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DEPARTMENT OF MINES AND RESOURCES

BUREAU OF MINES

CANADA

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Ottawa, September 23, 1946.

REPORT

of the

ORE DRESSING AND METALLURGICAL LABORATORIES.

Investigation No. 2112.

(Further to Investigation)
(Reports Nos. 1693 and 1748,)
(Aug. 2 and Nov. 18, 1944.)

Metallurgical Examination of Stainless Steel
and Inconel Exhaust Stubs Used on Mosquito Aircraft.

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(Copy No. 8.)

Bureau of Mines
Division of Metallic
Minerals
-
Physical Metallurgy
Research Laboratories

DEPARTMENT
of
MINES AND RESOURCES

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Origin of Material and Object of Investigation:

In December of 1944, Group Captain W. M. Keddie, B.A.C. representative, Federal Aircraft Limited, Insurance Exchange Building, 276 St. James St. W., Montreal, Quebec, during a personal visit, requested the aid of these Laboratories in determining the causes of premature failures in stainless steel exhaust stacks used on Mosquito aircraft. It was reported that failures generally occurred in less than 5 hours of flying time. Because of these premature failures several thousand exhaust stacks were purposely withheld from

(Origin of Material and Object of Investigation, cont'd) -

installation on the planes and it was therefore imperative that immediate action be taken to determine cause of failure in the hope of obtaining some method of salvaging the remaining exhaust stacks. Work on this problem was to be carried out in co-operation with Group Captain Keddie, Mr. R. W. Howe, production supervisor of Federal Aircraft Limited, and the De Havilland Aircraft of Canada Limited.

The existence of two prior investigation reports, No. 1693, dated August 2, 1944, and No. 1748, dated November 18, 1944, on the subject of Mosquito exhaust stacks was brought to the attention of Group Captain Keddie.

By arrangement with Group Captain Keddie, 6 unused sets of stainless steel exhaust manifolds (120 units) were submitted for test purposes on January 8, 1945, by De Havilland Aircraft of Canada Limited. (One complete set consists of 16 single and 4 double part exhaust manifolds.)

On March 1, 1945, upon instructions from Group Captain Keddie, 12 used stainless steel exhaust stacks (see Figures 1, 2, 3 and 4) were submitted to these Laboratories for examination. These stacks, which had all cracked prematurely in service, were removed from Mosquito aircraft.

On February 5, 1945, Group Captain Keddie submitted extracts from the De Havilland file, dealing with Mosquito Merlin Exhaust Stacks, with the object of offering further assistance in our investigation.

PROCEDURE:

1. Chemical Analysis.

Table I shows the results of chemical analyses made on four of the unused Canadian-built exhaust stacks submitted to these Laboratories. These stacks are typical of those

(Procedure, cont'd) -

which gave very poor service (less than 5 hours flying time for the single port and somewhat more for the double port).

Table II shows the results of chemical analyses made on Canadian-built exhaust stubs which gave considerably better service life than that of Table I (up to 16 hours for single exhaust stacks and 52 hours for the double stack).

Table III includes the results of chemical analyses made on English-built stainless steel exhaust stacks. These stubs were said to have given excellent results (no failures reported).

Both Tables II and III were taken from the De Havilland files and were prepared by Cockshutt Plow Company Limited, Brantford, Ontario.

Table IV includes figures taken from Tables I, II and III, and is intended to show the relationship between the service life and the carbon and titanium contents of the exhaust stacks.

TABLE I.

Canadian-built Exhaust Stacks (Very Poor Service).

		Single Port		Double Port	
		- Per Cent -			
Carbon	-	0.10	0.08	0.09	0.09
Manganese	-	1.32	1.50	1.82	1.70
Silicon	-	0.61	0.65	0.55	0.51
Nickel	-	9.80	8.96	13.90	15.44
Chromium	-	17.27	16.98	20.03	20.76
Molybdenum	-	0.05	0.05	Trace.	0.02
Titanium	-	Nil.	Nil.	Nil.	Nil.
Columbium	-	"	"	"	"

Note: Single Port Exhaust Stocks are 18-8 unstabilized.
Double " " " " 20-15 "

(Procedure, cont'd) -

TABLE II.*

Canadian-built Exhaust Stacks (Better Service).

	Single Port		Double Port	
	- Per Cent -			
	Stack No. 1	Stack No. 2	Stack No. 3	Stack No. 4.
Carbon -	0.066	0.04	0.044	0.055
Manganese -	1.27	1.21	1.24	1.56
Silicon -	0.50	0.57	0.59	0.42
Nickel -	9.82	9.69	9.67	15.86
Chromium -	17.07	17.04	17.05	20.89
Molybdenum -	-	-	-	-
Titanium -	0.339	0.299	0.230	0.270

Note: Single Port - 18-8 stabilized with titanium.
Double " - 20-15 " " "

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TABLE III.*

English-built Exhaust Stacks
(Very Good Service Life).

	Single Port	Double Port
	- Per Cent -	
Carbon -	0.044	0.040
Manganese -	0.47	1.10
Silicon -	0.59	1.09
Nickel -	9.01	18.30
Chromium -	18.22	25.42
Molybdenum -	-	-
Titanium -	0.59	0.456

Note: Single Port is 18-8 stabilized with titanium.
Double " " 25-20 " " "

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(Continued on next page)

* Tables II and III taken from De Havilland (Canada) files.

(Procedure, cont'd) -

TABLE IV.

*Comparison of Service Life of Stainless Steel Exhaust Manifolds.

Single Port

Description		Carbon, per cent	Titanium, per cent	Service Life
Canadian -	18-8 -	0.08	Nil.	Less than 5 hours.
"	" -	0.10	"	" " " "
"	" -	0.08	"	" " " "
" (No. 1)	" -	0.065	0.339	6 hr. 15 min.
" (No. 2)	" -	0.044	0.230	11 " 15 "
" (No. 3)	" -	0.040	0.299	15 " 55 "
British	" -	0.044	0.590	No failure.

Double Port

Description		Carbon, per cent	Titanium, per cent	Service Life
Canadian -	20-15 -	0.090	Nil.	20 hours.
" (No. 4)	" -	0.055	0.270	52 hr. 10 min.
British	25-20 -	0.040	0.456	No failure.

* Note: (1) High titanium content of British stacks results in long service life.
(2) 25-20 stainless steel is superior to 18-8 (other conditions being equal).
(3) Low carbon and high titanium contents result in long service life.

2. Measurement of Residual Stresses in Unused 18-8 Exhaust Stub.

Residual stresses, induced by welding, were measured by means of strain gauges which were attached to an unused stainless 18-8 exhaust stack. The gauges were attached on both inside and outside surfaces in the area of the trailing edge. This particular area was selected because it was noted from examination of the failed exhaust stubs that failure originated in every case at the trailing edge.

The results are as follows:

Gauge	Stress
1	-8670 p.s.i.
2	-2670 p.s.i.
3	-6000 p.s.i.

(Continued on next page)

(Procedure, cont'd) -

3. Microscopic Examination.

Figure 6, taken at X50 magnification, shows cracking in an Inconel exhaust stack, occurring in the fusion zone of the weld at the trailing edge B. The corrosive attack of the gases on the interior of the manifold is also evident. This photograph was taken from Investigation Report No. 1748.

Figure 7, taken at X200 magnification, shows the thickness of the nickel coating, which was applied electrolytically in these Laboratories, on a set of unused stainless 18-8 mosquito exhaust stacks.

DISCUSSION:

The report of Investigation No. 1693, entitled "Examination of Stainless Steel Exhaust Stub from Canadian-built Mosquito Aircraft," contained the results of an investigation made on the remaining portion of a stainless steel exhaust stub which had been removed from an aircraft after arrival in England. This exhaust stub, which had been submitted by A/C A.L. Johnston, for Chief of Air Staff, Department of National Defence for Air, Ottawa, Ontario, had apparently broken in two during flight. Since the outlet portion of the stack was not available it was impossible to trace the origin of the failure and to determine whether failure was in any way associated with the welding. Failure was attributed to stress-corrosion and it was recommended that 18-8 stainless steel stabilized with columbium or titanium be used in the future, followed by a stress-relieving anneal at 1350° F. for 1 hour. The use of 25 Cr /20 Ni and Inconel in place of the stabilized 18-8 stainless steel was also recommended.

The report of Investigation No. 1748, entitled

(Discussion, cont'd) -

"Metallurgical Examination of Welded Inconel Exhaust Stub for Mosquito Aircraft," contained the results of an investigation on an Inconel exhaust stub which had been submitted by De Havilland Aircraft (see Figure 5). Cracks which developed after service in flight, and which occurred at the welded areas A and B, were attributed to faulty welding technique. The investigation revealed the existence of cracks in the fusion zones of the weld at the trailing edge in the area marked B, (see Figures 5 and 6). The photomicrograph in Figure 6 clearly shows that the crack originated on the interior surface, that is, the surface exposed to the corrosive exhaust gases.

On examination of the failed stainless steel exhaust stacks, it was found that the mechanism of failure was exactly similar in every case, including the single port 18-8 and the double port 20-15. Failure in every case originated at the trailing edge in the welded area, then followed the weld longitudinally, and then spread out at right angles, very often resulting in complete severance of the outlet end from the fixed end (see Figures 1, 2, 3 and 4). This mechanism of failure also applied to the Inconel stack, as is shown in Figure 6.

The results of the chemical analyses made on the exhaust stacks forwarded by Group Captain Keddie (see Table I) revealed that both single and double port stacks had been fabricated from stainless steel not stabilized by either titanium or columbium. The analyses also showed that the single port stacks were made from 18-8 (18 per cent chromium, 8 per cent nickel), whereas the double port stacks were made from 20-15 (20 per cent chromium and 15 per cent nickel). These analyses were found to be in agreement with that reported under Investigation No. 1693. These exhaust stacks

(Discussion, cont'd) -

when placed in service were found to give very poor life. The single port stubs usually failed in less than 5 hours flying time, and the double port gave a slightly better service.

Examination of the data, as supplied by Cockshutt Plow Company Limited, from De Havilland Aircraft files, for stainless steel manifolds stabilized with titanium showed much improved service life (see Tables II and IV). The life reported for these stacks varied from 6 to 16 hours for the single port 18-8, and approximately 52 hours for the double port 20-15 manifolds. The titanium content reported varied from 0.23 per cent to 0.34 per cent.

Further examination of the figures pertaining to the English-built manifolds which apparently did not fail at all in service revealed the presence of higher quantities of titanium (see Table III). The titanium content of the single port stacks was 0.59 per cent and that of the double port stack 0.45 per cent. It should also be noted that the British-made double port stack approximated the 25-20 composition as compared with 20-15 for the Canadian counterpart.

In addition to the variation in titanium content and its effect upon the service life, another equally important factor, as revealed by the analyses in Tables I, II, III and IV, is the variation in the carbon content. Whereas the carbon content of the Canadian-built manifolds examined in these Laboratories, and which failed prematurely in flight, was found to be in the range of 0.08 to 0.10 per cent, the carbon contents of the Canadian manifolds stabilized with titanium and of the British manifolds were in the range of 0.04 to 0.044 per cent.

The above observations lend themselves ideally to

(Discussion, cont'd) -

the following explanation for the failures:

It is common metallurgical knowledge that when stainless steel that is not stabilized with either titanium or columbium is heated to within the so-called sensitizing range of 900° to 1500° F., there is a precipitation of chromium carbides at the grain boundaries (thereby depleting the chromium content of the steel at the grain boundaries) which renders the steel very susceptible to intergranular corrosion when placed in contact with a corrosive medium. By the addition of titanium or columbium a precipitation of titanium or columbium carbides occurs, and the danger of intergranular corrosion is greatly decreased. Also, the greater the carbon content the greater will be the danger of this type of failure. During the welding operation the steel in the vicinity of the weld passes through a wide range of temperatures, during which time excessive precipitation of carbides occurs. Hence welding unstabilized stainless steel invariably results in the formation of a steel most susceptible to intergranular corrosion. In the case of stabilized materials it is necessary to have sufficient amounts of titanium and columbium to combine with the carbon present. Hence, the greater the carbon content the greater is the quantity of these elements required. The usual specification calls for a titanium content equal to 5 times the carbon. For columbium it is 10 times the carbon content. However, it is also commonly accepted that titanium which oxidizes readily, is partly lost during welding. For this reason, where several welds are applied in a small area it, is necessary to have a larger titanium content than that usually specified. This will explain why the British manifolds (which contain 0.59 and 0.44 per cent titanium, as

(Discussion, cont'd) -

compared with 0.2 and 0.3 for the Canadian) gave superior service life.

The fact that failure in every case originated at the trailing edge (where there are several welds immediately adjacent to each other) seems to lend strong support to the theory of intergranular corrosion. It was also noted that this type of failure occurred in all of the austenitic chromium-nickel alloys including Inconel (see Figure 6). However, it was noted, from a study of the available data, that, provided other conditions are the same, the service life of alloys higher in chromium and nickel is greater than that of alloys lower in these elements. Hence Inconel, which contains 80 per cent nickel and 12 per cent chromium, should give better service life than the 25 Cr-20 Ni stainless steel, which in turn should be superior to the 18-8 variety. The superiority of the 20 Cr-15 Ni alloy, which was used on the double port stack, over the 18 Cr-8 Ni alloy used on the single port stack was clearly shown in Table IV. (It is not known whether the British directive to discontinue the use of Inconel manifolds in favour of stainless steel was motivated by economic or for other reasons.)

As a result of the recommendations contained in Investigation Report No. 1673, and with the co-operation of Group Captain Keddie, two sets of unused stainless steel exhaust stubs were annealed at 1350° F. for 1 hour, and then shipped to the De Havilland Aircraft Limited on January 23, 1945, for test in flight. Nothing more was ever heard of these manifolds and further correspondence failed to reveal their whereabouts. The object of this heat treatment was to remove the stresses, introduced by the welding, which were

(Discussion, cont'd) -

found to be considerable, and so reduce the danger of stress-corrosion. However, in the light of subsequent disclosures the effectiveness of this heat treatment is considered doubtful.

In addition to the above, one set of exhaust manifolds involving 16 stacks (only single port stubs were so treated) were nickel-plated and forwarded to De Havilland Aircraft on April 2, 1945. The object of this measure was to prevent access of the corrosive gases to the stainless steel, and thus prolong the service life. After considerable delay it was ascertained from Mr. F. H. Burrell, technical service manager of De Havilland Aircraft Limited, that this set which had been installed on aircraft KA385 was tested in flight for a period of 5 hours and 40 minutes and had been found to "behave perfectly in every respect." Unfortunately, due to a directive from the government to terminate the contract, the test was discontinued and the plane handed over to the R.C.A.F. for storage. It is regrettable, from a technical point of view, that this test was terminated, in view of the valuable information regarding this method of salvaging unstabilized 18-8 exhaust stacks which might have been forthcoming.

In the manufacture of stainless steel exhaust stubs, certain authorities (see references 1, 2 and 3) recommend the use of electric arc welding in preference to gas welding because of the prevention of carbon pick-up and for other reasons. Titanium-bearing welding rods are seldom used with titanium-stabilized stainless steel, because of the prohibitive loss of titanium. Hence, columbium-bearing rods are employed.

Conclusions:

1. Failures in flight of the stainless steel exhaust manifolds used on the Mosquito Aircraft were undoubtedly due to the use of stainless steel lacking in stabilizing elements such as titanium and columbium, or containing insufficient quantities of these elements.

2. Failures originated at the trailing edge of the manifolds, where the temperature was a maximum, and followed the welds longitudinally along the stack, then spread at right angles, very often resulting in bisection of the manifold.

3. The immediate cause of failure is due to intergranular corrosion in the weld areas caused by the precipitation of carbides during the welding operation. Such failures can be minimized by the use of stabilized stainless steels.

4. This type of failure was observed in all austenitic chromium-nickel alloys. However, the more highly alloyed steels result in better service life.

5. The carbon content of the inferior manifolds was found to be greater than those which gave better service life.

Recommendations:

1. Since the indications are that useful information may be obtained, some consideration should be given to the advisability of continuing the test of the nickel-plated exhaust stubs, attached to plane KA385, in order to determine the effectiveness of this method of salvaging unstabilized stainless steel manifolds.

2. In the manufacture of stainless steel exhaust stubs the use of unstabilized materials must be strictly prohibited.

3. If titanium-stabilized steel is employed the titanium content should be in the neighbourhood of 0.5 to 0.6 per cent.

(Recommendations, cont'd) -

4. The carbon content should be kept as low as possible (around 0.04 per cent).

5. Electric arc welding should be used in preference to gas welding.

6. Columbium-bearing welding rods should be employed.

References:

1. "The Effect of Stabilizing and Stress Relief Heat Treatment Upon Welded 18-8 Stainless Steel," by W. D. Hubbell, in Steel Processing, March, 1946.

2. "Investigation of a Type of Failure of 18-8 Stabilized Stainless Steel," by W. Kahn, H. Oster and R. Wachtell, in Transactions A.S.M., Vol. 37, 1946.

3. "Welding Stabilized 18-8 Stainless," by R. J. Hafstein, in Iron Age, July 11, 1946, Page 60.

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(Figures 1 to 7 follow, on Pages 14 to 17.)

Figure 1.

Figure 2.

SINGLE PORT STAINLESS STEEL EXHAUST STACKS FAILED PREMATURELY IN SERVICE, SHOWING TYPICAL FAILURES.

Figure 3.

Figure 4.

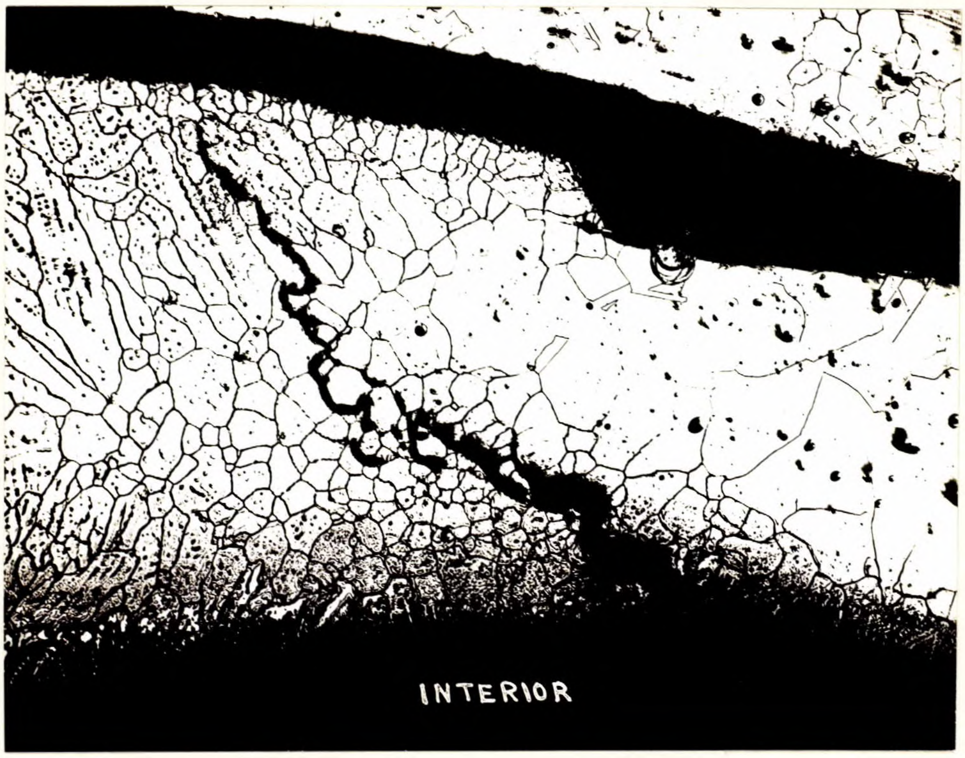
DOUBLE PORT STAINLESS STEEL EXHAUST STACKS
FAILED PREMATURELY IN SERVICE, SHOWING
TYPICAL FAILURES.

Figure 5.*

INCONEL EXHAUST STACK, SHOWING LOCATION OF CRACKS AT WELDED AREAS.

Cracking in stainless exhaust stacks originates in the area of the trailing edge at B.

Figure 6.



X50 (Etchant - Glycerine, HCl.HNO_3).

INCONEL EXHAUST STACK, SHOWING CRACKING OCCURRING IN THE FUSION ZONE OF THE WELD AT THE TRAILING EDGE, B.

Note corrosion along interior of manifold.

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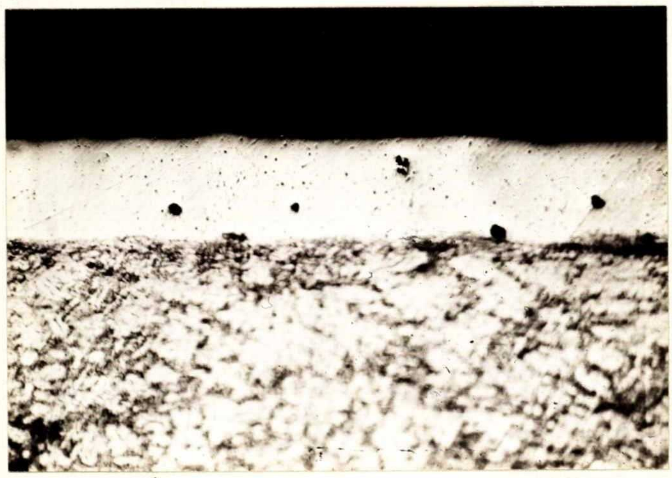
* Note: Figures 5 and 6 are taken from Investigation Report No. 1748.

Figure 7.



X200, etched.

NICKEL-PLATED STAINLESS STEEL 18-8 EXHAUST STACKS, SHOWING THICKNESS OF NICKEL LAYER (APPROXIMATELY 0.0025 INCH).

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