was evident at the apparent initiating point of the one failure in the bell-mouth inlet which was not welded.

The steel in the assemblies conformed to the pertinent specification except for some of the tubing, associated with the one failure in the bell-mouth inlet, which was not welded. This steel was in the cold worked condition rather than in the annealed condition required by the specification. This could, conceivably, contribute to fatigue failure.

There was evidence that grain boundary oxidation, at the inner surface of some of the tubes, had contributed to the formation of cracks. An improvement in the surface condition of the tubes during processing and fabrication should be considered, where possible, with a view to lessening grain boundary oxidation attack during service.

Sensitization, of varying degrees, was found in the samples, thus proving that the steel was not stable under the service conditions. Although sensitization would be expected to lessen resistance to grain boundary oxidation, this was not shown conclusively by the investigation.

The absence of any clear-cut metallurgical explanation for the failures indicates that significant improvement in service life will be obtained only as a result of some design modification, or some change in maintenance practice, which will lessen the severity of cyclic stresses at locations that now are liable to fatigue failure.

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CONTENTS

INTRODUCTION

Failures in the exhaust assemblies of reciprocating engines on CS2F "Tracker" aircraft have been experienced by the Royal Canadian Navy (RCN). A request for assistance in determining the cause of failure was submitted by the RCN in a letter, which is reproduced below.

> Reference NS 7805-146 (DGA):
>
> ...Your assistance is requested in investigating the problem of cracking exhaust assemblies on this Naval aircraft.
>
> The problem of the fracturing exhaust assemblies was discussed by Dr. G.P. Contractor and other members of your division and Mr. V.T. Baker of the Director General Aircraft. Two sample fractured assemblies were left with Dr. Contractor for examination. These units display failures which are typical of those being experienced. During the past year the Canadian Navy has replaced 450 exhaust assemblies due to fracturing.
>
> The photostat page of 502 of MICN 3-35-09 which was supplied shows the four exhaust assemblies. Available records indicate that bell-mouth attachment flange failure has occurred on most of the nine cylinder connection points. The other crack location has been the welded cross-connection. The only support for the exhaust assemblies is provided by the clamped joints.
>
> It is requested that the defective samples be examined to determine what has caused the fractures and what steps may be taken to eliminate the problem. Of particular interest are the following questions:
>
> (a) Does the SAE 321 stainless steel tubing and sheet of which the assemblies are fabricated meet the composition requirements of MIL-T-8606 and MIL-S-6721?
>
> (b) Is the welding of inferior quality?
>
> (c) Has the steel become sensitized due to exposure to high temperatures?
>
> (d) If so has this been the cause of the cracks developing?
>
> (e) If no indications of inferior material or workmanship are evident, what changes in material or design are possible which would improve the reliability of these components?

(f) Can a welding technique be devised which would permit repair of cracked assemblies in Naval maintenance facilities?

Your assistance in this matter would be very much appreciated. ...

It is understood that the assemblies were manufactured by Bristol Aero Industries Ltd., Winnipeg, Manitoba, in accordance with drawings originating with the Grumman Aircraft Company in the USA, and that a liaison concerning the manufacture of the assemblies was maintained between the two companies during the period of manufacture.

It is also understood that the RCN has received information which shows that the U.S. Navy experiences about one-tenth the replacement of the same type of assemblies, in similar service.

Two considerations stated by the RCN to be of importance are:

(1) The hazard associated with these failures due to the possibility of enforced engine stoppage in flight,

and (2) The high replacement costs.

After examining the two assemblies, which were mentioned in the above letter, a meeting was held with Mr. Baker to discuss the findings. As a result, it was decided that additional failures should be examined. Three assemblies, which had been rejected due to cracking, were received on April 11, 1963. After examination of these assemblies, and a further discussion with Mr. Baker, it was agreed that no additional assemblies would be examined, at present, and that a report on the examination to date should be prepared.

DESCRIPTION OF ASSEMBLIES

The four exhaust assemblies, and their location on the engine, are illustrated in Figure 1.

The assemblies are attached to the cylinders of the engine by means of split ring clamps such as shown in Figure 1 in association with Part 89P1280-5. These clamps fit over the bell-mouth ends of each assembly and over corresponding attachments on each engine cylinder. The fitting on the cylinder extends on the inside of the bell-mouth to the second bend from the open end. These connections provide the entire support for each exhaust assembly. Only assemblies having part numbers 89P1280-5 or 89P1285-1 were submitted for examination. Figures 2 and 3 show two of the five assemblies submitted.

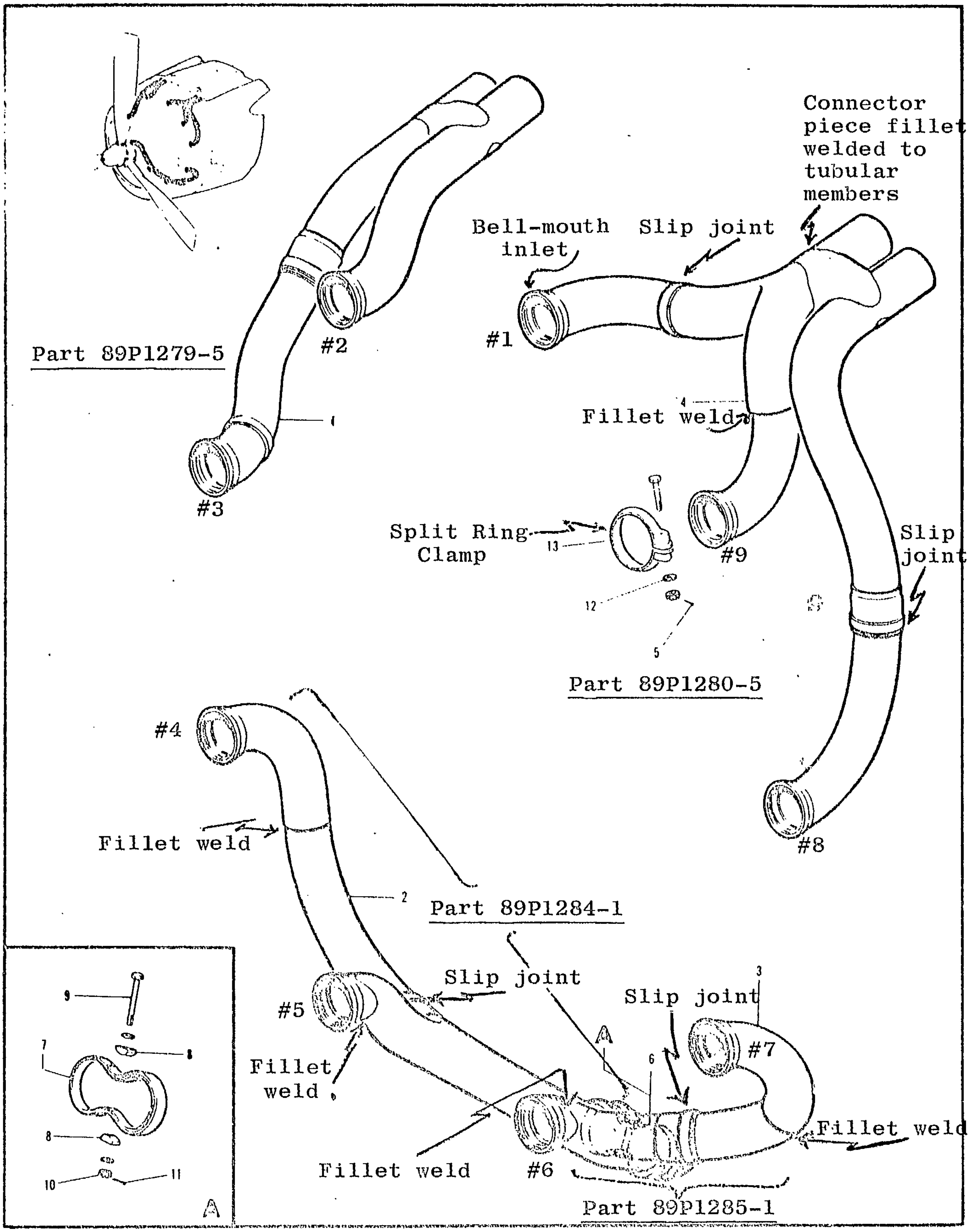

Figure 1. Layout of Exhaust Assemblies. The numbers at the bell-mouth inlets correspond to the number of the cylinder.

Figure 2. Assembly of Part 89P1280-5 as-received. Rejected due to cracking of transverse connecting tube near discharge end. Identified in Table 1 as Sample A. Approx. 1/4 size.

Figure 3. Part 89P1285-1, as-received, except for saw cutting to remove section for microexamination. Severe cracking along toe of fillet weld between bell-mouth end piece and fabricated Y piece, and extending away from weld into the Y piece. Identified in Table 1 as Sample D. Approx. 1/4 size.

In Part 89P1280-5, (see Figures 1 and 2) the exhaust gases from cylinders No. 1 and 9 are collected and discharged through a Y-shaped member. This member is fabricated by butt-welding two sheet metal stampings along a central axis. The tube containing the bell-mouth connection for cylinder No. 9, is fillet welded to the Y-shaped member. Seamless or welded tubes containing the bell-mouth connections for cylinders No. 1 and 8 fit into slip-joints in the assembly. The Y-shaped member is joined to the tube from the No. 8 cylinder connection by means of a transverse connecting tube, which is fillet welded to the adjacent members along what is termed, in this report, a "fish-mouth" joint. This connecting tube is made by butt-welding two half pieces along a central axis. Further details of the fillet welded joint will become evident on examination of pictures of weld cross sections, which appear subsequently.

The Y-shaped member of Part 89P1285-1 (see Figures 1 and 3) is also made by butt-welding stamping along a central axis. This member collects and discharges exhaust gases from cylinders No. 6 and 7. It is joined directly to cylinder No. 6 through a bell-mouth connection on one leg of the Y, and through a slip-joint to a seamless tube containing a bell-mouth end piece to cylinder No. 7 on the other leg of the Y. The direct connection to cylinder No. 6, is made at a bell-mouth end piece which is fitted over the tubular end of the fabricated Y piece and fillet welded to it along a fish-mouth joint. Part 89P1285-1 is attached to Part 89P1284-1 by a clamp illustrated at the lower left corner of Figure 1.

Table 1 identifies the submitted samples and provides a correlation with the corresponding inspection reports (Form C.N.A.-21) supplied by the RCN. An identification number has been assigned on Table 1 to each of the assemblies submitted, to enable more convenient reference in the subsequent discussion. The examination of welded joints is given in Part 1 of the present report, and the examination of the bell-mouth end piece whose failure was not associated with welding, i.e. Sample C, is given in Part 2.

TABLE 1

Identification of Assemblies Submitted for Examination

Part No. (See Figure 1)	Mines Branch Identification	Reason for Rejection	Data from Form C.N.A.-21		
			Report Serial No.	Hrs. of Service	Other Comments
89P1280-5	A	Cracking in connector tube and Y-tube, associated with weld (see Figures 2 and 4).	152/62	796.2	(1) "Found during 800 hr "B" inspection (2) This is the third identical defect discovered on this part in less than 2 weeks".
89P1280-5	B	As above. (see Figure 19).	No report supplied	-	Note: A tag, accompanying part, states that part was removed from a CS2F, MK2 aircraft having serial number 1556 on March 3, 1963.
89P1280-5	C	Complete fracture of bell-mouth connection of centre tube. (see Figures 31 and 32).	VX-10-41-62	?	(1) "Found during before flight inspection. (2) Exhaust stack not held secure. (3) Considered isolated case as this type of fracture not similar to previous failures".
88P1285-1	D	Severe cracking, espe especially of main tube at end close to fish-mouth shaped weld joint between bell-mouth connection and main tube (see Figures 26 and 27).	124/62	494.3 (?) (Figures in report not clear)	(1) "No similar experience in 1962 (2) Suggest collar on No. 6 cylinder exhaust stack joint be made wider, and welding process inspected more closely".
89P1285-1	E	Similar to above (see Figures 28 and 29	No report supplied	-	-

PART 1 - EXAMINATION OF WELDED JOINTS

Procedure

(1) Chemical analyses were performed on metal removed from the connecting tube and the adjacent Y-shaped stamping in Sample A on the side of the assembly that exhibited cracking, i.e. from the side shown in Figure 4. An analysis was also made on drillings machined from the Y-shaped stamping of Sample D on the side shown in Figure 3.

(2) All assemblies were examined visually to determine crack locations and extent of cracking. Except for Samples B and C, all inspection was made in the "as-received" condition. Samples B and C were cleaned by sand blasting and then subjected to penetrant inspection on the external surfaces around the weld joining the connecting tube to the two exhaust tubes, and on the inside surface of the Y-tube in the joint area. It will be noted in Table 1 that Sample C had been rejected due to the fracturing of the bell-mouth connection rather than to cracking at the connecting tube.

Several photographs were taken to illustrate the cracking evident by visual examination. Except for Sample B, these pictures illustrate the appearance of the samples essentially as-received. The pictures, showing the crack locations in Sample B, were taken after sand blasting and penetrant inspection.

(3) The fit of all slip-joints in Samples A, B, C and E was checked at room temperature by determining if the tubes could be inserted easily into the matching part. No check was possible on Sample D because the matching tube member was not submitted.

(4) Sections were removed from the locations shown subsequently in Figures 4 and 5 of Sample A and Figure 19 of Sample B. Three sections were cut from Sample C at short indications found by penetrant inspection along the toe of the weld junction with the connecting tube. One section was cut from each of Samples D and E at corresponding locations across the fillet weld joining the bell-mouth end piece to the fabricated Y piece (see Figure 3). Sections were also cut remote from the welds, in each of the Y-shaped stampings in Samples A and D. Some of the sections were examined in the unetched condition but most of the microscopic examination was performed after electrolytic etching in 10 per cent solutions of either oxalic acid or sodium cyanide. The oxalic acid, being more aggressive, was used only when sections were to be photographed at low magnification. Representative photomacrographs and photomicrographs were taken.

(5) Tukon micro-hardness tests, using a 500 g load and a 10.25 mm objective, were made on sections from Samples A, B and E to determine hardness levels remote from and at the welds. The values obtained were converted to the Rockwell scale.

Results and Discussion

The results of chemical analyses are compared in Table 2 with the limits given in specification MIL-S-6721B - Military Specification, Steel, Corrosion - and Heat-Resistant (Chemically Stabilized) Plate, Sheet and Strip - June 9, 1960.

The results given in Table 2 show that the material thus examined was in conformance with the composition requirements of specification MIL-S-6721B.

All of the slip-joints in Samples A, B and C were assembled readily without binding. The slip-joint in Sample E could be assembled only with difficulty, due to binding of the mating parts.

Tukon hardness tests remote from the welds, gave values, by conversion, of 80-92 Rockwell B in the Y-tubes and connecting tubes of Samples A and B, and in the Y-tube of Sample E. Similar values were found in the heat-affected zones of the welds. This indicates that the steel was in the annealed condition, or at least had been subjected to only a small amount of cold working during fabrication. Fully annealed type 321 stainless steel would have a hardness of about 85 Rockwell B. Hardness values of fused zones were in the range 83 Rockwell B to 25 Rockwell C. This shows that greater variation in hardness exists in the fused metal.

TABLE 2

Results of Chemical Analyses*

Identification	Element (Per Cent)									
	C	Mn	P	S	Si	Cr	Ni	Mo	Cu	Ti
Y-shaped stamping of Sample A	0.06	1.46	0.03	0.012	0.63	17.63	10.20	N.D.**	0.32	0.51
Connecting tube of Sample A	0.04	1.4***	-	-	0.58***	19.3***	9.6***	N.D.**	0.27	0.35
Y-shaped stamping of Sample D	0.06	-	-	-	-	18.28	10.13	0.13	0.27	0.35
Specification Limits (max limits except where noted)	0.08	2.00	0.040	0.030	0.040-1.00	17.0-19.0	8.0-11.0	1.50	0.50	6X carbon min 0.75 max

*Mineral Sciences Division Reports MS-AC-63-302, MS-AC-63-884, MS-AC-63-917 and SL 63-048.

**Not detected by spectrographic analysis.

***Determined by quantitative spectrographic analysis; all other determinations were by gravimetric chemical analysis methods.

Sample A, of Part 89P1280-5 was rejected during inspection when severe cracking was observed in the connecting tube as shown in Figure 4.

Figure 4. Sample A, showing cracking in the connecting tube along the toe of the fillet weld at its junction with the connecting tube. Small pieces of weld metal have been dislodged. The locations of three sections which were removed for microexamination are also shown. The Y-tube is at the top. Approx. 1/2 size.

The crack path turns away from the weld toe at a point where a widening of the bead ripple occurred, i.e., section C2 was taken near this location. A short distance beyond the location where the small pieces of weld metal were dislodged, the crack crosses the weld and extends for a short distance into the Y-tube. This extension of the crack is evident in Figure 5, i.e. the crack across which section C4 was taken.

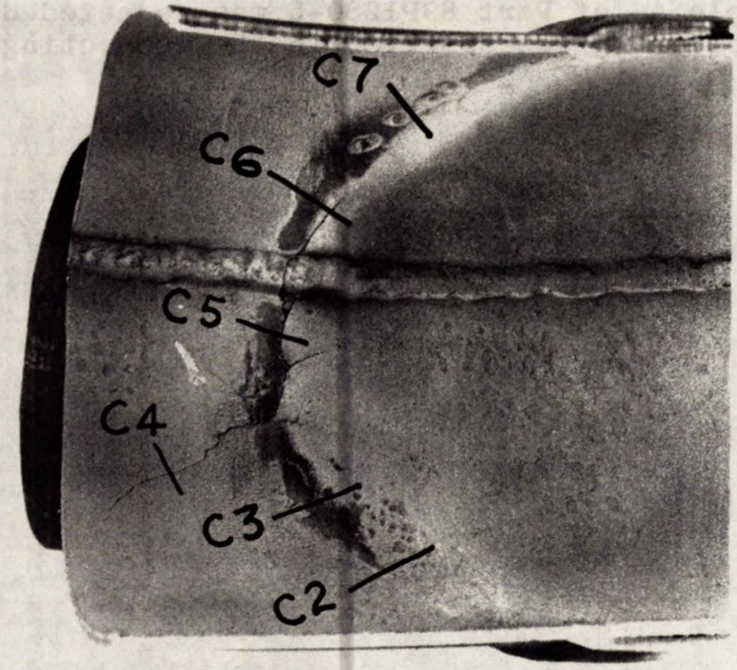

Figure 5. Sample A, showing inner surface of Y-tube below the weld with the connecting tube. Locations of microsections are also shown. Approx. full size.

Several branching cracks into the Y-tube are also evident in Figure 5. The main crack path is approximately in line with the root of the fillet weld, which has tended to penetrate through the Y-tube. Evidently, excessive penetration of this weld was ground off during manufacture, although a small amount of penetration was not removed, as at the location of Section C7. It will be observed in Figure 4 that only the portion of the connecting tube immediately adjacent to the Y-tube has been heated to a sufficiently high temperature to result in a dark oxide formation.

Section C2 (see Figure 4) is illustrated in Figure 6. (In this and all subsequent photographs of sections from Samples A, B and C, the Y-tube is in the horizontal position.)

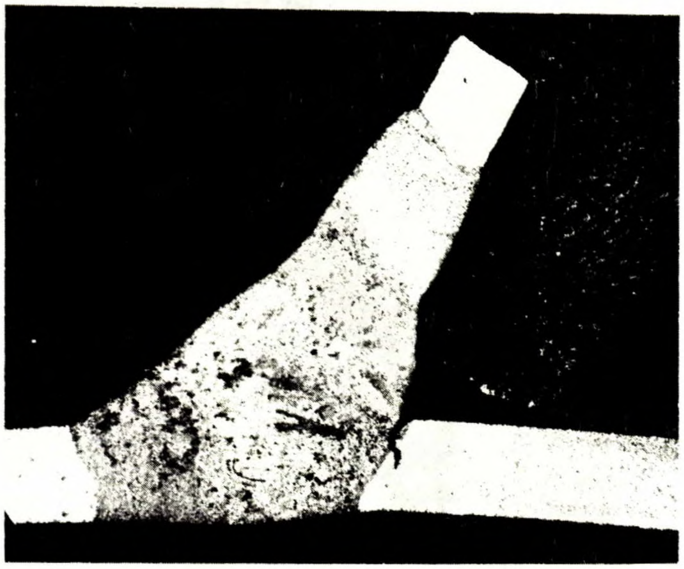

Figure 6. Section C2, showing fracture of connecting tube (at top of picture) and crack starting at inner junction of the weld with the Y-tube, and extending partly through the wall. Note that the weld penetrates through the Y-tube.
Etched Oxalic Acid X8

This section illustrates a location along the fracture path, seen in Figure 4, just a short distance away from the point where the crack begins to veer away from the weld toe. At this location, the fracture of the connecting tube is less than 1/16 in. from the toe of the fillet weld. The outer surface of the weld has a smooth transition with the connecting and Y-tubes. However, a sharp re-entrant angle exists at the inner junction of the weld with the outer surface of the Y-tube. A crack has been initiated at this notch, running initially through weld metal and then extending into the tube to about mid-wall thickness. It should be noted that such a crack is completely hidden from view before sectioning, and thus could not be found by visual inspection of the assembly during service. Figure 7 shows the uppermost portion of this crack at higher magnification.

A portion of the fracture in the connecting tube is illustrated in Figure 8.

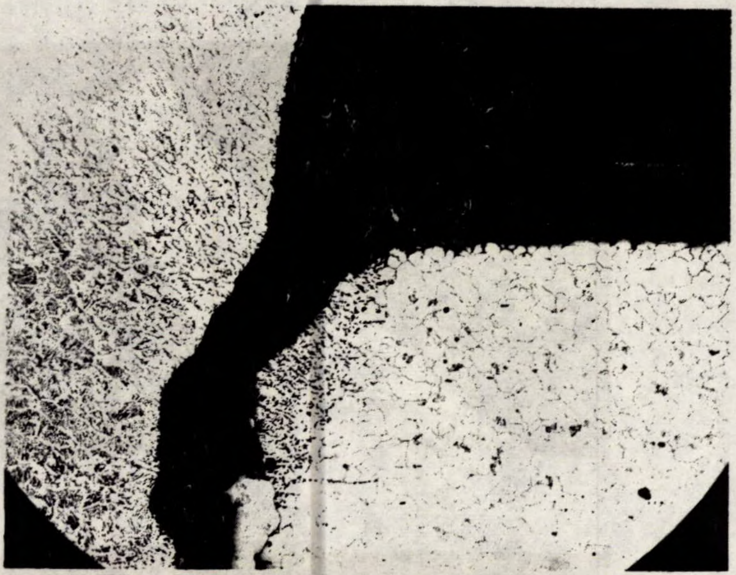

Figure 7. Section C2, showing the upper portion of the crack in the Y-tube, seen in Figure 6. Note carbide precipitation and oxide penetration at grain boundaries along outer surface of the Y-tube. The weld is on the left side. Etched NaCN X60

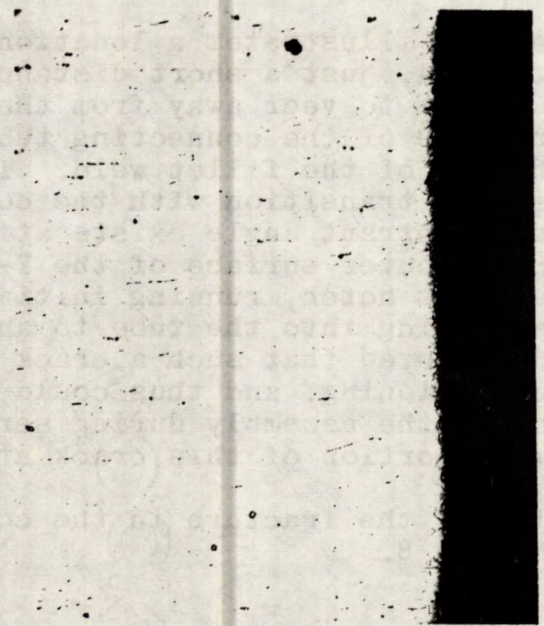

Figure 8. Section C2, showing transgranular path of fracture in the connecting tube, and absence of carbide precipitation. Etched NaCN X250

It will be noted in Figures 7 and 8 that there is considerable grain boundary carbide precipitation on the Y-tube but none in the connecting tube. In fact, carbide precipitation was not found in the connecting tube in any of the sections that were examined from Samples A, B or C. The fractured edge in section C1 (see Figure 4) was quite similar to that shown in Figure 8, although there was evidence of greater metal deformation. This would result from the two fractured surfaces working against each other for some period of time after the fracture had occurred.

Figure 9 is of Section C3 that was cut across the fracture where a small portion of weld metal had been dislodged. (See Figures 4 and 5).

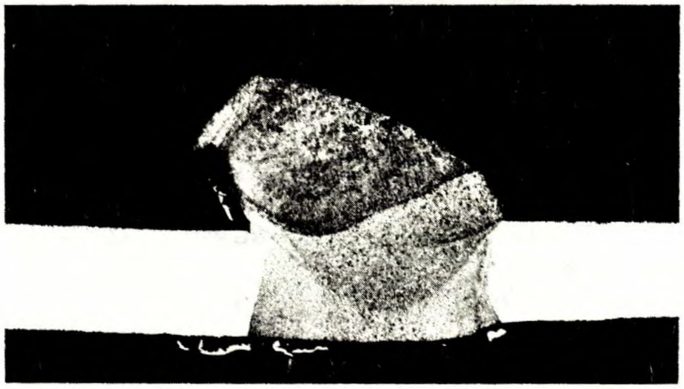

Figure 9. Section C3, showing fracture in weld metal near junction with connecting tube. Etched Oxalic Acid X8

Again, the sharp re-entrant angle at the inner junction of the weld with the outer surface of the Y-tube is present. However, no cracking has occurred, although this section was not more than 1/2 in. from Section C2 shown in the previous figure.

Section C5 was removed from a location bounded by two cracks visible on the inner surface of the Y-tube. (See Figures 5 and 10).

At this location, the welder did not achieve good penetration and fusion at the weld root, with the result that the connecting and Y-tubes were bridged across with weld metal, leaving severe notches at the root. The fracture in the Y-tube at the weld root is shown in Figure 11, and the crack extending inward from the partially-penetrated root is shown in Figure 12 at greater magnification.

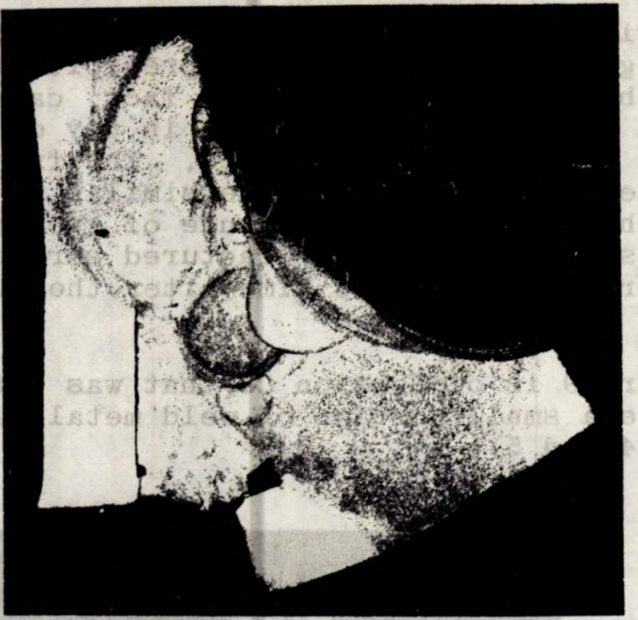

Figure 10. Section C5, showing fractures of the Y-tube (horizontal piece) on each side of the weld penetration, and the presence of lack of penetration and severe lack of fusion at the weld root.
Etched Oxalic Acid X8

Figure 11. Section C5, showing fracture in Y-tube at weld root, and cracking extending inward from outer surface of the tube starting at a partially-penetrated weld root. Extensive carbide precipitation is apparent.
Etched NaCN X50

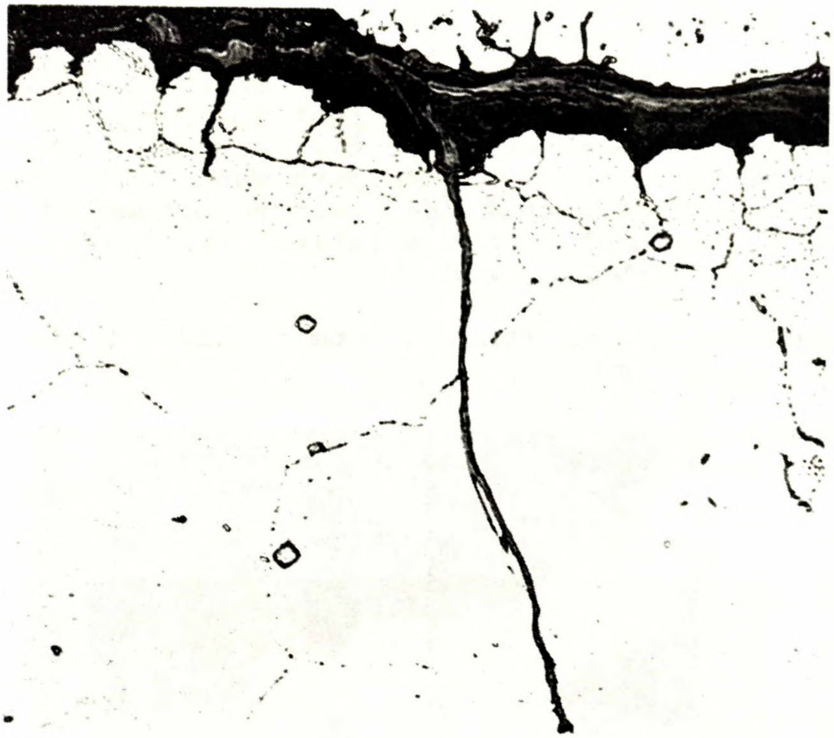

Figure 12. Section C5, showing upper portion of larger crack evident in Figure 11. The crack is oxidized and does not follow the grain boundaries in which chromium carbide has precipitated. This crack has started, most probably, from a notch formed by penetration of oxide along surface grain boundaries, such as shown above.
Etched NaCN X1000

Penetration was also incomplete at the weld root in Section C6, as is evident in Figure 13.

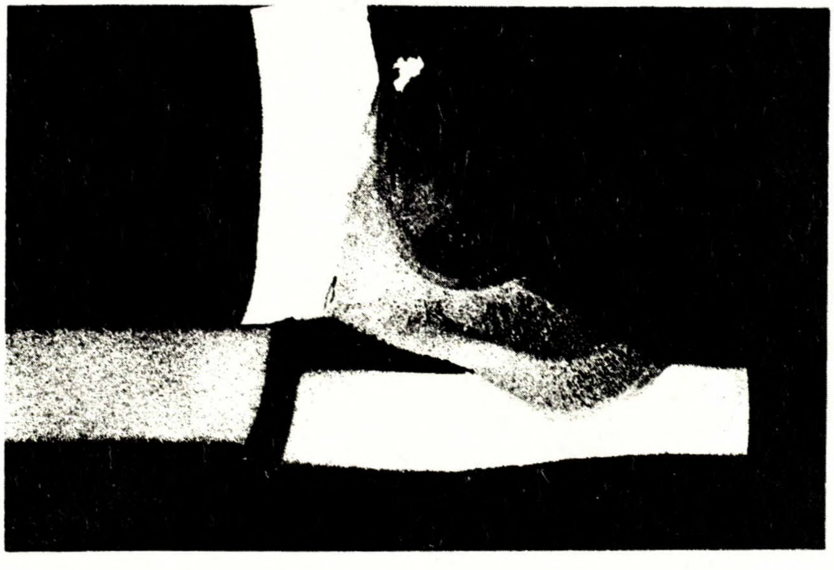

Figure 13. Section C6, showing incomplete root penetration and fracture of the Y-tube at the weld root.
Etched Oxalic Acid X8

Despite the incomplete root penetration evident in Figures 10 and 13, it is unlikely that the resultant notches were a prime factor in the cracking of the Y-tube. In both sections (Figures 10 and 13), the fracture path was not located at these notches. This suggests that the fracture proceeded from some more severe notch, most likely a fatigue crack that gradually extended in line with the weld root.

Section C7 was removed from a location where no crack was apparent (see Figure 5).

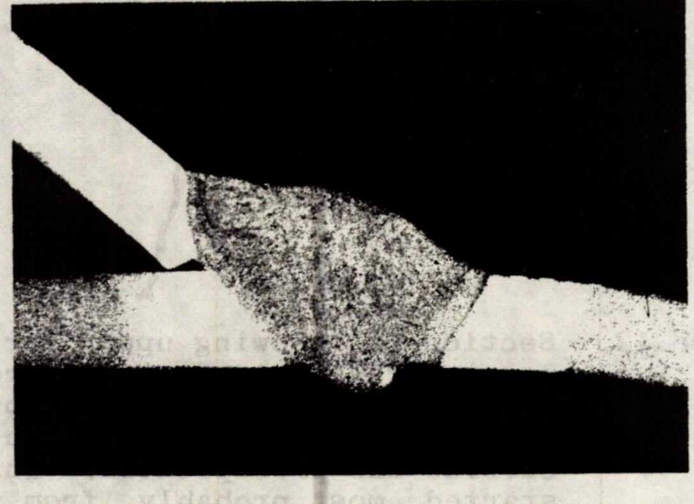

Figure 14. Section C7, showing a notch at junction of the weld with the two tubes, complete penetration of the Y-tube, and absence of cracking.
Etched Oxalic Acid X8

Figures 15 and 16, also of Section C7, are explained by their respective captions.

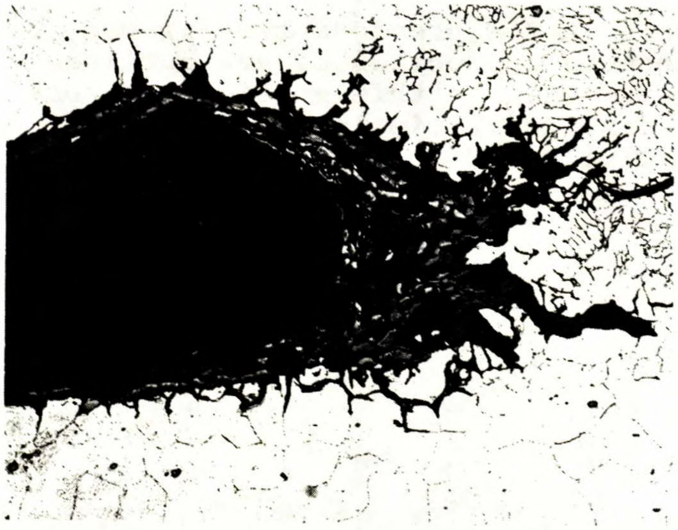

Figure 15. Section C7, showing junction of weld with Y-tube at the inner side of the connecting tube. Note the carbide precipitation, and the oxide penetration along grain boundaries at the surface of Y-tube. Etched NaCN X250

Figure 16. Section C7, at the inner surface of the Y-tube opposite the area shown in Figure 13. Note carbide precipitation and oxide penetration along grain boundaries. Etched NaCN X250

As shown in the previous two figures, the enlarged grains near the weld in Section C7 are outlined by fairly heavy carbide precipitation. In this section, at some distance away from the weld, carbide precipitation of a more random nature was noted, as illustrated in Figure 17.

Figure 17. Section C7, at the inner surface of the Y-tube away from the weld. Note considerable carbide precipitation, but more random than in Figures 15 and 16. There is less tendency for oxide penetration along grain boundaries than exhibited by Figures 15 and 16.
Etched NaCN X250

The penetration from the surfaces of the Y-tube of oxide along grain boundaries appeared to be greatest in the weld region. This was associated with the coarser grain size near the weld.

Figure 17, which represents the microstructure away from the weld in the stamping on one side of the Y-tube (i.e. the side away from that shown in Figure 4), should be compared with Figure 18. This shows the coarser grain size and moderately severe carbide precipitation, away from the weld, in the stamping on the side of the Y-tube shown in Figure 4. At higher magnification, it is evident that precipitation is not continuous along the boundaries, but consists of intermittent carbide particles.

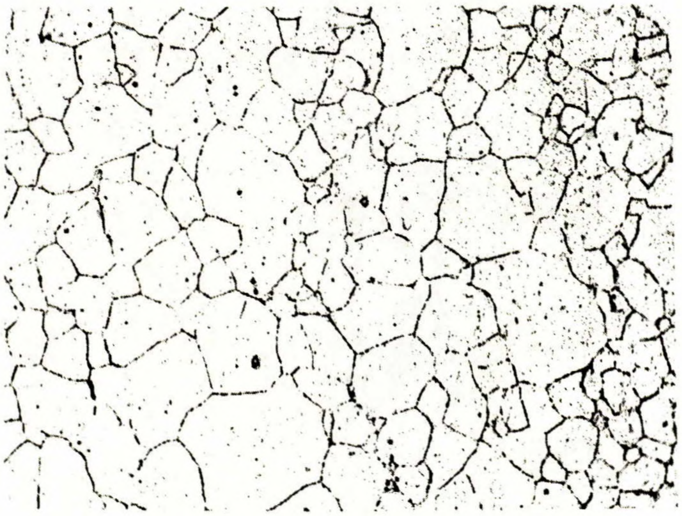

Figure 18. Showing microstructure of Y-tube stamping remote from weld on the side shown in Figure 4.
Etched NaCN X250

Thus, in Sample A (Ref. Table 1), carbide precipitation was found remote from the weld deposit in both stampings making up the Y-tube assembly, although more pronounced intergranular precipitation occurred in one stamping than the other. It should be noted that the chemical composition of the stamping containing the more pronounced intergranular precipitation was shown by analysis to conform to the specification requirements.

The cracking on the external surface of Sample B is very similar in appearance to that of Sample A, as shown by comparing Figure 19 with Figure 4.

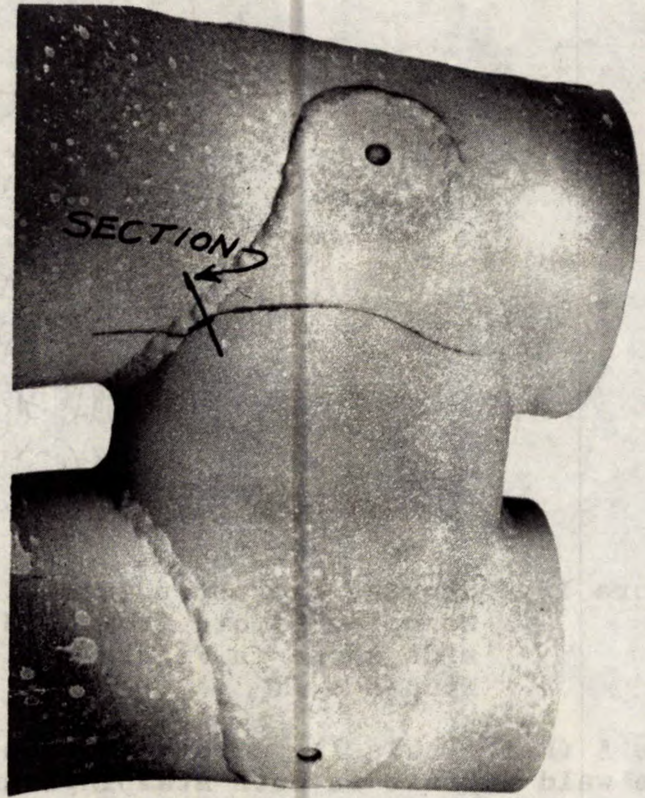

Figure 19. Sample B, after sand blasting and penetrant inspection, showing path of cracking. Approx. 1/2 size.

As is evident in Figure 20, the cracking in the Y-tube has not extended along the outline of the weld penetration into the Y-tube as was the case in Sample A (compare with Figure 5).

Figure 20. Sample B, showing inner surface of Y-tube at weld with connecting tube, after sand blasting and penetrant inspection. Approx. 2/3 size.

One section was cut from this sample from the location marked in Figure 19, and is shown in Figure 21.

Figure 21. Section from Sample B, showing fracture and secondary crack in the connecting tube. Etched NaCN X40

The path of fracture through the connecting tube is almost identical with that shown in Figure 23 for Sample C. The weld penetration in the Y-tube was even less than that shown in Figure 23. This shallow penetration is in contrast to that found in most of the sections from Sample A (see Figures 6, 9, 10 and 14). However, from Figure 20, it is evident that the weld has penetrated through the Y-tube wall of Sample B in at least some locations.

A comparison of Figure 22 with Figure 12 shows that the crack in the connecting tube of Sample B is similar to the crack in the Y-tube of Sample A.

Figure 22. Crack and fracture shown in Figure 21 at higher magnification.
Unetched X600

In this section, no intergranular carbide precipitation was found in the portion of the connecting tube, but precipitation varying between that shown in Figures 17 and 18 was observed in the portion of the Y-tube. Much less intergranular carbide precipitation than illustrated on Figures 15 and 16 was found in the Y-tube close to the weld. Also, there was very little oxide penetration from the surfaces extending inward along grain boundaries.

Penetrant inspection of the outer surfaces of the connecting tube and Y-tube in Sample C, revealed three 1/8 in. long crack indications at the junction of the fillet weld with the connecting tube. Two of the indications were close together at a location such as shown in Figure 19 for removal of the section from Sample B. The third crack indication was in a corresponding position on the other half of the connecting tube i.e. on the side opposite that represented in Figure 19. Two of the three sections, removed from these indications, confirmed the presence of cracking. One of the sections may have failed to intersect the crack indication. The two sections, which confirmed the penetrant inspection findings, are shown in Figures 23 and 24.

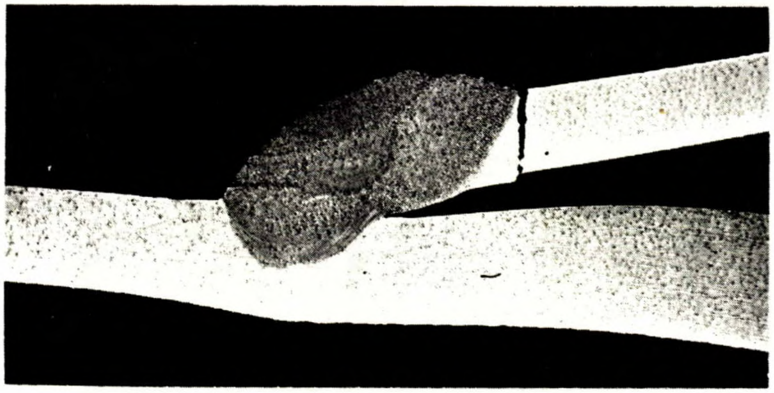

Figure 23. Section through 1/8 in. long crack indication found by penetrant inspection. The crack has started at the toe of the weld with the connecting tube in Sample C on the side such as shown in Figures 4 and 19 for Samples A and B respectively.
Etched Oxalic Acid X8

Figure 24. Section through 1/8 in. long crack indication found by penetrant inspection at fillet weld junction with connecting tube in Sample C on the side of the assembly opposite that illustrated by Figures 4 and 19 for Samples A and B respectively.
Etched Oxalic Acid X8

Further details of the crack in Figure 24 are illustrated by Figure 25.

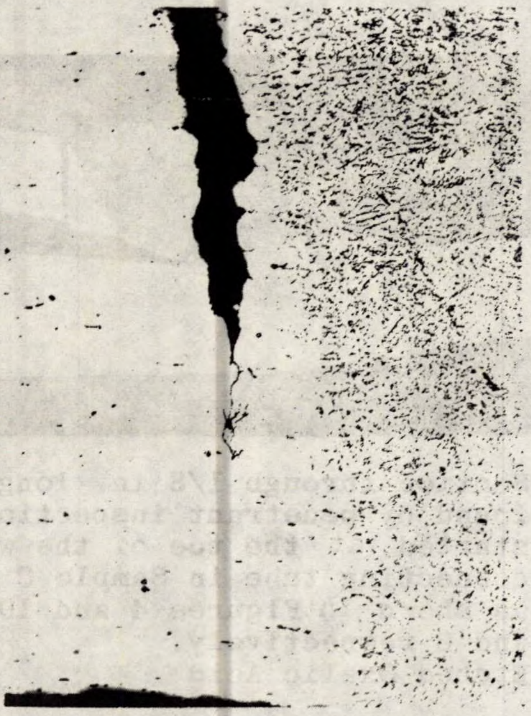

Figure 25. Section as in Figure 24, showing lower portion of crack and absence of carbide precipitation in the connecting tube.
Etched NaCN X100

No carbide precipitation was found in the connecting tube portion of either section. In the Y-tube portions, in the regions away from the weld, carbide precipitation similar to that shown in Figure 17, was noted. Near the weld, the section shown in Figure 23 had intergranular precipitation, more random than illustrated by Figures 15 and 16. The other section had relatively little carbide precipitation near the weld. Both sections had considerably less oxide penetration on the inner surface of the Y-tube opposite the weld than that shown in Figure 16.

The cracking in the two samples of Part Number 89P1285-1 is illustrated by Figures 26 to 30 inclusive.

Figure 26. Sample D. View of probable crack initiation location at the toe of a fillet weld. Crack extends into the fish-mouth piece at the lower side and into the tube at the upper side, relative to this picture. Approx. full size.

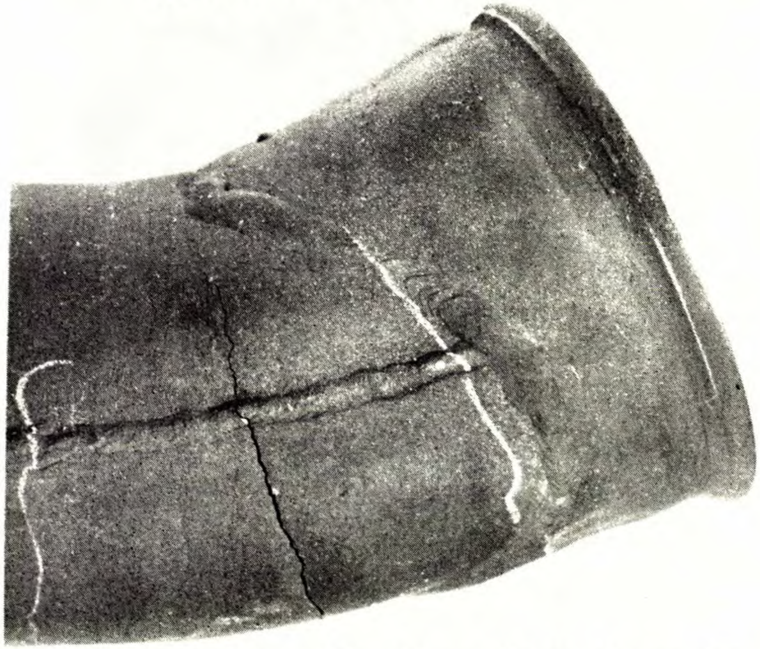

Figure 27. Opposite side from that shown in Figure 26. Approx. full size

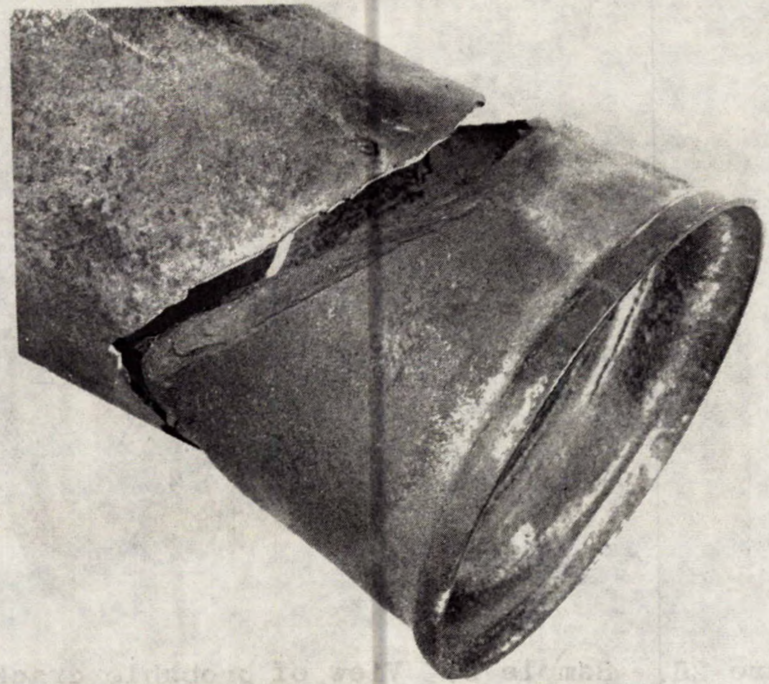

Figure 28. Sample E. View of probable crack initiation location at toe of fillet weld. Approx. full size.

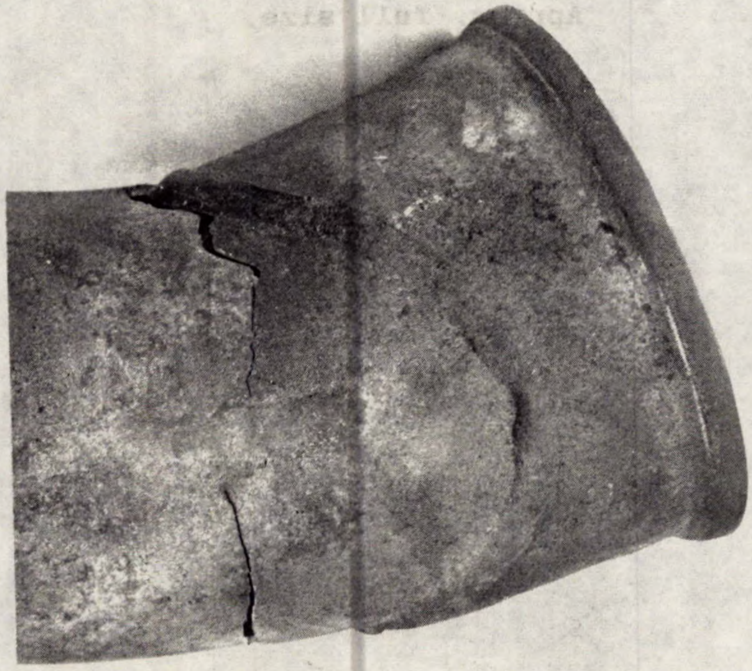

Figure 29. Opposite side from that shown in Figure 28. Approx. full size.

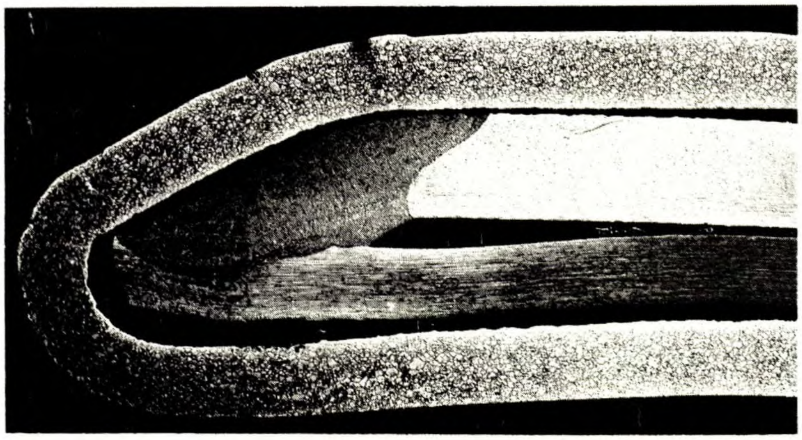

Figure 30. Representative of each section removed from corresponding locations in Samples D and E, at probable crack initiation locations. The bell-mouth portion is the upper member joined by welding. (Disregard enclosing U shaped piece, used to protect the edge of the specimen during polishing).
Etched Oxalic Acid X8

As indicated by Figures 26 to 30 inclusive, the welds appeared to be of satisfactory quality without providing abnormally sharp intersections with the tube.

The microscopic examination of the section from each sample showed that the fractures were transgranular, and intergranular carbide precipitation was present in the main tubes but not in the bell-mouth pieces. Away from the welds, the precipitation in the main tubes, was similar to that illustrated in Figure 18, but around grains of smaller size. Relatively little intergranular precipitation, or oxide penetration from the surface along grain boundaries, was observed adjacent to the weld deposit or at the location of fracture.

Summary

Failures in the weld regions of Part 89P1280-5 and Part 89P1285-1 are of the fatigue type. All fractures and cracks are transgranular, and all failures are associated with cracking along the toes of fillet welds which are known to be points of stress concentration. The occurrence of a crack starting at the notch formed by the connecting tube and the Y-tube, at the weld root in Sample A (see Figures 6 and 7), also indicates progressive failure under repeated loading. Similarly, small cracks found in Sample C at the toe of the weld in the connector tube (see Figures 23, 24 and 25) support this conclusion.

Although a considerable amount of intergranular carbide precipitation was found in the Y-tubes of Samples A, B and C and in the main tubes of Samples D and E, it cannot be stated with certainty that this is a major factor in the occurrence of cracking. In the Y-tube of Sample A, greater oxide penetration occurred along boundaries of coarse grains containing precipitated carbide close to the weld, than along boundaries of smaller grains also containing precipitated carbide remote from the weld,i.e., compare Figures 16 and 17. These surface grain boundaries, penetrated by oxide, provide notches that can initiate fatigue cracks such as illustrated in Figures 11 and 12. Thus, it is possible that the fatigue failure in Sample A was initiated by this mechanism. In any case, it is likely that the deep penetration of the fillet weld into the Y-tube, with resultant grain coarsening combined with intergranular carbide precipitation and surface oxide penetration along the boundaries of the coarse grains, has aggravated the cracking in the Y-tube. Much less cracking was found on the inner surface of the Y-tube of Sample B (compare Figures 5 and 20). This may be due in part to the lower penetration of the fillet weld into the Y-tube wall combined with a reduced amount of intergranular carbide precipitation and oxide penetration in the Y-tube near the weld. No cracking was found on the inner surface of the Y-tube in Sample C, and again it was observed that the weld penetration and intergranular oxide penetration found in the Y-tube were less than in Sample A.

The similarity of the crack path in Samples A and B, and the finding of small cracks at the junction of the weld with the connecting tube in Sample C, at locations corresponding with part of the fracture paths in Samples A and B, suggest that the most likely point of initiation of failure is at the weld junction with the surface of the connecting tube. If so, cracking propagates through the connecting tube wall as in Figures 23 and 24, and along the weld junction, until, at one end, the crack veers away from the weld and travels around the connecting tube, and at the other end the crack traverses the weld and runs into the Y-tube. It may then run on either side of the fillet weld, approximately at right angles to it and also may travel along the edge of the penetration bead if penetration is heavy as in Sample A.

In Samples D and E, very little carbide precipitation and oxide penetration were found adjacent to the weld deposit and the fracture. Therefore, the cracking in these samples must have been due to flexing of the main tube at the edge of the fillet weld. The fact that the main tube is thinner than the bell-mouth piece (see Figure 30) would accentuate the tendency to flex about the junction of the fillet weld with the main tube.

The findings of this investigation indicate that modifications in the design should be considered with a view to reducing the severity of notches in critical areas. For example, design changes, which would eliminate fillet welds, might be considered. The bell-mouth and piece of Part 89P-1285-1 might be made by deforming the end of the fabricated Y-tube, thus avoiding any circumferential weld. If this is not feasible, a formed bell-mouth end piece could be butt-welded to the fabricated Y-tube, and the internal and external reinforcement beads could be ground off flush.

Some suggestions can also be made for modification of Part 89P1280-5. Possibly, some improvement might result if the present connecting tube is replaced by a clamp similar to that shown in the lower left of Figure 1. Increasing the thickness of the connecting tube might reduce stress levels at the edge of the fillet weld so that failure of the connecting tube is avoided. However, it is quite possible that failures would then be initiated at the junction of the fillet weld with the Y-tube.

There appears to be some similarity in the mode of failure of Part 89P1280-5 with that illustrated in offset brackets fillet welded to torque tubes, and described briefly by Koziarski(1). This writer reports that fatigue failures occurred in the brackets when the bracket was extended beyond its point of tangency with the torque tube, and that failures were avoided by terminating the bracket at this point of tangency. He states, "It is obvious that any wrap-up extension of the bracket plate above tangency is not only expensive and heavy, but also produces parasite bending and buckling loads that ultimately lead to fatigue failure under cyclic loads". Although the cracking and stress conditions in the collector tube assembly are more complex, and thus presumably less well understood than in the case of the torque tube, it is possible that a similar modification might be beneficial, and it should, therefore, be considered.

In view of the findings of this investigation, welding repairs to cracked assemblies cannot be recommended.

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(1) J. Koziarski - "Some Considerations on Design for Fatigue in Welded Aircraft Structures" - Welding J. 38(6), 565-575 (June 1959).

Conclusions

(1) Improved service life will be obtained mainly as a result of modifications in design which reduce cyclic stresses at critical locations and possibly as a result of improved maintenance procedures.

(2) Failures due to fatigue cracking, along characteristic crack paths, occurred in two samples of Part 89P1280-5 and two samples of Part 89P1285-1. The apparent initiation of fatigue cracking was found in a third sample of Part 89P1280-5.

(3) Fatigue failures in Part 89P1280-5 were initiated by (a) cracking starting at the junction of the fillet weld with the top side of the connecting tube (when the assembly is installed as in Figure 1) or (b) by cracking starting in the Y-tube at surface notches resulting from oxidation along boundaries of coarse grains in the weld area. It is not certain which of these two factors had the dominant role in the failure of Sample A, as both factors were present. The second factor appeared to be dominant in Sample B. Considering all the findings for Samples A, B and C, it is thought that the geometrical notch at the junction of the fillet weld with the connecting tube is the most likely source of fatigue initiation in this part.

(4) The chemical composition requirements of MIL-S-6721B, for titanium stabilized stainless steel, were met by members in which severe cracking had occurred, i.e., the Y-tube and connecting tube of Sample A, and the Y-tube of Sample D. Hardness tests indicated that the steel had been supplied in the annealed condition as required by the specification. A slight amount of cold working may have occurred during fabrication.

(5) The steel was sensitized close to and remote from the fillet weld in Sample A. Varying degrees of sensitization were found both close to and remote from the fillet welds in the other four Y-tube samples. The most severe carbide precipitation, such as found in Sample A, was considered to be of moderate severity because the precipitate was discontinuous along the grain boundaries. No sensitization was found in the connecting tubes of Part 89P1280-5 or in the bell-mouth end pieces of Part 89P1285-1.

(6) Although some welding defects such as lack of fusion and penetration were noted, it was concluded that these had not played any major role in the fatigue failures. The contours of the fillet welds were considered to be typical of normal production.

PART 2 - EXAMINATION OF SAMPLE C WHICH FAILED IN THE BELL-MOUTH ATTACHMENT FLANGE REMOTE FROM WELDS

Procedure

The failed region of the exhaust collector was first examined visually and at low power magnifications.

Chemical analyses by gravimetric and spectrometric methods were carried out to determine whether or not the material was a stabilized stainless Type 321 steel made to the requirements of specification MIL-T-8606-A. Samples were taken from the failed tube of Sample C and from a corresponding location in the unfailed tube of Sample A.

Microscopic examinations at the failed section and at more remote regions in this tube and in other tubes were conducted to observe the microstructure, to check for defects, and to try to find evidence of a cause for failure.

Finally some corrosion and heat treatment tests were conducted to try to determine whether an improvement in the material might be obtained by certain heat treating procedures.

Hardness tests were carried out for the purpose of estimating the mechanical properties of the material. Standard tensile specimens were not tested due to the shape of the material.

Results

Visual Examination

Figure 1 shows a sketch of the layout of the exhaust collector system. An assembly of collectors for cylinders No. 1, 9 and 8 is shown in Figure 31 and the arrow indicates the location of the failure of the bell-mouth attachment flange at its junction with the cylinder. Photographs of the fracture are shown in Figure 32.

There were areas where no deformation was apparent and areas where considerable deformation was observed. These were not continuous and were interpreted, after further detailed examination, as an indication that several fatigue cracks had developed.

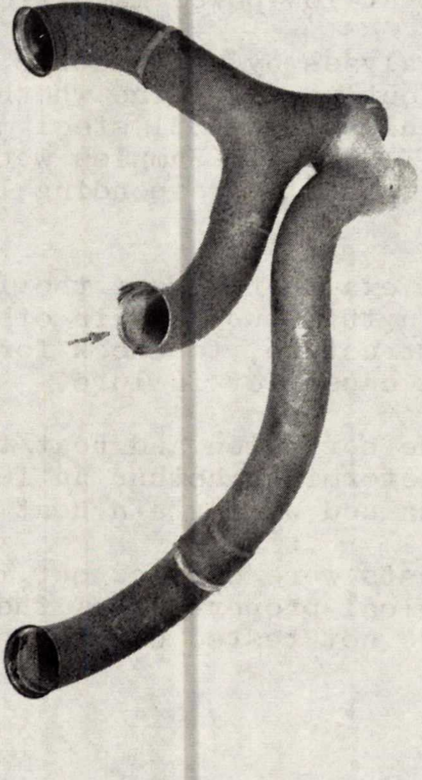

Figure 31. Collector assembly for cylinders No. 1, 9 and 8 showing failed section on No. 9. 1/8 actual size.

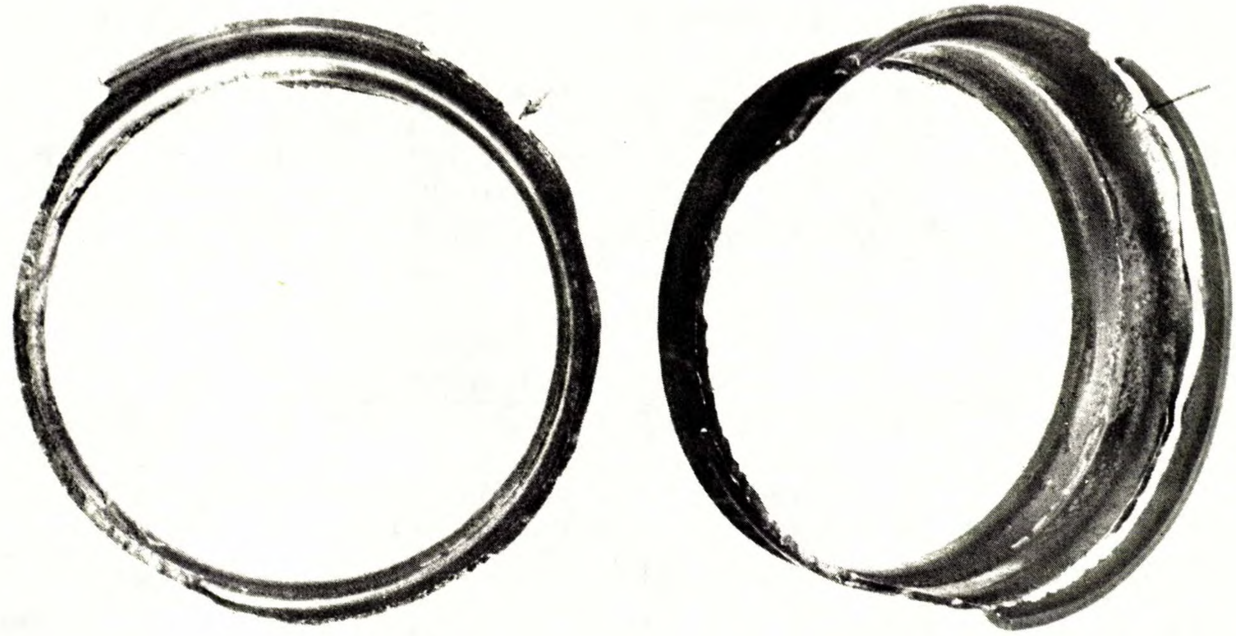

Figure 32. Fracture in collector pipe for No. 9 cylinder with arrow indicating location where fracture probably originated. This location is just under the edge of the ring clamp when assembled. The fracture progressed clockwise at the bend, longitudinally to the line which marked the location of the edge of the internal fitting, then continued circumferentially to failure.

Regions which showed severe deformation were those regions which failed, finally, due to overload. It was not determined with certainty at what location fatigue cracks had first developed, although the dominating crack or cracks probably occurred at the region of the pipe oriented uppermost on the installation. (See arrow Figures 31 and 32).

The fracture apparently originated beneath the ring clamp near the outer bend, progressed approximately half way around the tube following the first bend, then progressed longitudinally to the edge of the internal fitting and continued to complete failure circumferentially at the line of intersection between the tube and the inner fitting.

An exhaust deposit, observed on the inner surface of this pipe, was analysed. There was no indication from visual examination that this deposit had contributed to the failure.

Chemical Analyses

It was shown by Specification MIL-T-8606A that Type 321 or Type 347 stabilized stainless steel was intended for this service. Analyses were conducted to determine whether the correct steel had been used. The following table shows a comparison of the pipe material with the specified requirements for Type 321 stainless steel.

TABLE 3

Gravimetric Analyses*

Element	Identification and Composition % MIL-T-8606A Type 321	Failed Tube Sample C	Unfailed Tube Sample A	Clamp
Carbon	0.08 max	0.07	0.06	0.08
Manganese	2.00 max	1.42	N/A**	N/A
Silicon	1.00 max	0.63	N/A	N/A
Chromium	17.00-20.00	17.82	17.55	17.75
Nickel	9.00-13.00	9.63	N/A	11.59
Titanium	6 x C min (0.75 max)	0.43	0.41	0.44
Copper	0.70 max	0.31	N/A	N/A
Nitrogen	-	0.005	N/A	N/A

*Mineral Sciences Division Internal Reports MS-AC 63-303
63-541
63-367

**N/A - not analysed.

Elements were also checked spectrographically on these materials. The results of these checks did not show residual elements in sufficient quantity to be considered significant.

The compositions show that these units of the exhaust collectors were made of Type 321 stabilized stainless steel in accordance with the composition requirements of Specification MIL-T-8606-A.

The composition of the scrapings from the exhaust deposit was shown by analyses, to be $2PbO.PbBr_2$ as a major constituent, and $3PbO.PbBr_2$ as a possible minor constituent (Internal Report MS-63-35). This is known chemically as "lead oxy-bromide". The composition was determined by checking with X-ray fluorescence and confirmed by X-ray diffraction using a powder method with a Debye-Scherrer camera and filtered CoK radiation.

Mechanical Tests

The material was not ideally shaped for conventional tensile testing, therefore hardness readings were taken in order to estimate the tensile properties of the material in Sample C. These tests showed that the average hardness, of the material was 30 Rockwell 'C' scale by conversion from Knoop hardness readings. This hardness is compatible with a tubing material cold drawn to 1/4 hard temper or approximately 130,000 psi ultimate tensile strength. The hardness was also tested on a specimen which had been annealed at 1065°C (1950°F). The hardness was approximately 85 Rockwell 'B' scale which would be representative of an ultimate tensile strength of approximately 80,000 psi.

Hardness tests on a cross section of the belled end gave similar hardness values for the length of the belled section. However, these values averaged 25 Rockwell 'C' which is lower than the average (30 R'C') in the tube at a distance from the belled end. Cold finishing is also indicated by a hardness of 25 Rockwell 'C'.

Further tests on pipes available, other than Sample C, showed evidence that cold drawn material was used, and also showed wide variations in cold work in the belled section. The hardness values on belled sections in one tube ranged from 92 to 98 Rockwell 'B' and in another from 24 to 32 Rockwell 'C'. These indicate a heating cycle for the belling operation, and a considerable variation in the finishing temperature resulting in wide variations in degree of cold work.

Microscopic Examination

The visual appearance of the fracture indicated that it was a fatigue failure, probably resulting from the combining of several individual cracks, although possible nuclei were not easy to detect.

The microscopic examination was conducted to observe the condition of the material in the regions where fatigue cracks might have originated, and to examine the microstructure for service effects.

The microstructure shown in Figure 33 represents the inner surface of the pipe and the surface of the fracture at the location where the major crack was believed to have originated (See arrow in Figure 32). The microstructure in Figure 34 represents a similar field, but was taken on the pipe almost diametrically opposite that shown in Figure 33. These microstructures resemble annealed austenite grains and, from the grain size it was estimated that the material had been annealed at a temperature near the lower end of the annealing range 980°C (1800°F) to 1065°C (1950°F) for this material. The only cold

work visible microscopically was observed at the fracture. Although the hardness of the material indicated that it had been cold drawn to the 1/4 hard condition, which corresponds to approximately 10% cold reduction, this would not be detectable in the microstructure.

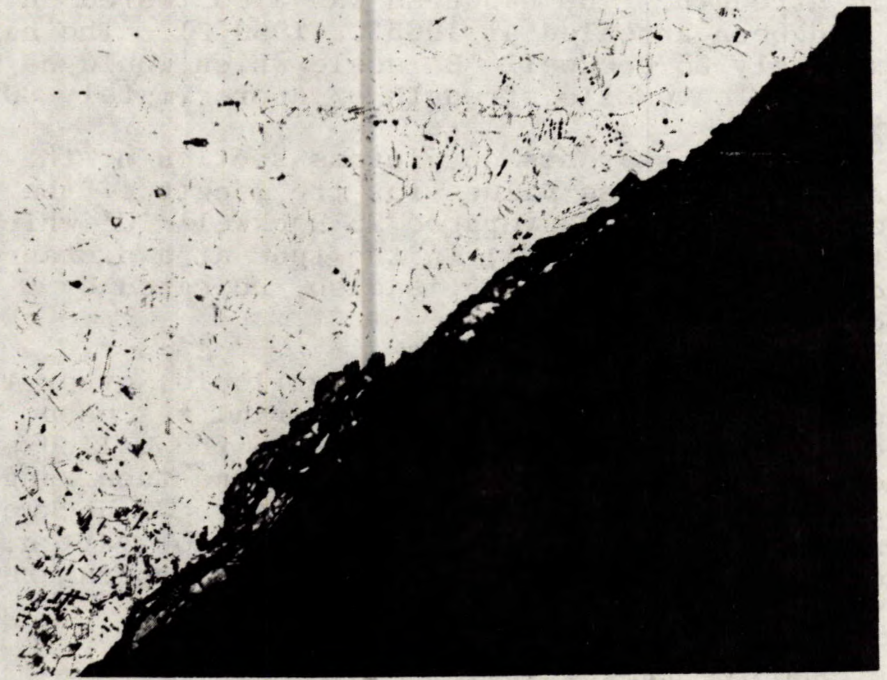

Figure 33. Microstructure and surface of the fracture (right) near the location where the fracture was believed to have originated (arrow Figure 32). There was no evidence of sensitization and the fracture was mainly transgranular such as normally occurs in low temperature fatigue fractures. Etched electrolytically in 10% oxalic acid. X250

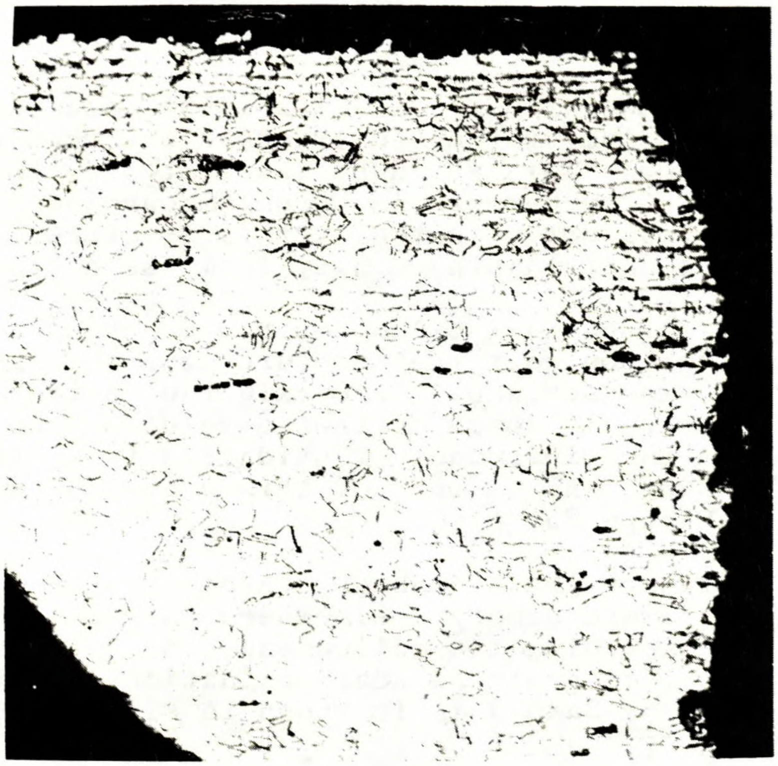

Figure 34. Section of fracture (right) and inner surface (top) at the bell-mouth. This field is almost diametrically opposite the field shown in Figure 33. The fracture is partly intergranular. Etched electrolytically in 10% oxalic acid. X250

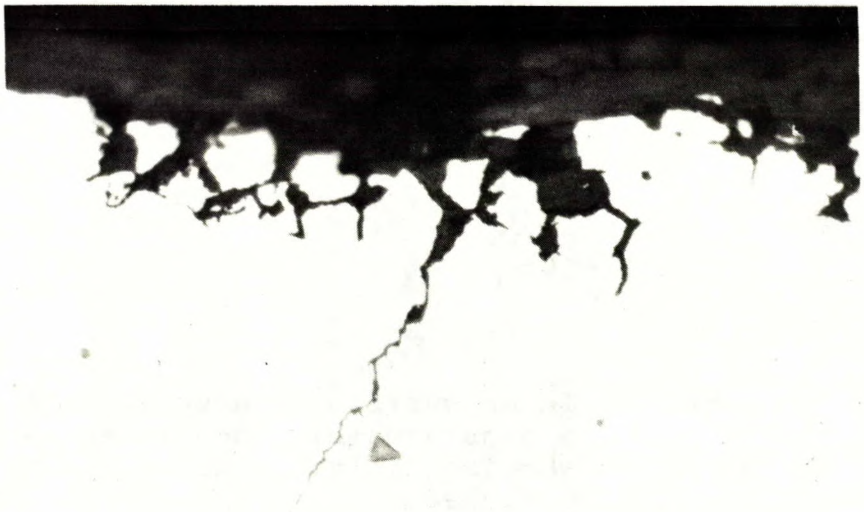

Figure 35. Grain boundary oxidation and crack which had propagated from the inner side of the tube near the fracture and adjacent to the field shown in Figure 34.
Unetched X1000

Because Type 321 is a stabilized stainless steel containing titanium, the microstructure was examined for evidence of sensitization. This would be manifested by the precipitation of a grain boundary network of chromium carbides. Carbide precipitation was not detected at this fracture, but was evident in this tube a short distance away from the belled end.

Grain boundary oxidation had occurred on the inner surface of the tube near the fracture to a much greater depth than on the outer surface. This oxidation attack frequently developed deep roots which further developed into cracks apparently under the combined influence of oxidation from exhaust gases and cyclic stressing. An example of this condition near the fracture is shown in Figure 35.

Although grain boundary carbides were not evident at the fracture, they were observed elsewhere in the same pipe and in other pipes, including the belled end. An example of this condition, and severe grain boundary oxidation associated with it in a belled end from Sample A, is shown in Figures 36 and 37.

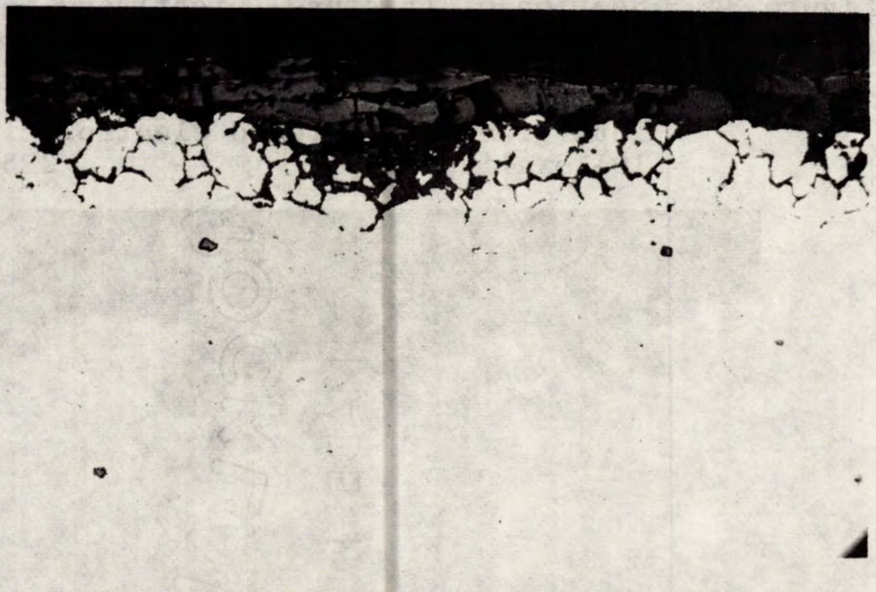

Figure 36. Inner surface at a bell-mouth from a pipe assembly identified as Sample A showing typical grain boundary oxidation.
Unetched X250

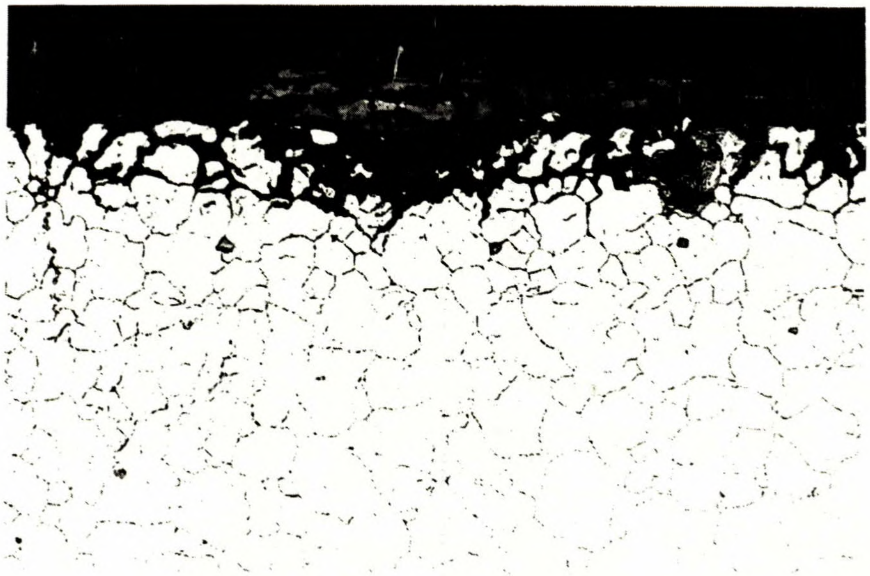

Figure 37. Same location as Figure 36. A similar grain boundary carbide pattern was observed in the failed pipe but not at the fracture.
Electrolytic etch in 10% NaCN X250

Sensitization Tests Using Nitric Acid (Huey Tests)

This test consists of weight loss measurements after boiling in nitric acid under standardized conditions. The samples, tested in triplicate, were selected and prepared as follows for comparison:

I From the end of the pipe remote from the fracture and where a carbide network was evident at the grain boundaries.

II From the belled end adjacent to the fracture where a carbide network was not evident.

III Material from the pipe which had been quench-annealed at 1065°C (1950°F) in an air atmosphere.

IV Material which had been annealed in an air atmosphere at 1065°C (1950°F), then cooled to 900°C (1650°F) and soaked for 2 hours at this temperature prior to cooling in air.

These tests provided the information presented qualitatively in Table 4.

TABLE 4

Results of Huey Tests

Condition	Results
I	Very severe attack
II	Severe attack
III	Moderate attack, normal for Type 321 annealed stainless
IV	Similar to III

A microscopic examination of a sample from I showed that grain boundaries had been severely attacked. On samples from the other three conditions, the attack tended to proceed at the grain boundaries slightly faster than the general attack, but evidently at a slower rate in condition II and at a much slower rate in conditions III and IV.

These tests show the advantage in this environment of the absence of a carbide network at grain boundaries.

Qualitative Oxidizing Treatments

An attempt was made to demonstrate oxidation tendencies at high temperatures while soaking under air atmosphere conditions. Specimens bent to create a region with a further degree of cold work were treated as follows:

(1) One side ground (to fresh surface), annealed at 1065°C (1950°F).

(2) One side ground, annealed at 1065°C (1950°F), stabilized 2 hours at 900°C (1650°F).

(3) Stabilized specimen reground on one surface, bent and soaked for 10 days at 565°C (1050°F).

(4) Stabilized specimen reground on one surface, bent and soaked for 10 days at 650°C (1200°F).

The results, in general, showed that a stabilizing heat treatment provides greater resistance to sensitization than annealing only, after soaking periods at 565°C (1050°F) and 650°C (1200°F). However, after long soaking periods some grain boundary precipitate occurred despite the stabilizing treatment.

Oxide penetration or "rooting" to an estimated depth of 5 x 10^{-4} inch was observed after both the annealing and the stabilizing heat treatments. However, after cleaning a surface by grinding and soaking specimens for up to 10 days at 565°C (1050°F) and 650°C (1200°F), no further oxide rooting was apparent after either heat treatment.

Summary and Discussion

The failure at the belled end was due to fatigue which probably originated at the location indicated in Figure 32 where little or no oxide rooting was evident. However, there was evidence that numerous small cracks had developed at areas where intergranular oxidation had occurred, and these had progressed and abetted the fatigue failure becoming a part of the main fracture.

There are several ways in which excessive stresses might have been incurred which relate to the design of the collector and possibly to the operation of the aircraft. For example, this region of the pipe would be subjected to cantilever bending stresses, vibrational stresses, possibly aggravated by resonant frequencies, and possibly thermal stresses and restriction at the junction with the clamp. However, in view of the isolated nature of this particular failure, its correction is considered to be secondary to those associated with welds at other locations in the assembly.

It was observed that this material was not truly stable in this service. There is some evidence in the literature that oxidation attack on Type 321 Stainless is less selective when the material is truly stable. Some improvement in resistance to sensitization was evident after a stabilizing heat treatment when compared with material which had been annealed only. However the material did precipitate some grain boundary carbides during the periods of soaking, and the improvement was judged by a greater length of time to precipitate and a greater dispersion of the carbides. Despite this improvement, when freshly ground surfaces were soaked in the sensitizing range in an air atmosphere, no oxide penetration was evident either after annealing only or after annealing plus stabilizing. These tests would indicate that if a cleanly ground surface was put into service in the sensitizing temperature range, either treatment would be suitable from the aspect of oxide rooting. However, time did not permit a sufficient number of tests, and dynamic and environmental conditions, which might have influenced the results, were not duplicated.

The heat treating tests did show that oxide rooting will occur in an uncontrolled atmosphere during annealing and stabilizing and that the oxide roots may penetrate to a depth of 5 x 10^{-4} in. Where cyclic stressing and further oxidation in service are likely to occur, such rooting would likely be detrimental to resistance to fatigue.

The Huey tests (nitric acid) do show that the grain boundary network is a hazard under oxidizing corrosion conditions. This test would favour a stabilizing heat treatment. However, there is a difference of opinion evident in literature references concerning thevalidity of interpolating this liquid environmental condition to that of high temperature corrosion attack in exhaust fumes.

From this examination and from information available in the literature, it is suggested that the best resistance to intergranular oxidation would be expected in Type 321 stainless steel after solution treating at the low end of the heating range and stabilizing for 2 hours at 870°C (1600°F) to 900°C (1650°F). If Type 347 is used the stabilizing treatment is not generally considered to be as necessary as for Type 321. However, it should be mentioned that service experience has thrown some doubt on the value of the stabilizing treatment(2).

The preferred finish prior to placing in service would appear to be a grinding or polishing operation to remove any surface condition formed during processing or fabrication. This may not be practical because of the complex shape of the assembly. Annealing in a controlled atmosphere would be expected to provide a better surface than either annealing in an air atmosphere, or pickling.

Although some of the pipe material had evidently been put into service in a cold drawn condition, there is no direct evidence that this condition was associated with the failure. Cold working would normally provide greater fatigue strength in the absence of a notch but could increase susceptibility to fatigue failure when notches are present. Therefore it is logical to assume that any benefit to be derived from cold finished tubes might be nullified in the presence of severe notches and cyclic stressing at high temperatures.

In general, it appears that emphasis should be placed upon improving design and assembly techniques to reduce mechanical notches where possible. Improvements in material processing and fabrication could be conducive to longer life by reducing the severity of metallurgical notches which contribute to stress concentrations.

Conclusions

1. This pipe failed in fatigue apparently originating just under the edge of the bell-mouth clamp and progressing part way around the pipe at the edge of the clamp. The remainder of the fracture occurred at the edge of the fitting on the inside of the bell-mouth.

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(2) Wilson G. Hubbell - "Result of Stabilizing Heat Treatment on Welded 18-8 Stainless" - Iron Age Vol. 155, April-June 1945.

2. The cause of the initial fracture was not determined. However, there was evidence that several cracks eventually joined to contribute to the failure and some of these cracks originated at the tip of oxide roots which had penetrated from the inside of the pipe.

3. The hardness of the material was compatible with tubing that had been cold drawn to "$\frac{1}{4}$ hard". This was contrary to the specification which specified annealed tubing.

4. There was no evidence that the exhaust deposit had contributed to the failure. However, the grain boundary oxidation resembled what is sometimes referred to as exhaust gas corrosion.

5. The material was not stable under service conditions. A stabilizing heat treatment would improve the degree of stability although it might not make the material completely stable under all possible conditions.

6. Oxide rooting would be present after an annealing treatment in an air atmosphere. When this is removed by grinding, rooting does not recur after a soak at 650°C (1200°F) for up to 10 days with no cyclic stressing in an air atmosphere.

RECOMMENDATIONS PART 1 AND PART 2

1. Determine from the most accurate data possible, the reason why the consumption of exhaust assembly parts in Canadian service is higher than in the U.S.A. Such information should have reference to design, service conditions, and maintenance practice, including tightening of the ring clamps. Possibly, assemblies such as currently manufactured in the U.S.A., could be obtained and submitted to close examination.

2. Consider design modifications with a view to reducing stress concentrations at critical locations, and to reducing cyclic stresses by damping of vibrations of the assemblies.

3. Require high quality welds, free of defects such as lack of fusion, or lack of penetration, and which merge smoothly with adjacent members.

4. Consideration should be given to possible improvements in surface conditions and uniformity of properties which might be obtained by heat treating techniques and mechanical cleaning.

5. Ensure that slip-joints do not bind at elevated temperatures.