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DEPARTMENT OF DEFENCE

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MELBOURNE, VICTORIA

REPORT

MRL-R-984

INVESTIGATION OF COATING PERFORMANCE AND CORROSION OF COMPRESSOR COMPONENTS IN THE TF30-P-3 ENGINE OF F111C AIRCRAFT

L.V. Wake & B.S. Smith

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This report examines factors involved in the degradation of the protective coating, Chromalloy S-A12, employed on the low pressure compressor stators in the Pratt and Whitney TF30-P-3 engine of an RAAF F111 aircraft. The study is confined to the 7th stage of the engine (4th stage; low pressure compressor). The stator examined had experienced considerable corrosion after only 427 hours operation. Stators on other engines are failing for similar reasons. Small corrosion nodules were present on specific areas of each stator vane coating. Sections on the outer ring or shroud were found to be corroded along a geometric arc around the 6 o'clock position of the stage. These included - (a) both surfaces of the outer shroud or ring (b) the air seal around the shroud and (c) the area underneath the air path seal or 'rub strip'. The corrosion nodules on the vanes were associated with discontinuities in the coating. These discontinuities resulted in breakdown of the diffusion coating in surrounding areas forming aluminium, chromium and iron oxides. The elements sulphur and chlorine and to a lesser extent calcium and potassium were also found in the corrosion deposits. These elements are present in the local water supply and a detergent used for aircraft washing. Examination of the compressor washing and drying procedures are recommended.

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POSTAL ADDRESS: Director, Materials Research Laboratories
P.O. Box 50, Ascot Vale, Victoria 3032, Australia

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AUTHOR(S) L.V. Wake B.S. Smith	CORPORATE AUTHOR Materials Research Laboratories P.O. Box 50, Ascot Vale, Victoria 3032

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This report examines factors involved in the degradation of the protective coating, Chromalloy S-A12, employed on the low pressure compressor stators in the Pratt and Whitney TF30-P-3 engine of an RAAF F111 aircraft. The study is confined to the 7th stage of the engine (4th stage; low pressure compressor). The stator examined had experienced considerable corrosion after only 427 hours operation. Stators on other engines are failing for similar reasons. Small corrosion nodules were present on specific areas of each stator vane coating. Sections on the outer ring or shroud were found to be corroded along a geometric arc around the 6 o'clock position of the stage. These included - (a) both surfaces of the outer shroud or ring (b) the air seal around the shroud and (c) the area underneath the air path seal or 'rub strip'. The corrosion nodules on the vanes were associated with discontinuities in the coating. These discontinuities resulted in breakdown of the diffusion coating in surrounding areas forming aluminium, chromium and iron oxides. The elements sulphur and chlorine and to a lesser extent calcium and potassium were also found in the corrosion deposits. These elements are present in the local water supply and a detergent used for aircraft washing. Examination of the compressor washing and drying procedures are recommended.

INVESTIGATION OF COATING PERFORMANCE AND CORROSION OF COMPRESSOR COMPONENTS IN THE TF30-P-3 ENGINE OF F111C AIRCRAFT

1. INTRODUCTION

For some time the RAAF has been concerned at the unacceptably high rates of corrosion occurring in both the compressors and turbines of the PWA TF30-P-3 turbofan engines of the General Dynamics F111 tactical fighter bomber (TFB) [1,2]. The corrosion is particularly severe on the stators of the low pressure (LP) compressor [1]. These compressor stages show specific patterns of coating breakdown and corrosive attack after several hundred hours. While coatings on early compressor stators are traditionally subject to higher erosion rates and salt intake than other stages, the RAAF would like to significantly extend the service life of these early LP stators.

Corrosion deposits, which have a brownish appearance on the stator vane coatings, are apparent on specific areas of the LP compressor surfaces and raise doubts on the efficacy of this protective coating. The coating employed on these LP compressor components, designated S-A12, is applied by Chromalloy Corporation, USA. This coating is reputedly sacrificial [3] and, consequently, the presence of undegraded coating would be expected to provide protection against corrosive attack of the underlying steel substrate. The effective life provided by this coating to LP compressor stages may be as low as 420-430 hours flying, a period considerably less than that provided by the present 'hot end' coatings to turbine components.

The low pressure compressor stators of the TF30-P-3 engine of the F111 aircraft are composed of AMS-5504 steel (12.5% chromium; see Table 1). As mentioned, these units are protected by a coating system developed and applied in the United States. This system comprises two parts, the basecoat being an intermetallic or diffusion coating produced at lower temperatures than conventional pack aluminising, the upper, an inorganic top coat, sometimes termed the 'conversion coat'which is fused to form a ceramic layer.

Corrosion associated with the 'rub strip' on the stator shroud has also been an area of concern to the RAAF in recent times. The air path seal or 'rub strip' is a band of plasma sprayed nickel-graphite, approximately 2 cm wide on the ring or shroud of the stator. The corrosion problems associated with this seal occur on the shroud surface directly underneath this strip.

This report examines possible factors involved in the breakdown of the protective coating on the LP stator of the TF30-P-3 compressor. The composition of the coating is analysed at failure points and the effect on the underlying steel substrate examined. Possible causes of coating failure are discussed in view of the corrosion patterns present on the stator vanes and components associated with the outer shroud of the compressor.

2. COMPRESSORS AND COATINGS: GENERAL BACKGROUND

Gas turbine engine operation involves compression of air ingested from the atmosphere through successive stages of the compressor. During this operation, the air is heated and may exceed 400°C [4]. Typically, stator vanes are subject to higher temperatures than rotor blades, whereas blades are subject to considerably higher stresses than the vanes [5]. The compressor of the TF30-P-3 engine consists of low pressure (LP) and high pressure (HP) units. The six stage LP unit, which is composed of steel, is constructed integrally with the fan to form a nine stage unit [4].

The materials of modern gas turbine engines are chosen primarily for mechanical properties rather than corrosion resistance [5]. Achieving high strength and meeting other mechanical goals has often been at the expense of alloying elements which promote good oxidation and corrosion resistance [6]. Protective coatings have therefore been developed in recent times which provide a measure of oxidation and corrosion resistance for these components [7].

The superiority of the protective system selected by the RAAF, reputedly derives from beneficial properties of both components of the coating which include:

(i) the diffusion coating provides excellent thickness uniformity on complex geometry components. The diffusion coating is formed by aluminium vapours produced in a retort, reacting with the steel substrate to form an aluminium-iron composite. As the coating is metallurgically bonded to the substrate, adhesion and spalling problems are avoided, and

(ii) the top coat of the system is formed by a water based chromate/phosphate/magnesium system which are applied to the diffusion coat and fused. This top coat provides enhanced chemical resistance to the diffused material. It is claimed that no coating corrosion products are formed until the top coat layer is penetrated [8]. It is also believed that the very smooth surface of the top coat improves aerodynamic flow.

The superior protective value of the diffusion-type coatings under salt spray conditions [7] compared to conventional paint coatings is beyond question and there is a growing volume of experience to support this. The RAAF also report appreciably lower turbine inlet temperatures of up to 30°C by the use of this coating which would be expected to extend engine life considerably.

One of the most important aspects in the maintainance of aircraft engine components is provided by a suitable compressor washing routine. It has been pointed out that "from the user's point of view, the minimising of internal corrosion in engines is largely a matter of compressor washing and there is no doubt that this is a routine which needs meticulous and thorough application to be effective" [7]. In view of the importance of this facet of aircraft maintainance and the characteristic corrosion pattern observed, compressor washing and drying are discussed in some detail in this report.

3. EXAMINATION OF COMPRESSOR STAGE

The 4th stage of the LP compressor was from an unidentified F111 operating out of Amberley, and was obtained from Head Quarters Support Command, Aireng 2. It was examined visually and corroded areas photographed. Each vane (total; 96) on the stage was inspected for coating failure and corrosion. A number of vanes were removed from the stage for microscopic examination and chemical analysis. Sections of the 'rub strip' associated with both corroded and uncorroded areas were also removed for inspection and analysis.

Corroded areas on the surface of the compressor vanes were examined by optical and scanning electron microscopy (SEM) and analysed by energy dispersive X-ray analysis (EDXA).

Cross sections through blades were taken at corrosion sites while controls were prepared in areas where the coating showed no observable deterioration. These blade sections were either metal plated and mounted, or directly mounted into a polyester mounting medium. The sections were examined optically and by SEM. Analyses of coating cross sections were carried out by EDXA or electron probe microanalysis (EPMA).

4. RESULTS

4.1 Corrosion of the Compressor Stage

The appearance of the 4th stage of the LP compressor was characterised by slight colour changes caused by the erosive loss of the top coat, the so-called conversion coating, from specific areas of the stator vanes. These areas had the dark steely grey appearance of the diffusion coating rather than the glossy dark green of the glazed top coat. The conversion coating had been eroded from the concave surfaces of the vanes and from two-thirds of the convex surface. The conversion coating remained intact on the leading edge, on the leading area of the convex surface and in a thin line along the trailing edge. The brown corrosion spots on the vanes were restricted to the eroded areas (see Fig. 1) and were present on both convex and concave vane surfaces.

A clearly defined arc of corrosion of approximately 150° was present on the shroud or outer ring of the stage and on components associated with it. The outer ends of 40 stator vanes were corroded adjacent to the point where they pass through the shroud along this corroded arc (Fig. 2). The most heavily corroded section on this arc was the area below the 'rub strip' (Fig. 3). This area was corrosively pitted resulting in the 'rub strip' lifting and partially detaching. The air-seal around the leading edge of the shroud also showed this arc of corrosion (Fig. 4) as did the inner and outer surfaces of the shroud (the blades missing in Figs. 2 & 4 were removed for analysis). (It will be seen later Sections 4.2 & 4.3 that corrosion present on the stator was generally the result of breakdown of the metallic diffusion coating rather than corrosion of the stator itself, except for the area under the 'rub strip').

4.2 Stator Vanes

4.2.1 Microscopic Examination

Examination of the surface coatings on the vanes by light and electron microscopy confirmed that large areas of the vane coating had lost the ceramic top coat (Fig. 5). As mentioned, corrosion spots were present on these areas. Occasionally, small depressions could be seen in the diffused coating surface (Fig. 6) which had a darker appearance than the surrounding areas when examined in the SEM. This is presumably due to the presence of oxidised material on the surface which is poorly electron reflective. Other corroded areas had more of this material which had formed small nodules.

The surface nodules were roughly circular in appearance and exhibited 'mud cracking'. The irregular pieces formed by the mud cracking were smaller around the periphery of the deposits and larger and thicker at the centre. When the pieces of mud cracked material detached, pores in the underlying coating were occasionally revealed.

Examination of cross sections through the vanes showed that coating degradation was extremely severe in certain areas. Total or partial coating failure could be seen adjacent to areas of uncorroded coating (Fig. 7). There was only minimal corrosion of the steel substrate of the vanes (Fig. 8) suggesting that the coating had acted sacrificially until failure. Small cracks were apparent in some areas of the coating leading to chipping (Fig. 9) and pinhole corrosion (Fig. 10). Following pore formation (Fig. 11), the coating oxidised and formed deposits over the existing surface. Continued breakdown caused further surface deposition of the oxidation products forming raised surface nodules. The fully oxidised coating in the corrosion nodules was almost double the original cross sectional thickness. The cracked and oxidised sections showed a lack of adhesion (Fig. 12).

4.2.2 Microanalyses of Coating

Analysis of the grey surface layers of the eroded vane coating by EDXRA showed that the elements which comprise the ceramic layer of an unused vane (Fig. 13) were barely detectable after 427 hours operation (Fig. 14). This is in agreement with the appearance of micrographs of coating cross sections (e.g. Fig. 5).

The surface composition of the corrosion products on the vanes, as determined by EDXRA, showed variation throughout the corrosion sites. As well as the corrosion products of aluminium, chromium and iron, the deposits also contained the contaminant elements sulphur, chlorine, potassium and calcium. Of these, sulphur was the most common, while chlorine and calcium were frequently present. Analysis of the central surface area of the nodules showed high levels of sulphur (Fig. 15).

The cracked areas of the coating around the periphery of the nodules also varied in composition. In some places iron compounds predominated (Fig. 16) whereas in others, calcium, potassium, sulphur or chlorine containing materials were present. Analysis at discontinuities in the coating were richer in iron and chromium products as might be expected.

Analysis of cross sections through failed areas of the coating also showed compositional variation depending on the section of the failure, e.g. pores in the coating (Fig. 17) were found to be associated with the cationic contaminants calcium and potassium whereas the poorly reflective oxidation products were found to have high levels of the anionic contaminants, sulphur and chlorine. Attack on the base metal of vanes can be seen in some of the badly failed areas (Fig. 18).

EPMA of cross sections through corroded areas of the coating showed that an oxidised deposit containing an aluminium product was present in a layer over components of the original ceramic top coat. Also present in this layer were oxygen, chlorine, and sulphur. This oxidised layer resulted in a cross sectional coating thickness much greater than that of the original protective system (Fig. 19). EPMA maps around the mouth of a pit in the coating showed the presence of oxide and sulphur materials (Fig. 20).

4.3 Gas Path Seal or Rub Strip

Cross sections through corroded and uncorroded sections under the rub strip' showed that there was no protective coating i.e. no diffused layer nor indeed any other layer under this strip. Like other flame sprayed materials, the 'rub strip' has a porous structure. The shroud was pitted under the strip and the composition of the corrosion products was complex and contained aluminium, silicon, sulphur, chlorine, potassium, calcium, titanium, chromium, iron and nickel.

5. DISCUSSION

The severity of the cold end corrosion is illustrated by the fact that the life of the compressor stator coatings may be less than half of that expected from the present 'hot end' turbine blade coatings. Most of the corrosion observed on the stage is from failure of the diffusion coating rather than the stator itself, except in the area of the rub strip indicated in 4.3 above.

The mechanism of coating failure on the vanes appears to be as follows: breach of the coating is followed by sacrificial corrosion of the diffused layer protecting the substrate. The corrosion products diffuse from the pore forming an oxidised layer over the surrounding surface. This continues until complete local degradation of the coating leads to loss of sacrificial protection and pitting of the base metal.

The failure pattern of the protective coating on the LP compressor stators is characterised by several features which assist in understanding possible causes of coating breakdown. The composition of the corrosion products suggests that several external factors are involved in coating degradation. The characteristic features of coating failure include:

(a) The corrosion pattern observed on the outer shroud and airseal

Enquiries have revealed that the arc of corrosion on the stage is centred at the six o'clock position in the engine. Subsequently, similar findings have been made at overhaul with other compressor stages. This observation is consistent with residual water being present in the engine, possibly in the casing below the compressor. Possible sources of this include compressor washing or environmental sources, e.g. rain, condensation on cooling (sweating).

Equipment is available at Amberley for carrying out compressor washing on the wing for the F111 aircraft. Deionised water, with or without nonionic detergent is recommended for this process. (The washing procedure is discussed in detail in Section 6 below). Padded bags are pushed into the inlet and exhaust openings on standing aircraft in the Amberley carports' which ssists in minimising problems arising from rain.

(b) Corrosion on vanes is restricted to areas where the top coat conversion coating has been eroded away

This observation is in agreement with the Chromalloy report [8] suggesting that corrosion of sealed diffusion coatings is prevented by the fused top coat. However, this is only true for vane corrosion and is not the case for failure of the shroud and airseal. The green top coat was present on these latter sections but showed a reduction in the degree of gloss along the corroded areas of these components. The dull top coat areas surrounded a number of corrosion deposits. It therefore appears that extended exposure of the complete S-A12 system can result in corrosion, despite assertions to the contrary. Presumably, this breakdown occurs through microdiscontinuities in the glazing or slow dissolution of the glaze.

(c) Corrosion underneath the 'rub strip'

This attack differs from that in other areas on the stage in that no protective coating is present on the steel substrate of the compressor stator under the 'rub strip'. Corrosion in this region is occurring directly into the stator assembly and represents the most serious problem to the stage.

It is understood that the 'rub strip' was applied by plasma spray, a process which results in the formation of a fairly porous material. Chromalloy suggest that this material repells water and is resistant to corrosion except where detergents have been used.

(d) The composition of the corroded coatings

The corroded areas of the coatings contained the elements calcium, sulphur and chlorine, all of which were found in high concentration in the local water supply. The town water supply at Amberley is extremely hard and has a total solids content of 368 ppm (see Table 2).

In addition, the supplier of the detergent presently used for compressor washing (Turco Pty. Ltd.) is of the opinion that a number of surfactants may also have been used in the past including Jet Clean B and Airwash which are highly alkaline detergents containing sodium, potassium and sulphur compounds. EPMA maps show widespread oxygen distribution in these poorly electron reflective areas of the coating as might be expected. Both chlorine and sulphur are well known catalytic agents in corrosion processes, particularly in high temperature attack. Sulphidation has been extensively studied [9, 10] in high temperature hot corrosion (HTHC) but is also known to cause severe wastage when the temperature is relatively low [11]. Likewise the acceleration of metal oxidation by chlorine has been the subject of considerable investigation by numerous workers [12, 13]. Consequently, the ionic composition of the Amberley domestic water supply renders it unsuitable for compressor washing.

Hammersley [7] reports that the use of detergents does not always find favour with the manufacturers of some sealed type diffusion coatings. Likewise, the use of alkaline materials is not recommended in the compressor as the top coat conversion coat is soluble in hot alkaline solutions. Coatings based on aluminium, such as the underlying diffused coating, are more sensitive to mildly alkaline cleaners than to mildly acidic ones [14]. Sensitization of the aluminium coating is due to breaks in the oxide layer which normally protects the coating from corrosion. The coating is unable to establish a protective film at the sensitized spots rapidly enough to avoid attack. As well as the above, some workers believe [15] that detergents and water displacement agents of the sulphonate type, which are occasionally used in compressors, are susceptable to thermal oxidation above 300°C. As these temperatures are exceeded in parts of the compressor the compounds might be expected to form inorganic sulphates which are well recognised as corrosion promoting agents.

6. A COMPARISON OF COMPRESSOR WASHING PROCEDURES

6.1 F111 Washing Procedure [16]

There is considerable uncertainty about the details of the washing procedures employed throughout the life of the F111 aircraft. The regular change in personnel at the base with time makes accurate determination of the practice difficult. A number of RAAF personnel in the area believe that washing 'on the wing' was not carried out as it was difficult and time consuming. On the other hand, a RAAF officer involved, stated that fire hoses were used to clean the engines some time ago, a practice which is no longer carried out.

Following compressor washing, the engines are run to dry them by evaporation and mechanical displacement of the water. The possible use of domestic water would have resulted in a progressive increase in the ionic concentration of the washing solution subjecting the compressor components to conditions favourable for corrosion. The hygroscopic nature of encrusting salt deposits would have increased the likelihood of water adsorption and corrosive attack.

6.2 Recommended Washing Procedures

The following information appears in the F111 washing procedure AP 7214.010-6-4-2 and relates specifically to the application of the detergent and water washing procedures for the engine. Details of the mechanical procedures involved are omitted.

012 Engine Motor with Cleaning Solution

(A) Using starter, motor engine (ignition off) to 15-20 percent N2 RPM while spraying 7 gallons of mixed cleaning solution* into engine inlet using compressed air at the pressure required to obtain a flow rate of 7 gallons per minute. (* Mix 14 gallons of cleaning solution consisting of one part cleaning agent to four parts distilled or demineralised water [17]).

(B) Discontinue starter operation after one minute.

(C) Allow engine to stand for 10 to 15 minutes.

(D) Repeat cleaning solution injection process in one minute intervals at 7 gallons per minute until 10 to 15 gallons of mix is exhausted.

013 Engine Motor with Demineralised Water

A. Using starter, motor engine (ignition off) to 10-15 percent N2 RPM while operating wash cart, to spray 26 gallons of demineralised water into engine inlet at 35 to 40 PSIG. Release starter after 30 seconds.

B. Allow engine to drain for 5 to 10 minutes or until draining is completed.

014 Engine Motor with Demineralised Water

A. -NOTE- Subsequent rinses may be completed to ensure cleaning solution is rinsed from engine.

021 Engine Start

A. Start engine I.A.W. DI(AF) AAP7112.002-2-1 and run at idle.

B. Make engine data plate speed check to determine effect of cleaning.

6.3 Domestic Washing Procedure

Discussions with powerplant engineers of the domestic airlines have revealed that they experienced a similar corrosion problem on compressor stators some time ago. The engine involved was the JT8D-15 on the Boeing 727 aircraft which has a compressor resembling that of the TF30-P-3 engine. The problem experienced by the domestic operators arose as a result of the difficulty experienced in drying these particular engines after compressor washing. To minimise this problem, the engines are washed only on days when flying operations are to be undertaken.

The washing procedure now employed at the Ansett and TAA facilities is very similar and consists of straight (i.e. untreated) water washing 'on the wing' at intervals of three to four weeks. The drying procedure carried out is that where an aircraft will be operational within two hours of the washing operation, no drying of the engine is carried out other than passive drainage. Where an aircraft will be grounded for periods longer than two hours after washing, the engines are run at idle (50% max. high pressure (HP) compressor revs per minute RPM) for a few minutes. This dries the compressor but not the casing.

Parts of the JT8D-15 compressor are known to be more difficult to dry than other areas. Where air is bled from the casing, residual water is not a problem. However, in "deadheader" areas the cavities tend to retain water. The absence of drainage points from the LP compressor in the JT8D-15 engine is considered to be the major cause of problems in the LP section. The Ansett staff have found water in an engine LP compressor at overhaul two or three days after washing. This engine had between 15-20 hours flying time.

The domestic carriers do not like the use of water displacement agents in their engines. They believe that these materials can attract dirt which is subsequently difficult to move. Likewise they are reluctant to use liquid inhibiting sprays which they feel also can attract deposits. When liquid films such as these are used they are resistant to removal by water. Prior to adopting this straight water washing procedure in 1977, Ansett had a specific hot end section inspection at 6000 hours and the compressor was inspected at 8000 hours. Currently the first inspection is at 13000 hours. They report that there is little change in EGT at 13000 hours. They also report that stalling characteristics which occasionally occurred in number 2 engine have been absent since regular untreated tap water washing.

(At this time, Jan. 1986, it is intended that all F111 compressor washing will be carried out in the test cell. Any use of detergents will be followed by considerable distilled water washes and the drying time will be increased from 5 minutes to 20 minutes. Post washing engine trimming will increase this time to more than an hour).

6.4 *Discussion on Compressor Washing and Drying Procedures*

The casing around the LP compressor of the TF30 engine, like that in the JT8D-15 engine, has no drainage points. In view of the observation of residual water in this section of the casing of the JT8D-15, similar problems might be expected in the TF30-P-3 engine following compressor washing.

The corrosion pattern observed in the TF30 engine, namely of attack around the 6 o'clock areas of the outer flange, the outer surface of the shroud and the ends of the vanes where they pass through the shroud corresponds with what might be expected from residual water in the LP casing. Compressor washing with hard domestic water resulting in the formation of salt deposits on the stator vanes would further increase the corrosive action at these points on absorbing water vapor.

7. CONCLUSIONS

(1) Coating failure on the shroud and airseal displays a geometric pattern of attack. This arc of corrosion suggests the washing procedure and/or residual moisture in the compressor as a possible cause of this failure.

(2) The composition of corrosion products of the stator vanes suggests that local domestic tap water has been used in compressor washings.

(3) The relative absence of corrosion to the stator assembly under the coating suggests that the sacrificial nature of the diffused coating has been effective against corrosive attack.

(4) Corrosion under the 'rub strip' is occurring into the base metal of the shroud as sacrificial and barrier coatings are absent. It represents the most severe problem to the stage. Bond failure of the 'rub strip' is also occurring in this area.

8. RECOMMENDATIONS

(1) The above findings strongly implicate residual water as being the cause of compressor coating failure. As such, experimental techniques to determine the presence and quantity of residual water in the engine (thermohydrography, hydration of anhydrous salts, gels, etc.) would be of assistance.

(2) Practices which eliminate residual water and reduce moisture in the engine would assist. Such practices include washing prior to flying or the use of a continuous flow of ducted dry air through the engines on standing such as occurs with the AB Carl Munters system [18[used by the RAF, Swedish and Danish Air Forces.

(3) The introduction of an 'Aircraft Washing Work Card' system was recommended in the US following washing problems. These cards require personnel to tabulate information on the preparation carried out on aircraft for washing, materials to be used, the washing procedures and application of any corrosion preventive materials.

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TABLE 1

Composition of LP AMS 5504 Stator Vanes

Component	%
<Carbon	0.15
<Manganese	1.00
<Silicon	1.00
<Phosphorus	0.40
<Sulphur	0.30
Chromium	11.5-13.5

AMS 5504 = SAE 51410 = AISI 410

TABLE 2

Composition of Amberley Town Water Supply

Component	Content (ppm)	Range
Total Dissolved Solids	368	(597-158)
Chloride	105	(212-34)
Calcium	86	(126-46)
Sulphate	35	(85-17)
Sodium	46	(80-16)
Magnesium	86	(126-42)

pH 7.4

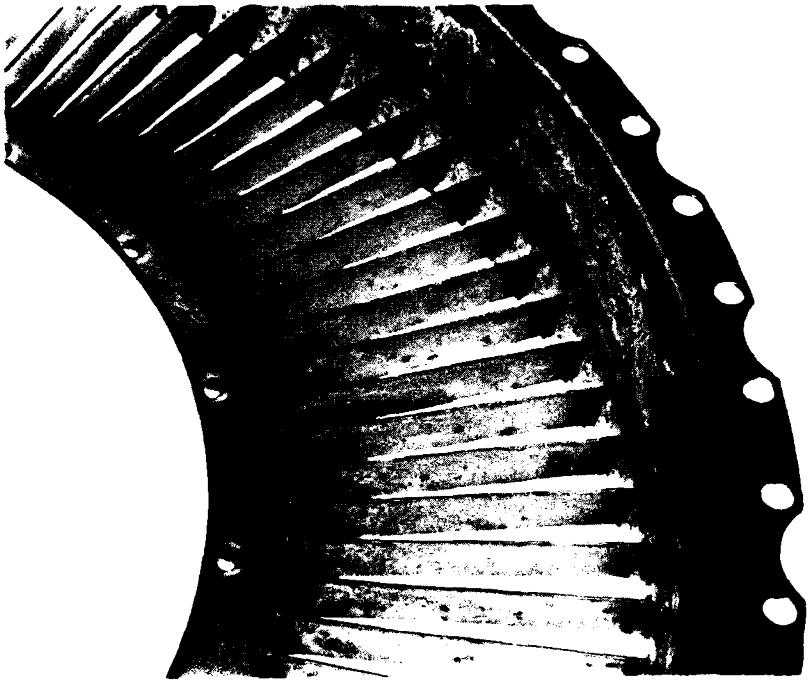

Figure 1. Section of the 7th stage of the compressor from RAAF TF30-P-3 engine after 427 h operation.

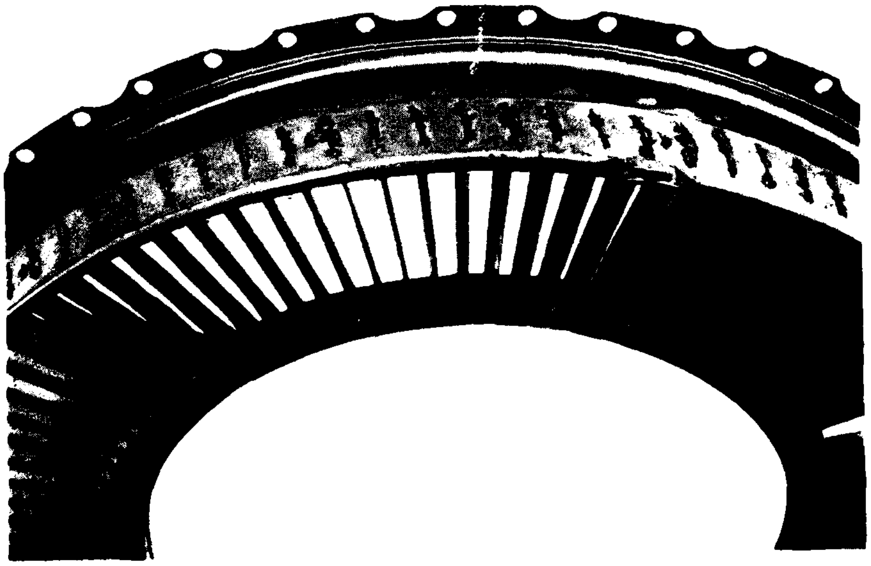

Figure 2. Coating failure and corrosion on the outer ends of the stator vanes where they pass through the shroud.

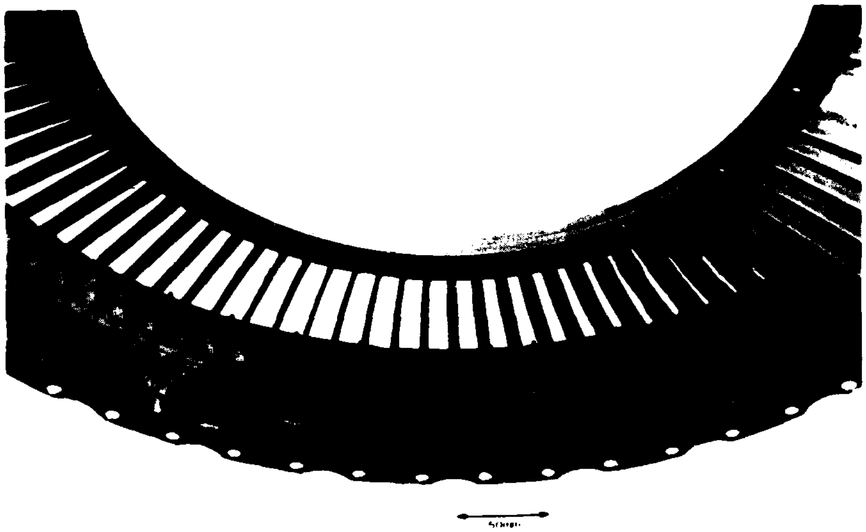

Figure 3. Failure of the rub strip and corrosion along the shroud.

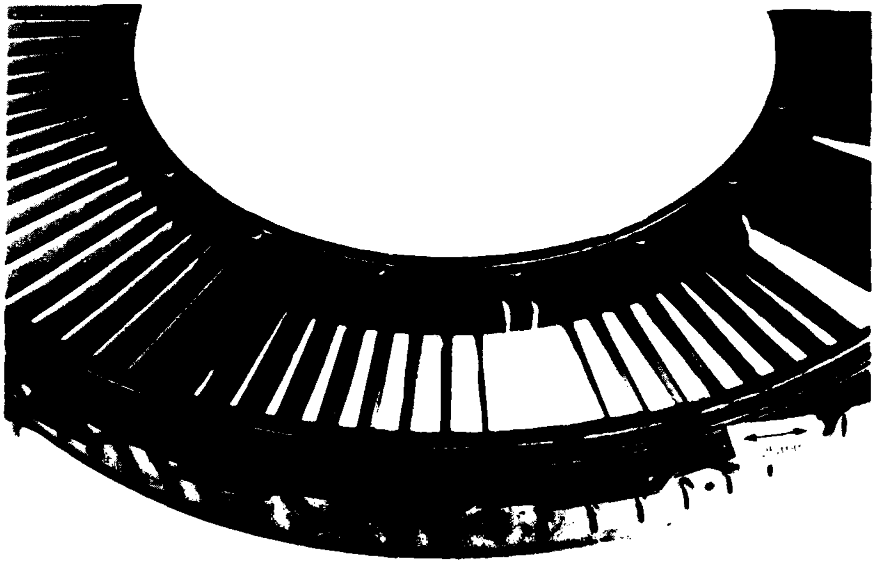

Figure 4. Coating failure along the air seal around the outside of the compressor stage.

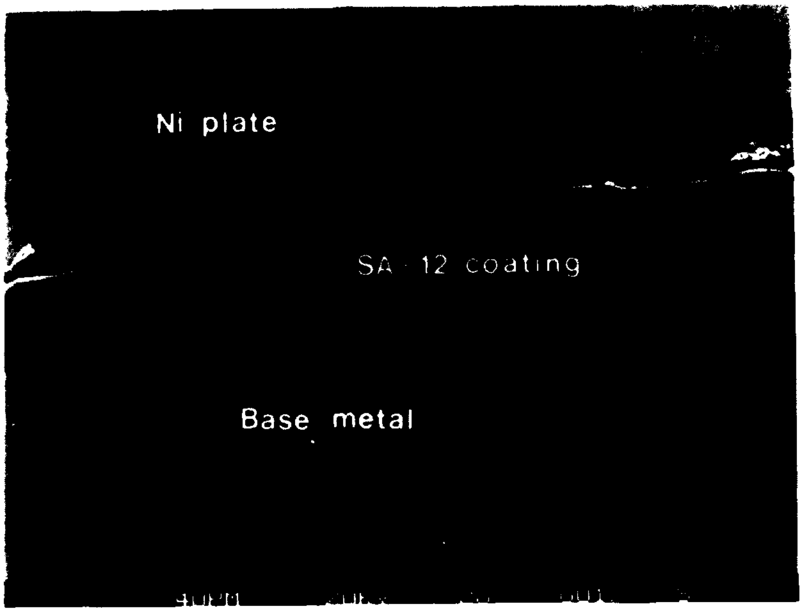

Figure 5. Scanning electron micrograph of coating section showing absence of glaze top coat.

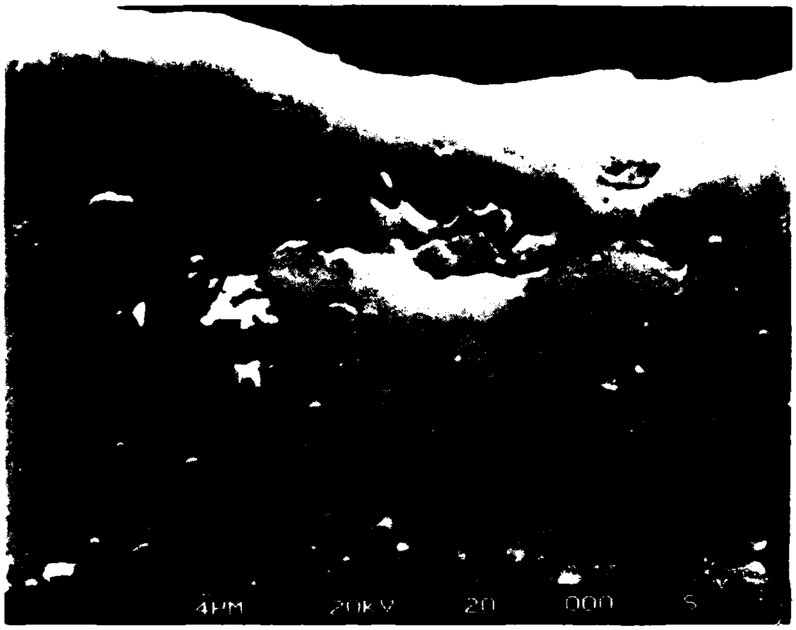

Figure 6. Scanning electron micrograph showing oxide formation and pit initiation in S-A12 coating.

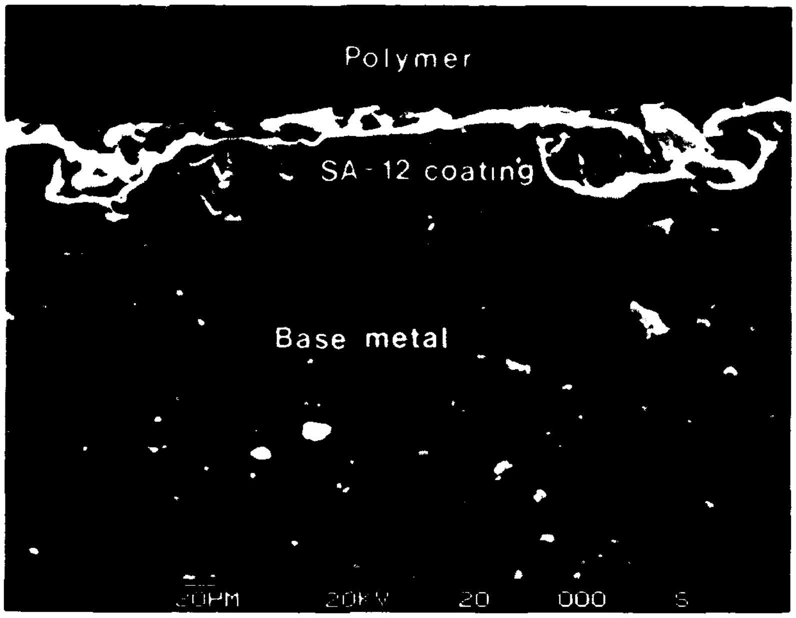

Figure 7. Scanning electron micrograph of S-A12 coating showing corroded and uncorroded areas.

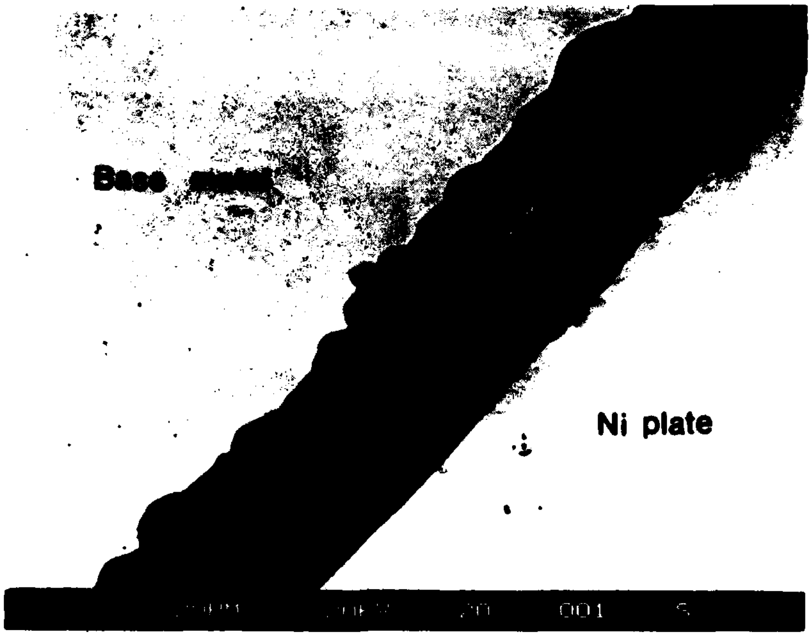

Figure 8. An oxidized section of coating which exhibited considerable pitting. Failure of the oxidized coating to stop base metal attack can be seen at one point in this scanning electron micrograph.

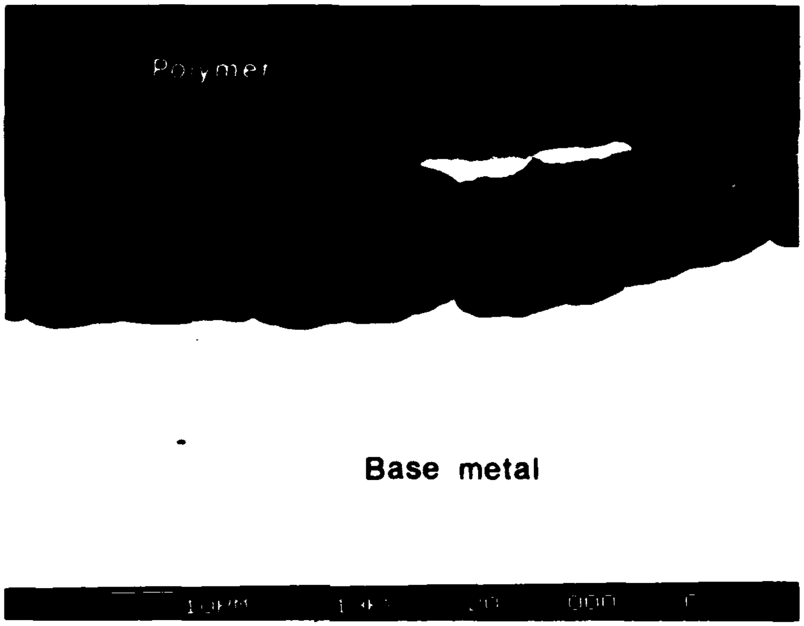

Figure 9. Occasional cracking and chipping of the coats are seen in cross sections under the scanning electron microscope.

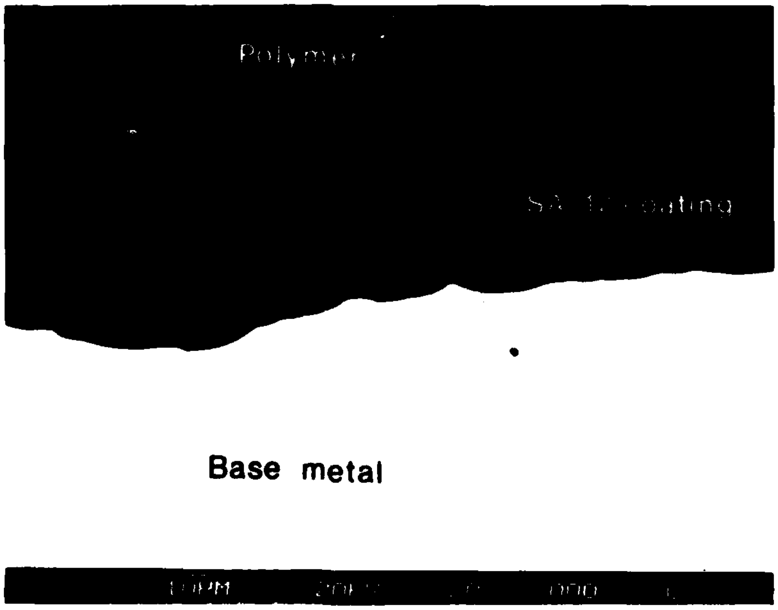

Figure 10. Scanning electron micrograph showing pinhole corrosion through the coating.

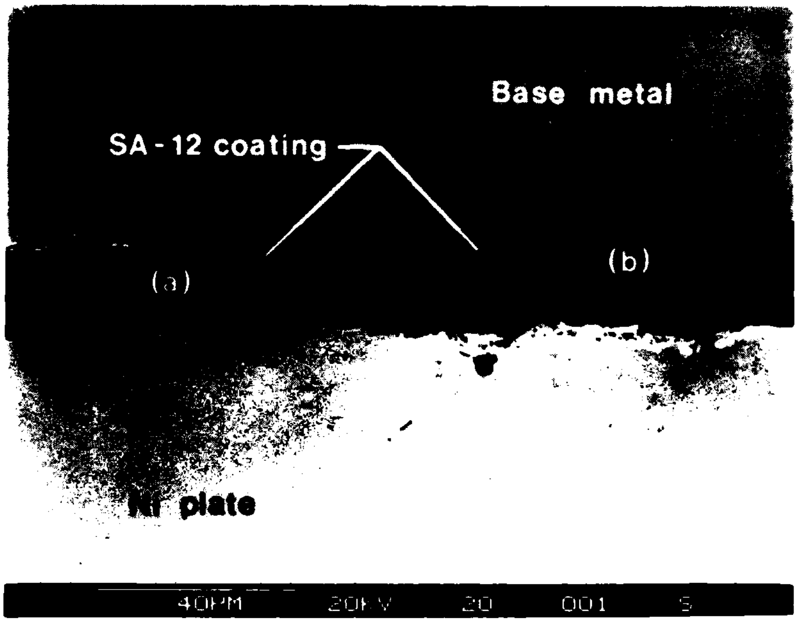

Figure 11. Scanning electron micrograph showing oxidized coating adjacent to intact coating areas.

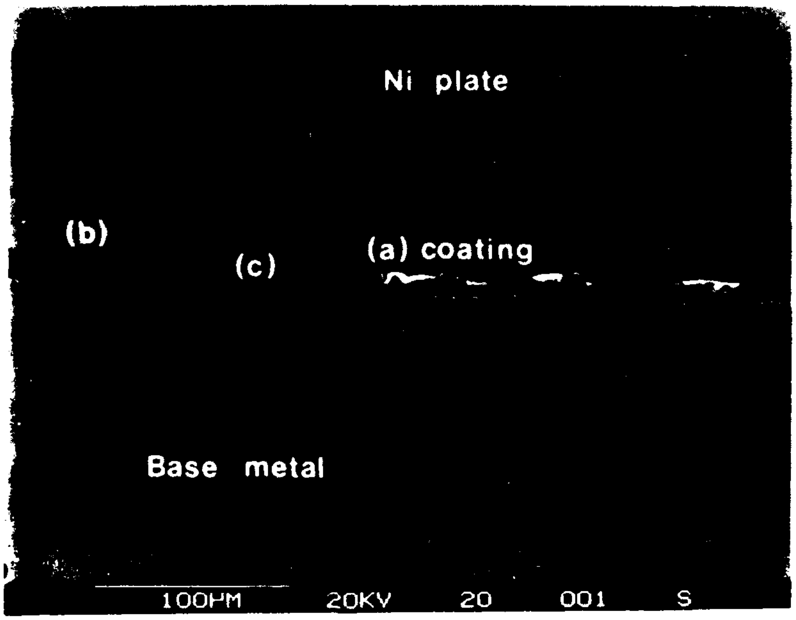

Figure 12. Scanning electron micrograph showing coating sections

(a) corroded
(b) unoxidized and
(c) detached

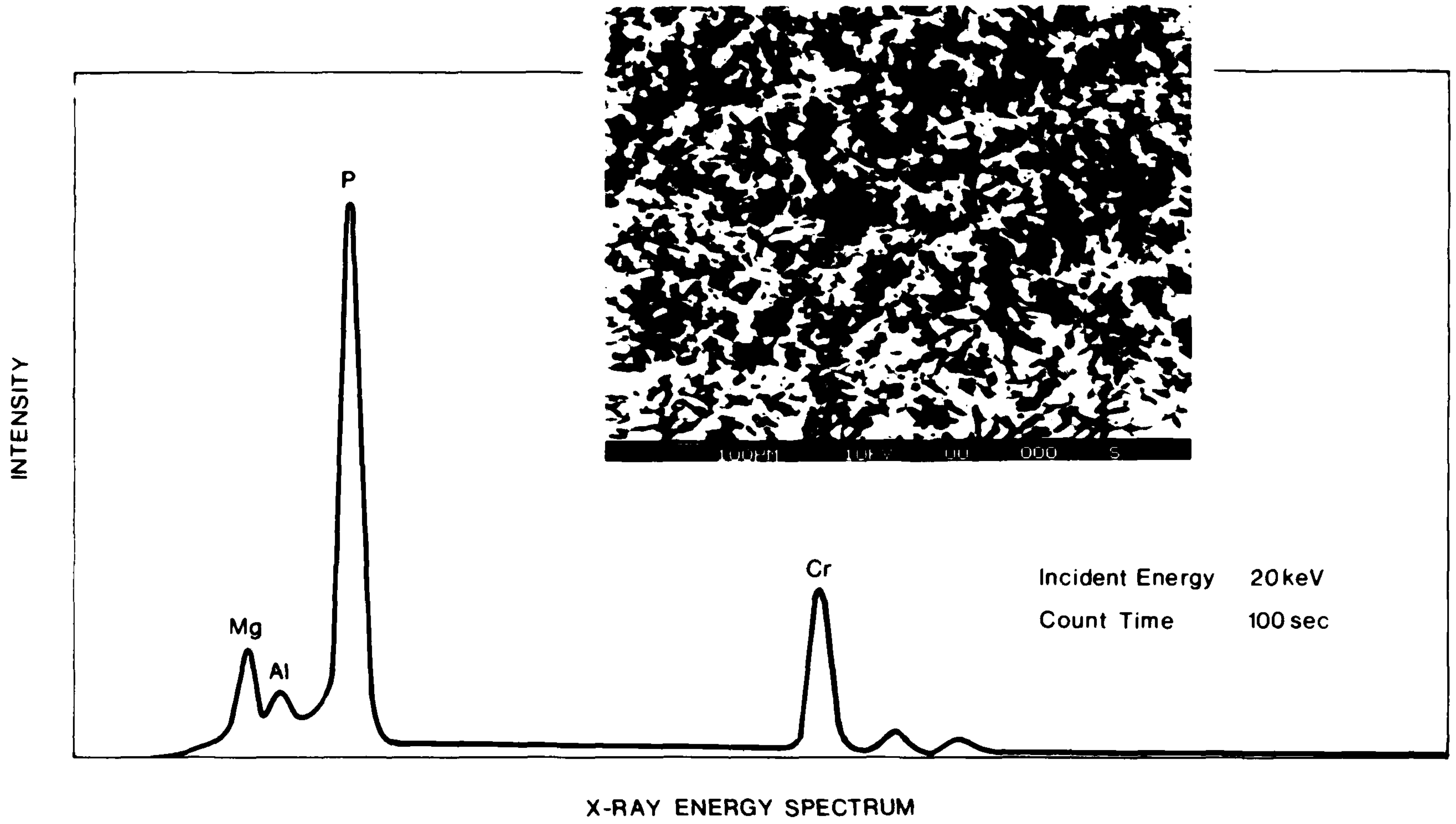

Figure 13. EDXRA surface analysis of unused blade showing the presence of the phosphate/chromate/magnesium top coat.

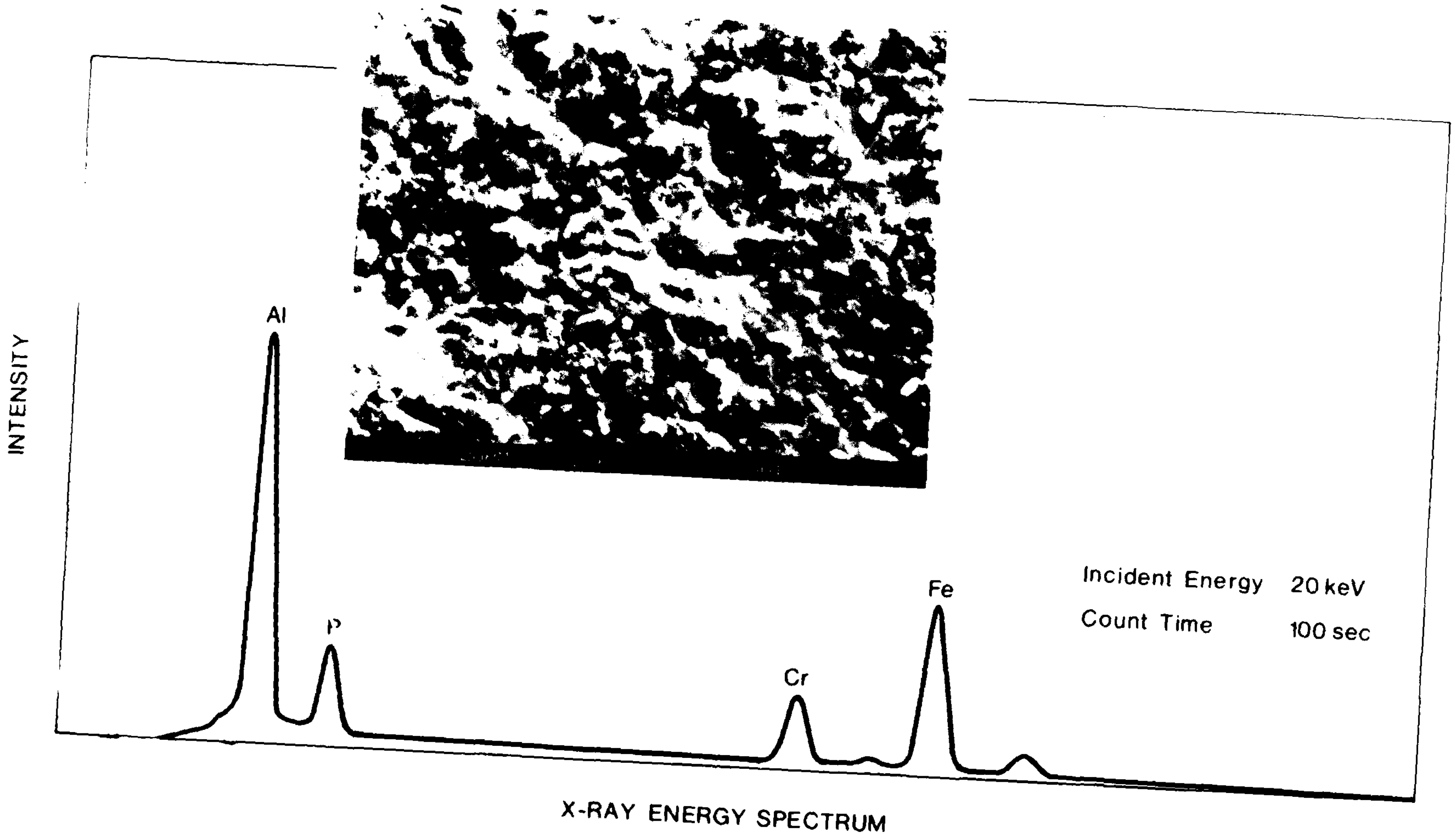

Figure 14 EDXRA surface analysis of eroded blade surface dominated by aluminide/iron components in base coat.

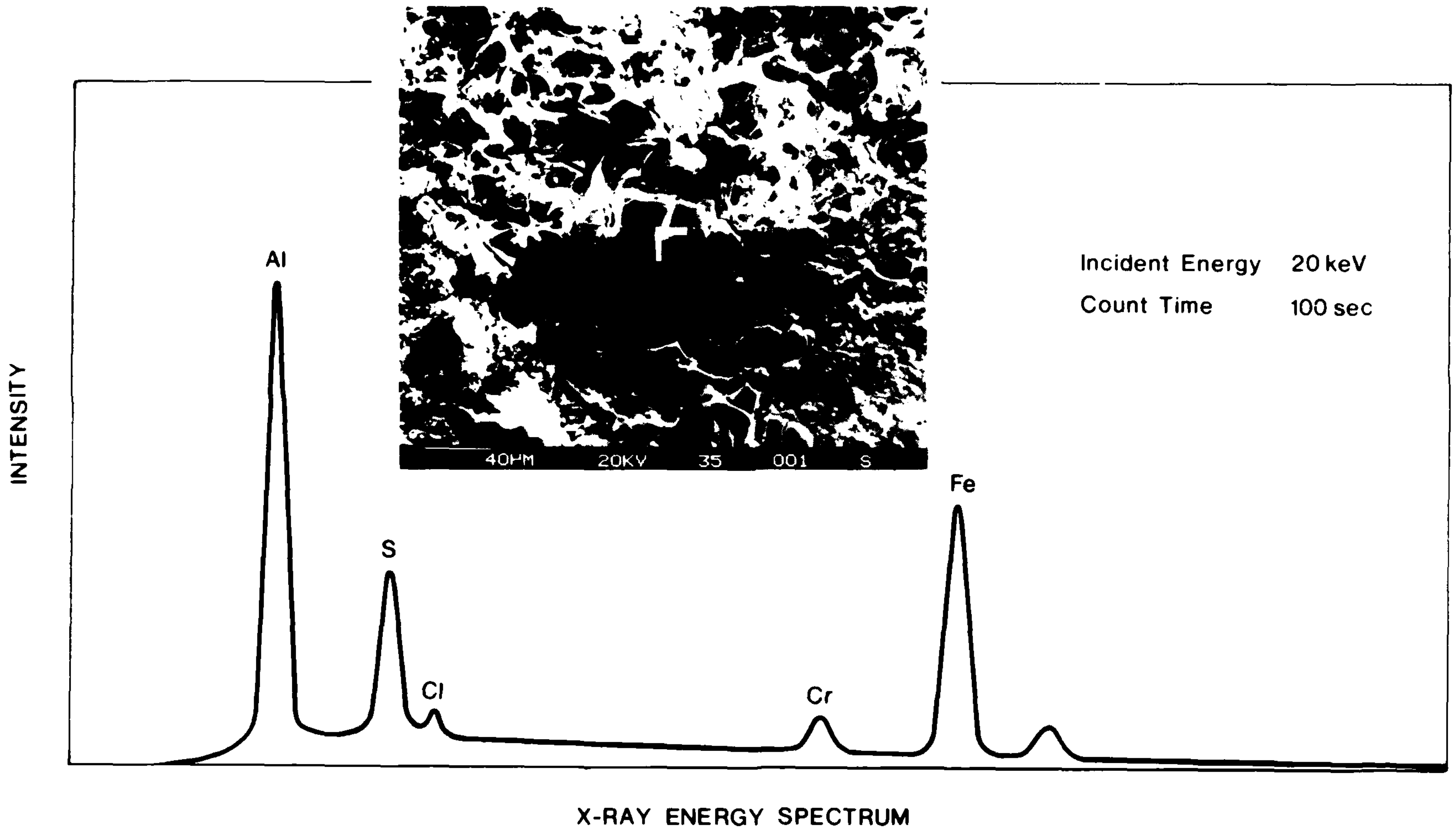

Figure 15 EDXRA surface analysis of a corrosion nodule in which high levels of sulphur materials were present

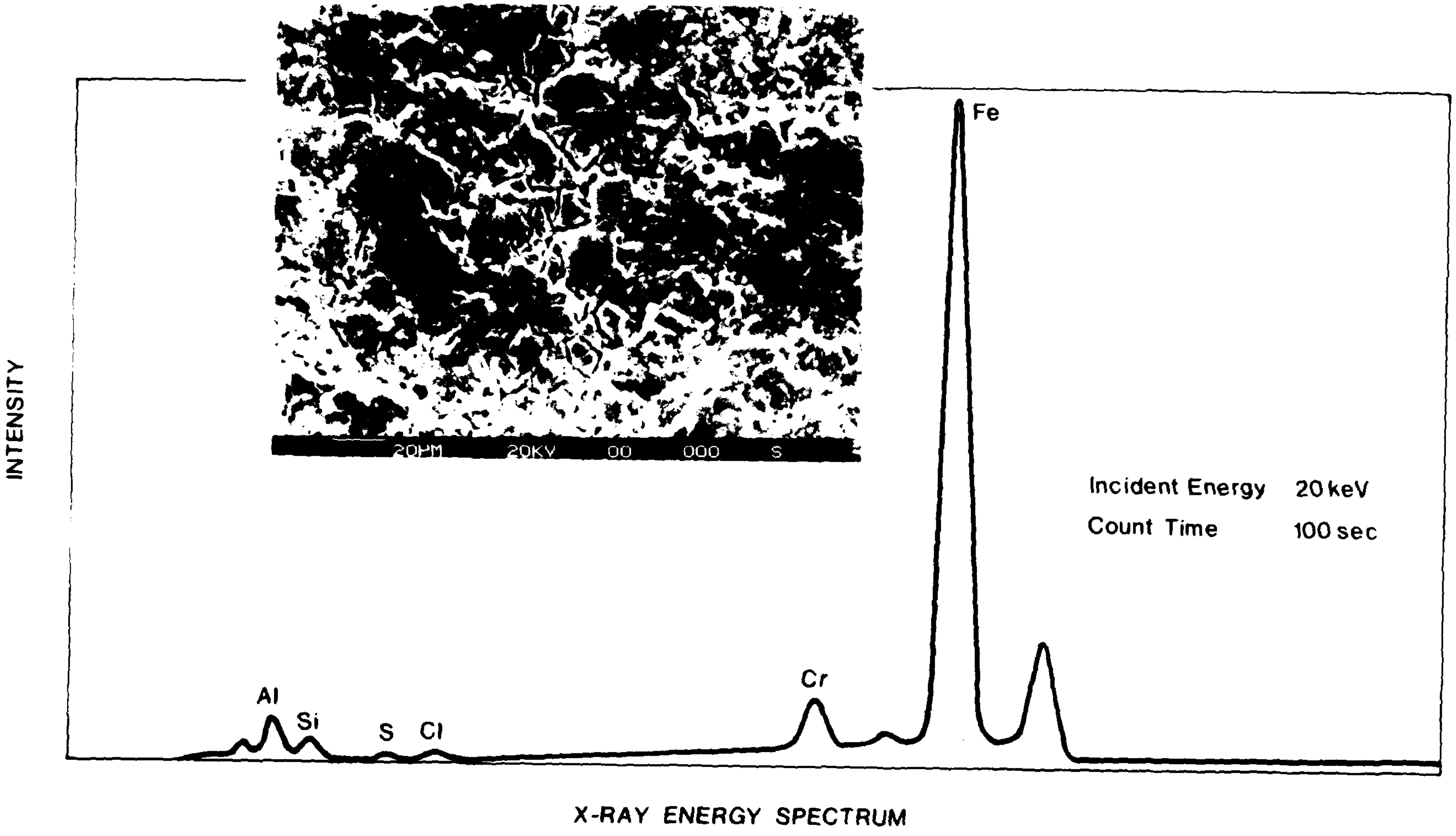

Figure 16 EDXRA surface analysis of cracked coating showing the presence of high levels of iron compounds

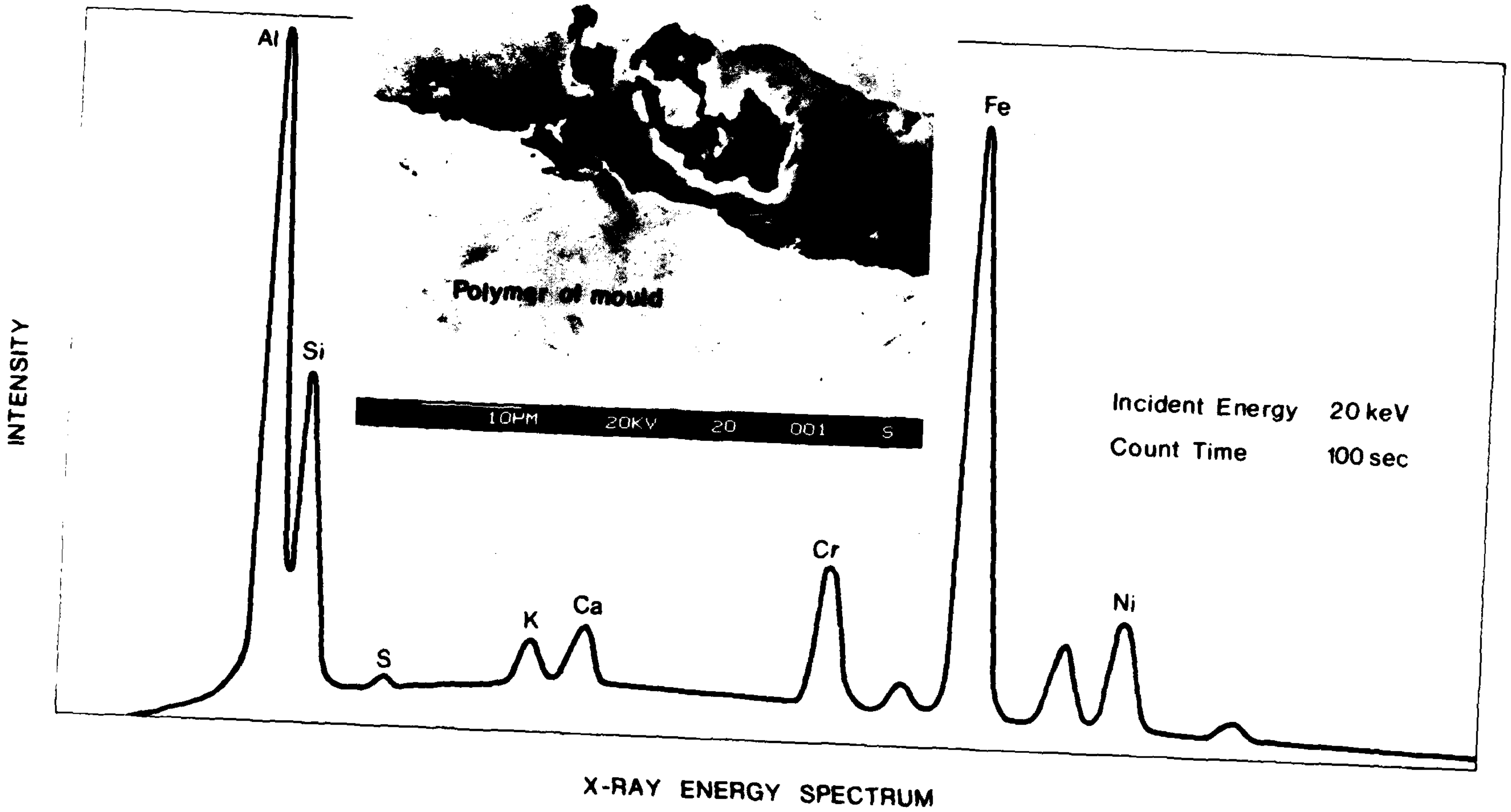

Figure 17 EDXRA of cross section through pore in coating. Calcium and potassium compounds are apparent.

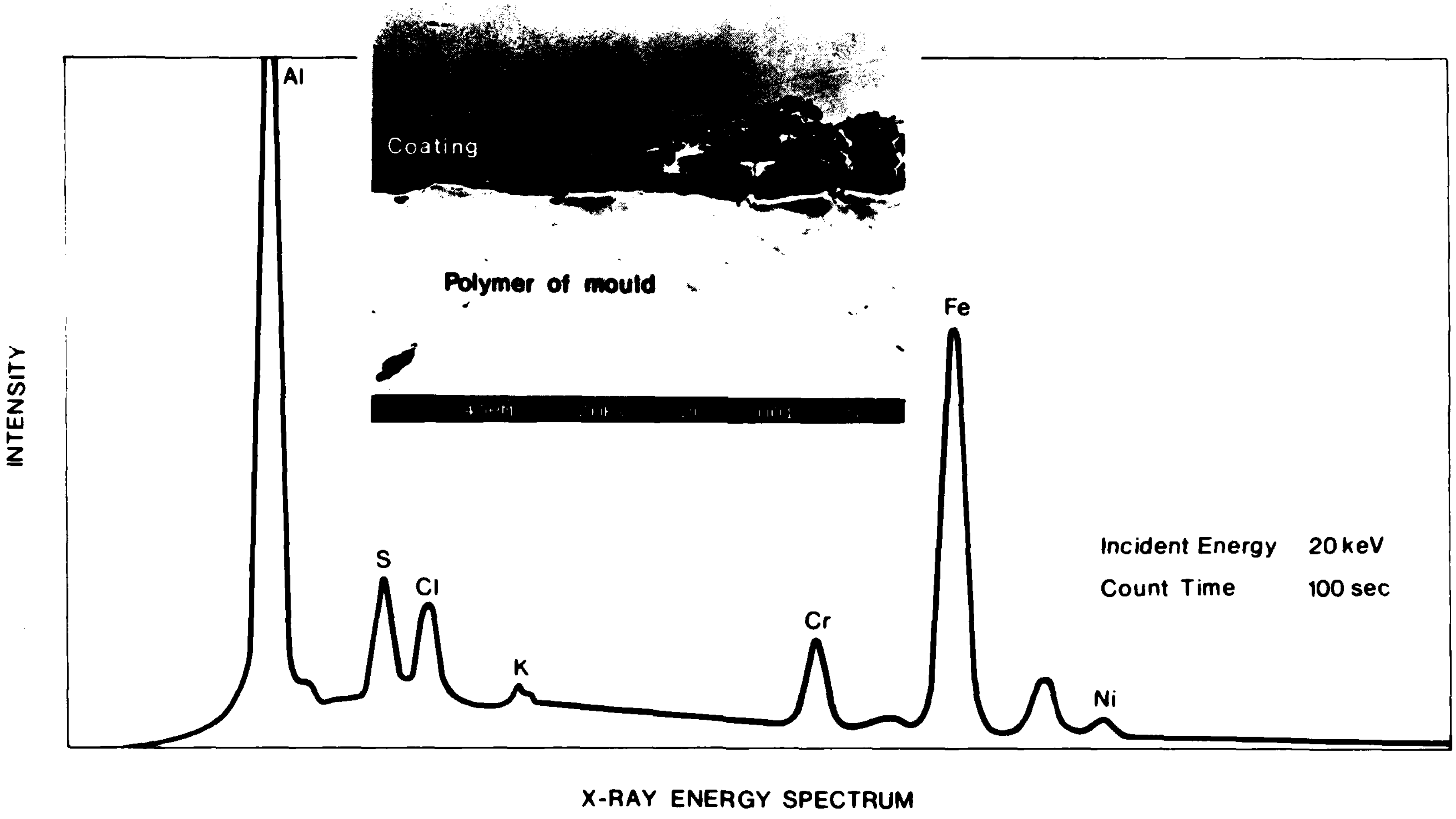

Figure 18. EDXRA of cross section through cracked and corroded coating. Sulphur and chlorine compounds are apparent. Note pitting of substrate.

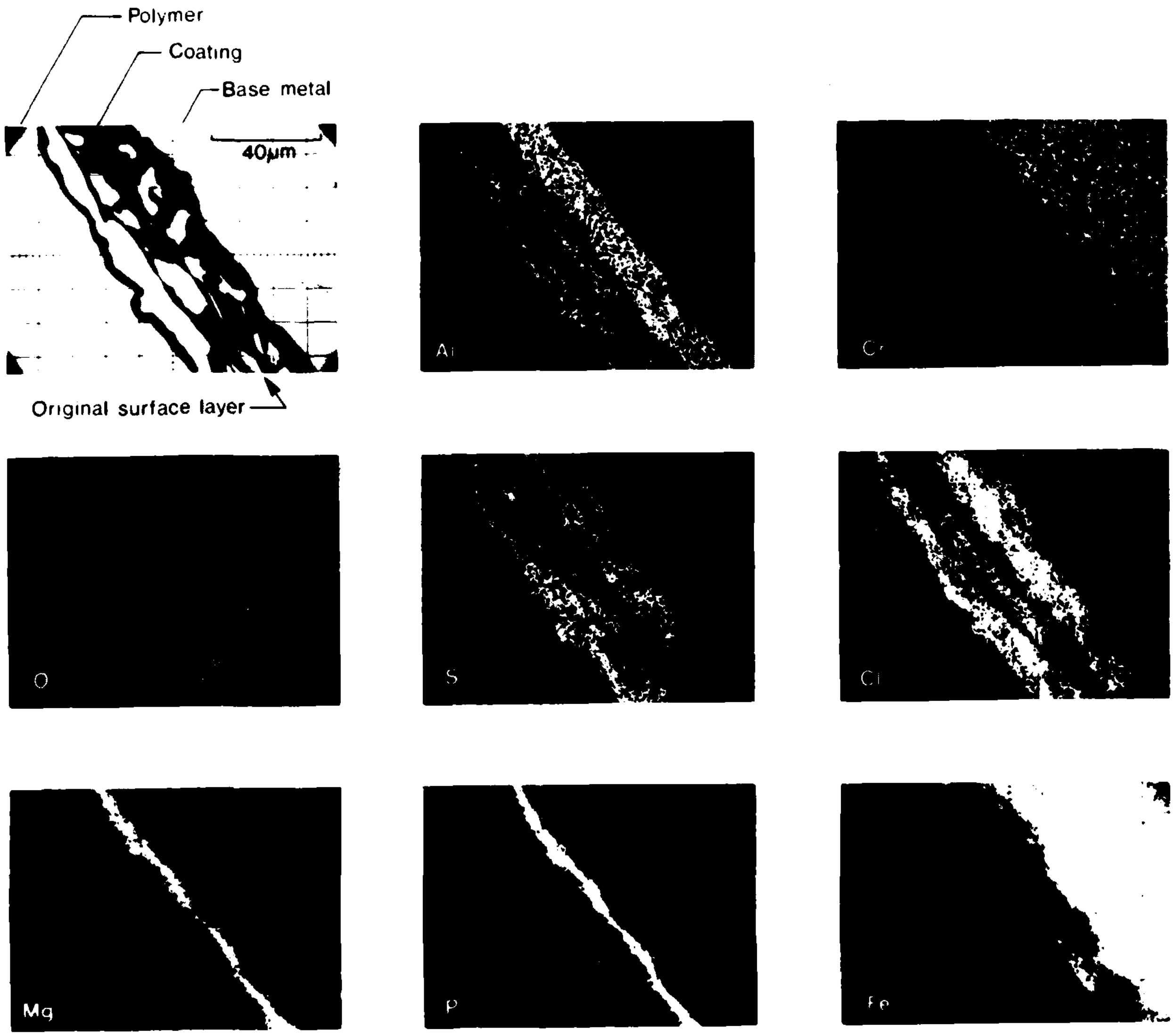

Figure 19. EPMA area scans of a degraded section of the surface coating. The corroded material lying over the original surface is composed of products rich in Al,O,Cl and S.

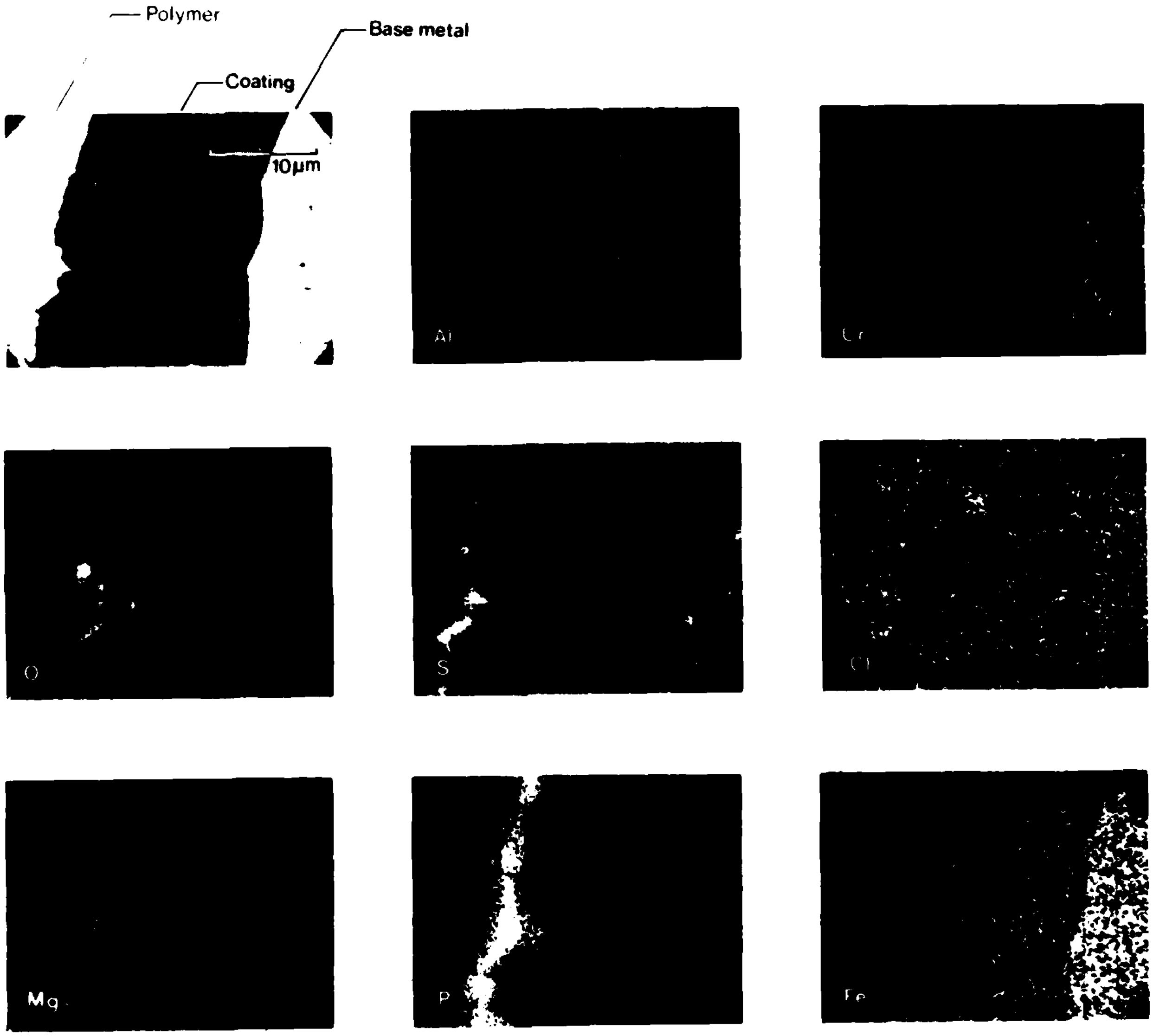

Figure 20. EPMA area scans of an oxidized crack in the surface coating.