Australian Government
Australian Transport Safety Bureau

ATSB TRANSPORT SAFETY INVESTIGATION REPORT

Aviation Safety Incident Report – 200403110

Final

Engine failure - Melbourne Airport, Victoria 25-Aug-2004

Boeing Company 777-312

9V-SYB

Australian Government

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Aviation Occurrence Report
200403110

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Abstract

At approximately 0104 Eastern Standard Time on 25 Aug 2004, the left engine surged during takeoff from Runway 34 at Melbourne Airport. The crew of the Singaporean registered Boeing 777-312 aircraft, 9V-SYB, subsequently reported that the surge occurred just at $V_{1.}$ The crew elected to continue the takeoff and the left engine surged multiple times during the departure, until they shutdown the engine. Due to forecast turbulence, the crew maintained an altitude of approximately 3,000 ft above ground level to dump fuel and reduce the aircraft's weight for landing. Air Traffic Services vectored the aircraft over Port Phillip Bay for the fuel dump, which took approximately 1 hour, before the aircraft was returned to Melbourne for an uneventful single-engine landing. There were 300 persons on board and there were no reported injuries.

An examination of the engine found that several of the High Pressure Compressor (HPC) casing liners had eroded to the point of reducing the efficiency of the HPC.

THE AUSTRALIAN TRANSPORT SAFETY BUREAU

The Australian Transport Safety Bureau (ATSB) is an operationally independent multi-modal Bureau within the Australian Government Department of Transport and Regional Services. ATSB investigations are independent of regulatory, operator or other external bodies.

The ATSB is responsible for investigating accidents and other transport safety matters involving civil aviation, marine and rail operations in Australia that fall within Commonwealth jurisdiction, as well as participating in overseas investigations involving Australian registered aircraft and ships. A primary concern is the safety of commercial transport, with particular regard to fare-paying passenger operations. Accordingly, the ATSB also conducts investigations and studies of the transport system to identify underlying factors and trends that have the potential to adversely affect safety.

The ATSB performs its functions in accordance with the provisions of the *Transport Safety Investigation Act 2003* and, where applicable, relevant international agreements. The object of a safety investigation is to determine the circumstances in order to prevent other similar events. The results of these determinations form the basis for safety action, including recommendations where necessary. As with equivalent overseas organisations, the ATSB has no power to implement its recommendations.

It is not the object of an investigation to determine blame or liability. However, it should be recognised that an investigation report must include factual material of sufficient weight to support the analysis and findings. That material will at times contain information reflecting on the performance of individuals and organisations, and how their actions may have contributed to the outcomes of the matter under investigation. At all times the ATSB endeavours to balance the use of material that could imply adverse comment with the need to properly explain what happened, and why, in a fair and unbiased manner.

Central to the ATSB’s investigation of transport safety matters is the early identification of safety issues in the transport environment. While the Bureau issues recommendations to regulatory authorities, industry, or other agencies in order to address safety issues, its preference is for organisations to make safety enhancements during the course of an investigation. The Bureau prefers to report positive safety action in its final reports rather than making formal recommendations. Recommendations may be issued in conjunction with ATSB reports or independently. A safety issue may lead to a number of similar recommendations, each issued to a different agency.

The ATSB does not have the resources to carry out a full cost-benefit analysis of each safety recommendation. The cost of a recommendation must be balanced against its benefits to safety, and transport safety involves the whole community. Such analysis is a matter for the body to which the recommendation is addressed (for example, the relevant regulatory authority in aviation, marine or rail in consultation with the industry).

EXECUTIVE SUMMARY

At approximately 0104 Eastern Standard Time on 25 Aug 2004, the left engine surged during takeoff from Runway 34 at Melbourne Airport. The crew of the Singaporean registered Boeing 777-312 aircraft, 9V-SYB, subsequently reported that the surge occurred just at V_1[1]. The crew elected to continue the takeoff and the left engine surged multiple times during the departure, until they shutdown the engine. Due to forecast turbulence, the crew maintained an altitude of approximately 3,000 ft above ground level to dump fuel and reduce the aircraft's weight for landing. Air Traffic Services vectored the aircraft over Port Phillip Bay for the fuel dump, which took approximately 1 hour, before the aircraft was returned to Melbourne for an uneventful single-engine landing. There were 300 persons on board and there were no reported injuries.

An examination of the engine found that several of the High Pressure Compressor (HPC) casing liners had eroded to the point of reducing the efficiency of the HPC.

As a result of the occurrence, the engine manufacturer has taken a number of steps to identify this failure mode during engine trend monitoring in order to reduce the likelihood of a recurrence.

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[1] V_1 is the take-off decision point at which, should the critical engine fail, the pilot can elect to abandon the takeoff.

FACTUAL INFORMATION

History of the flight

At approximately 0104 Eastern Standard Time, on 25 Aug 2004, the left engine surged during takeoff from Runway 34 at Melbourne Airport. The crew of the Singaporean registered Boeing 777-312 aircraft, 9V-SYB, subsequently reported that the surge occurred just at V_1[2]. The crew elected to continue the takeoff and the left engine surged multiple times during the departure, until they shutdown the engine. Melbourne Airport officers reported an amount of debris on Runway 34.

Due to forecast turbulence, the crew maintained an altitude of approximately 3,000 ft above ground level to dump fuel and reduce the aircraft weight for landing. Air Traffic Services vectored the aircraft over Port Phillip Bay for the fuel dump, which took approximately 1 hour before the aircraft was returned to Melbourne for an uneventful single-engine landing. There were 300 persons on board and there were no reported injuries.

The Australian Transport Safety Bureau (ATSB) dispatched an investigation team to Melbourne to examine the aircraft, where no obvious external damage was evident (Figure 1). The ATSB examination revealed that one of the left engine's composite core panels had broken and separated from the engine during the engine surge (Figure 2). The left engine, a Rolls-Royce Trent 800, Serial number 51067, exhibited only minor damage to a number of components. A borescope inspection of the engine compressor section revealed no significant anomalies with the engine compressor or turbine rotors or stators.

Figure 1: Trent 800 engine S/No. 51067 fitted to the left position of 9V-SYB

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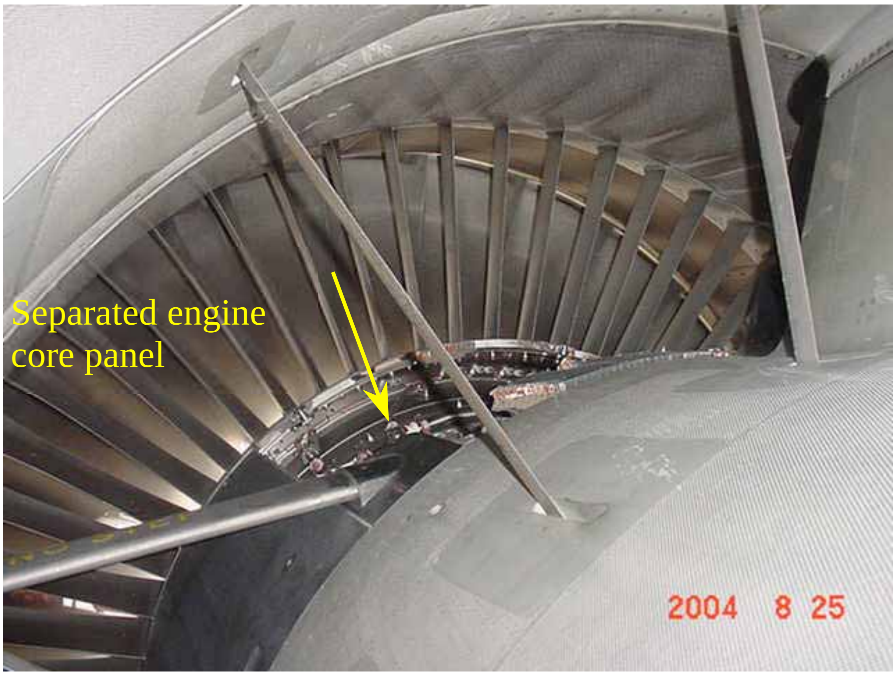
[2] V_1 is the take-off decision point at which, should the critical engine fail, the pilot can elect to abandon the takeoff.

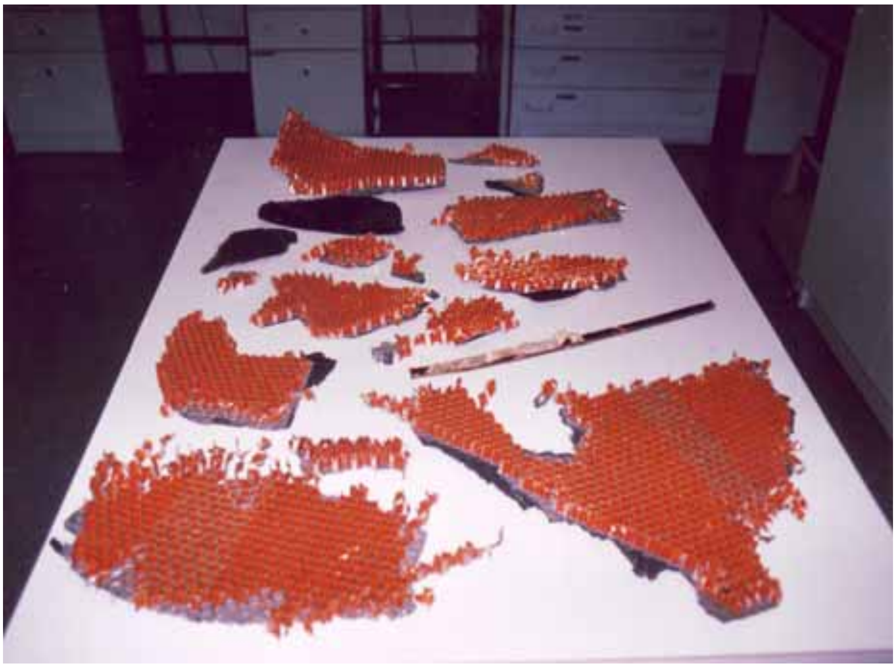
Figure 2: Separated composite engine core panel in cold stream duct



Damage to aircraft

An amount of debris was liberated from the separated left engine core composite panel and was recovered from the departure runway (Figure 3).

Figure 3: Composite panel remnants recovered from runway



Aircraft Information

Manufacturer	Boeing Company
Model	777-312
Serial number	28516
Registration	9V-SYB
Year of manufacture	1998

Left Engine Information

Manufacturer	Rolls-Royce Pty Ltd.
Model	Trent 800
Serial number	51067
Total time in service	15,614 Hrs
Cycles in service	4,527
Time since last repair	2,256 Hrs
Cycles since last repair	614
Date of last rework	Feb 2004
Date fitted to 9V-SYB	Feb 2004

Recorded Flight Information

The aircraft was fitted with both a solid state flight data recorder (FDR) and cockpit voice recorder (CVR). It was also equipped with an optical Quick Access Recorder (QAR). All recording devices were removed from the aircraft and forwarded to the ATSB to download the recorded information. The downloaded information was of good quality and indicated the following:

- During the takeoff roll, a loud bang was recorded on the CVR. This bang occurred 0.8 seconds before the automatic V_1 annunciation. Over the next 70 seconds, before the engine was shutdown, 57 bangs were audible on the CVR recording.
- At the time of the initial engine surge, the left engine N_1 values[3] decreased while the N_2 and N_3 values showed uncommanded increases.
- The maximum turbine gas temperature recorded for the left engine during the event was 910 degrees C.

A plot of the significant recorded left engine data is reproduced as Figure 15 on page 34 of Appendix A.

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[3] N values refer to the compressor rotating speeds. N_1 represents the Low Pressure compressor, N_2 represents the Intermediate Pressure compressor and N_3 the High Pressure compressor.

Left engine examination

The left engine was shipped to a joint engine overhaul facility in Singapore for detailed examination, supervised by investigators from the ATSB and the Air Accident Investigation Bureau of Singapore.

The engine examination revealed that the high pressure compressor (HPC) casing abradable linings had deteriorated in service. There was a visible loss of abradable rotor lining on several of the HPC compressor casings (Figures 4 and 5). The engine manufacturer advised that the HPC stage-6 casing-to-rotor clearance was critical to engine airflow control at the take-off thrust setting.

Figure 4: HPC stage 6 casing and liner assembly

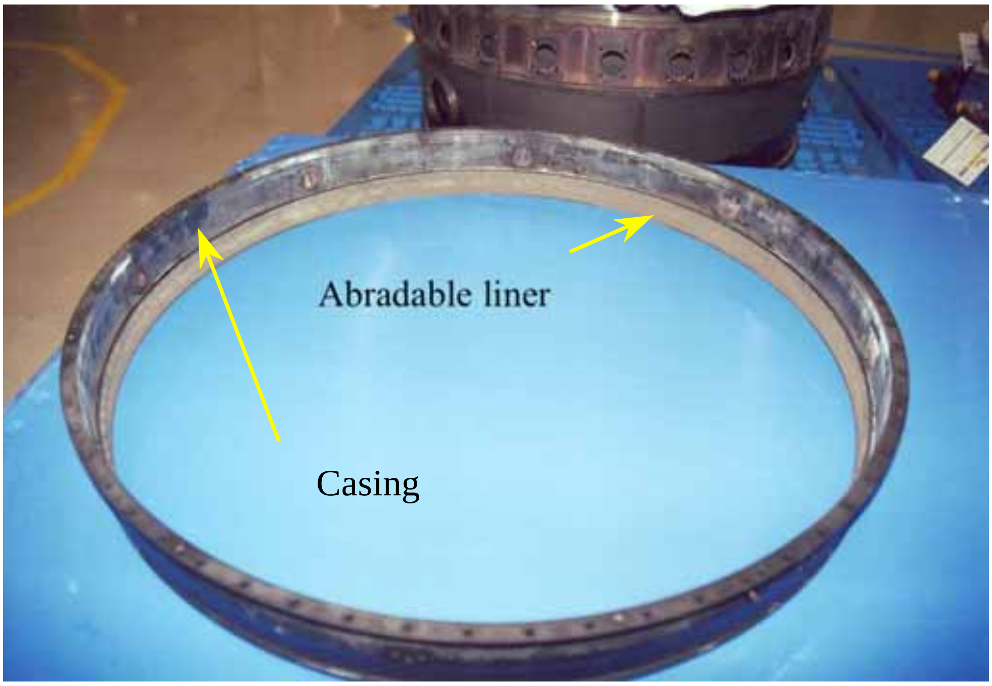
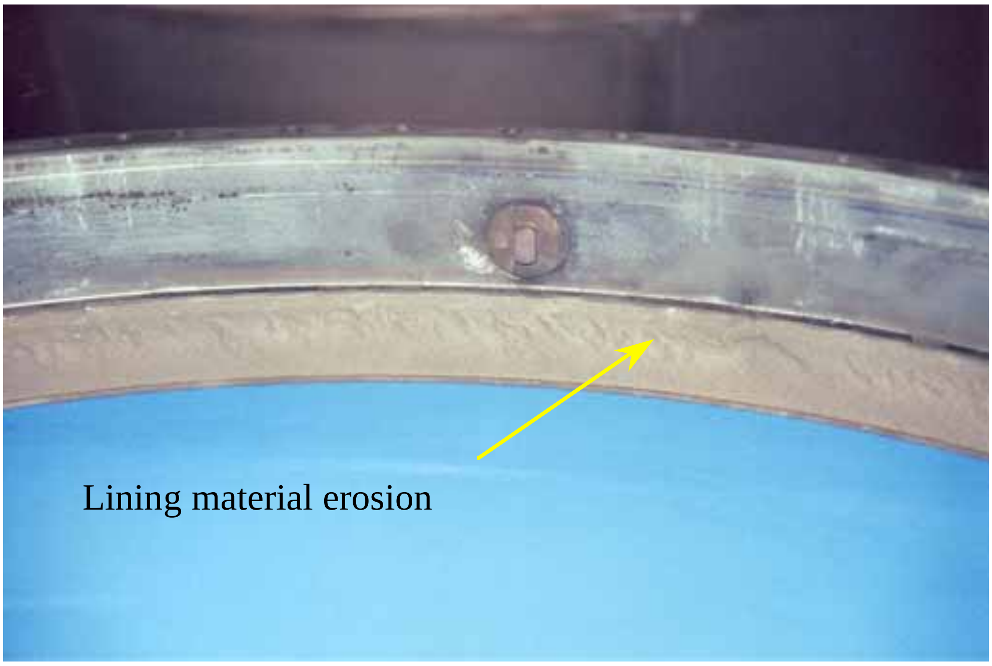


Figure 5: Detail of HPC stage 6 casing abradable liner erosion



Casing liner examination

All six HPC stage casings were sent to the engine manufacturer, Rolls-Royce in Derby, United Kingdom (UK), for examination, under the supervision of an investigator from the UK Air Accidents Investigation Branch. A copy of the detailed liner examination by Rolls-Royce is contained in Appendix A. The contractor responsible for the application of the lining material to a number of the casing liners, Praxair Surface Technologies, submitted a separate report to the ATSB based on their own examinations. A copy of that report is contained in Appendix B.

Engine health monitoring

Prior to this incident on 25 Aug 2004, the engine manufacturer had been monitoring the in-service health of Trent-800 engines. On 4 August 2004, an Engine Health Monitoring (EHM) alert was issued to the aircraft operator due to the identification of a step change in the engine's Turbine Gas Temperature (TGT) margin. As a result of this alert, the aircraft operator conducted the required engine inspection, including a borescope inspection of the HPC. Only minor damage, within acceptable limits, was noted to a small number of the stage-6 HPC blades, and the engine was returned to service. The borescope inspection only permitted limited examination of the HPC casing liner material in the immediate vicinity of the borescope inspection port.

Following this incident, the engine manufacturer conducted a review of other potentially affected engines with deteriorating HPC efficiency. That review found that two other Trent-800 engines exhibited performance degradation due to erosion of their HPC linings and both engines were removed from service.

Failed composite panel examination

An examination of the separated engine core composite panel indicated that all the panel fasteners were retained in their mounts after the panel failed (Figure 6). One fastener hole showed signs of wear, but there was no direct evidence to suggest that the fitting was loose at the time of the failure (Figure 7). It was apparent from wear in the fastener fitting that it may have been loose previously, and that this looseness may have contributed to some prior weakening of the panel structure, which contributed to the panel failure during the engine surge event.

Figure 6: Typical composite panel failure around mounting point

Figure 7: Elongated fastener hole showing signs of wear

ANALYSIS

The left engine surged at V_1 during takeoff from Melbourne Airport. The actions by the crew to continue the takeoff were appropriate for the circumstances and ensured a successful, single-engine, return to the airport.

The engine surge was as a direct result of a breakdown of the airflow within in the engine High Pressure Compressor (HPC). Directly contributing to that condition was a reduction in the HPC efficiency associated with the erosion and loss of HPC casing lining material, particularly at the rear stages of the HPC. The stage-6 lining material loss resulted in increased rotor tip clearances. The stage-6 lining material loss was the most critical stage for airflow control through the HPC during the takeoff.

The loss of HPC casing lining material was discussed in both the engine manufacturer and the sprayed coating contractors' reports (Appendixes A and B). As a result of the differing views presented in each report, the Australian Transport Safety Bureau (ATSB) conducted a review of both reports to determine the likely factors associated with lining material loss from the HPC casings. That review is included as Appendix C.

The ATSB review concluded that the coating quality issues were the most probable factor contributing to the premature degradation of the HPC casing lining leading to the engine surge. While acknowledging the possibility that oxidation may have weakened the coating particle cohesive strength, the significance of this effect had not been quantified in respect of the performance of the lining in service. Other proposed contributors such as Calcia-Magnesia-Aluminia-Silica (CMAS) ingestion, extended operation at elevated temperatures and the effects of thermal cycling were not substantiated by evidence. Similar casing liner issues were also apparent in all the other HPC casing liner stages in the engine.

If a step change was noted in the engine Turbine Gas Temperature (TGT) margin, the Engine Health Monitoring (EHM) program of the Trent-800 engines required a visual inspection of the HPC. However, this inspection was limited to examining the condition of the HPC compressor blades and was not capable of determining the extent of any deterioration of the HPC casing lining material.

The failed engine core composite panel was secondary to the engine surge event and did not contribute to the engine failure.

FINDINGS

Contributing factors

- The left engine surged during takeoff.
- The left engine High Pressure Compressor (HPC) casing liners exhibited lining material loss.
- The left engine HPC stage-6 casing lining material was eroded, increasing the rotor tip clearance and reducing the efficiency of the stage at take-off thrust.

Other safety factors

- The Engine Health Monitoring procedures detected the deterioration of the efficiency of the HPC, however the subsequent inspection requirements were unable to detect any deterioration of HPC lining material.

SAFETY ACTION

Engine manufacturer

As a result of this occurrence, the engine manufacturer, Rolls-Royce UK, advised the Australian Transport Safety Bureau that they have taken the following actions:

> Two engines that were identified as being at risk of surging due to degraded High Pressure Compressor (HPC) efficiency were removed from service.
>
> The Engine Health Monitoring (EHM) procedures have been changed. If an EHM alert is issued and troubleshooting reveals no findings to explain the observed change, the engine manufacturer will review engine parameter data in more detail. This may lead to a recommendation that the engine is removed from service.
>
> The aircraft maintenance manual will be updated to include an inspection check of the condition of the rotor path lining immediately adjacent to the borescope port hole and to contact the engine manufacturer if no evidence of lining loss.
>
> The engine manufacturer has also developed an algorithm to alert changes of HPC efficiency as part of the suite of automatically generated alerts produced for engine health monitoring purposes.

APPENDIX A – ROLLS-ROYCE SERVICE COMPONENT INVESTIGATION REPORT

REPORT NO: SCIR 64628 Iss 3

ISSUED BY
ROLLS ROYCE PLC
SERVICE ENGINEERING

SERVICE COMPONENT INVESTIGATION REPORT

OPERATOR : SINGAPORE AIRLINES	ENGINE TYPE : TRENT
SUBJECT: ESN51067 – HP Compressor Lining Loss Investigation	

ENGINE/MODULE DETAILS			PART DETAILS	
ENGINE MARK	TRENT 800		ATA REF	72-41-41
ENGINE NO	51067		MOD STD	SEE PAGE 2
MODULE NO	FM9795		PART NO	SEE PAGE 2
REMOVAL DATE	25 AUG 04		SERIAL NO	NA
AIRCRAFT/POSITION	9V-SYB POS 1		MATERIAL	SEE PAGE 2
LIFE :	ENGINE	MODULE	LIFE :	
TSN	15614	17488	TSN	SEE PAGE 2
CSN	4527	4935	CSN	SEE PAGE 2
TSR	2256	2256	TSR	SEE PAGE 2
CSR	614	614	CSR	SEE PAGE 2

REFERENCES		PART CONDITION	
MRA	SPIN PS 7609	SERVICEABLE (Subject to inspection)	
RECEIPT DATE	28 SEPT 04	REPAIRABLE	SEE PAGE 2
RECEIVED FROM	company A	SCRAP	SEE PAGE 2
REPORT REF	MFR43255	RETURN TO OPERATOR	

	NAME	SIGNATURE	DATE
COMPILED	Roll-Royce plc	On file	3rd April 2006
APPROVED	Roll-Royce plc	On file	3rd April 2006

Internal Circulation -

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1.0 INTRODUCTION

1.1 INITIAL ISSUE

Data Systems and Solutions (DS&S) issued an alert for 51067 on 04 August 2004 following a step change in TGT margin. Trouble-shooting was carried out on the engine in accordance with the aircraft maintenance manual (AMM). No anomalies were reported (note: inspection of the rotor path linings is only possible to a very limited extent) and the engine was allowed to remain in service.

On 25 August 2004 the engine surged just before V1, after rotation and during climb out of Melbourne. The engine was shut down and an air turn-back was performed after dumping fuel. As a consequence, this event became the subject of an investigation by the Australian Transport Safety Board (ATSB).

The ATSB requested that a borescope inspection of the HP compressor and HP turbine blades be carried out. A visual inspection of the VSV stage 1 and 2 levers was also requested. The borescope inspection revealed very minor leading edge damage to a small number of HPC stage 6 blades. All VSV levers were intact but upon opening up the ‘C’ ducts, it was revealed that the left hand upper composite fairing had released from it’s fixing points. The ATSB are carrying out their own investigation on the fairing.

The engine was stripped and examined at an appropriate overhaul base (company A). Strip of the 04 module revealed visible lining loss on all six stages of the HP compressor. The lining loss was severe at the rear stages. The casings were returned to R-R, Derby for investigation. This report details the examination findings.

The engine had been refurbished at an overhaul base in 2003 using a new HP compressor stage 1 casing and re-lined HP compressor stage 2 to 6. The stage 2 to 6 casings had been re-lined during October 2003 by the overhaul bases sub contractor (company B), based at the overhaul facility.

1.2 ISSUE 2

Since the initial issue of this report, it has been established that incorrect quality control (QC) samples were supplied to, and therefore investigated by, Rolls-Royce. ESNs 51067 and 51092 had both previously been into an overhaul base in May 2002. The HP compressor casings from 51092 were relined by company B and fitted into 51067 at that shop visit.

Company B record the ESN for which the casings have been removed, therefore, the correct QC samples to support the investigation were those identified as ‘51092’ not ‘51067’.

COMPANY C carried out an investigation on the following:

1. A section of the HP compressor stage 6 casing from 51067 supplied by Rolls-Royce and the correct QC samples

2. The HP compressor stage 6 casing and QC samples from 51363 (another lining loss casing re-lined by company B).

On completion of their investigation, company C sent the correct QC samples to Rolls-Royce for investigation.

Company C has now issued their own report (ref Technical Note No.05-14), which concurs with the Rolls-Royce investigation findings but suggests that the lining loss erosion has been caused by a different mechanism.

Issue 2 of this report includes an addendum, which summarises the company C investigation findings and states the Rolls-Royce investigation findings on the correct QC samples. It also provides the supporting evidence for rejecting company C's theory as to the cause of the lining loss.

1.3 ISSUE 3

Since issue 2 of this report company C have issued an addendum to company C Technical Note 05-14. The company C addendum states the following:

"Despite the evidence for erosion in service, the specification for the acceptable quality of the coating contains no evaluation for erosion' and the current R-R specification for the LCA-314 coatings is not adequate to insure the desired erosion resistance that the coating may experience in some service exposures.

Company C suggested a particle erosion test or a tensile bond test should be considered. The bond test would give the average adhesion strength between particles within the coating. This 3-way analysis of the quality panels would thus verify acceptable hardness and metal content and particle adhesion strength of the coating"

Issue 3 of this SCIR contains an additional addendum (see addendum 2), to address the erroneous elements of these statements.

2.0 CONCLUSIONS

- The engine surged approx 33 seconds after applying max take-off power, at a pinch point where HP compressor blade tip clearances are at their largest.
- The core fairing release was secondary to the core surge.
- The engine surged due to large rotor blade tip clearances, as a result of the lining loss at the rear stages of the HP compressor. The rear stages of the HP compressor are the controlling stages for operability at high power.
- The stage 1 Sherritt Gordon coating microstructure was satisfactory. Sherritt Gordon can suffer from age softening and thermal fatigue, leading to lining loss.
- HPC stages 2 to 6 all showed greater Metco 314 abradable loss than would normally be encountered. The stages 4 and 5 linings suffered almost total abradable loss down to the bondcoat and stage 6 suffered major loss in patches down to the bondcoat.
- The Metco 314 abradable coating on Stage 6 had a metal content of 29% compared to the guideline figure of 40% given in the R-R quality standard for sprayed coatings. Consequently there would be a higher proportion of bentonite and porosity than the guideline figure. There were also a higher number of particles than desirable, which had not been fully melted.
- There was insufficient abradable coating remaining on stages 4 and 5 to allow any definitive statements to be made but the coatings showed similar features to the coating on stage 6.
- Metco 314 coating loss occurred progressively by an erosion mechanism. This mechanism is considered to be attributable to the microstructure of the Metco 314, which caused it to be more friable than normal.
- The Ni-Al bondcoat structure is outside the R-R quality standard for sprayed coatings in terms of the amount of unmelts and porosity but the bondcoat is not considered to have had an influence on the loss of Metco 314 abradable.

- The microstructure of the abradable on the casings was inferior to that produced on the quality control test samples sprayed with the components. The hardness of the test samples were within the required limits of 45-55R_{15}Y and the microstructure contained 38% metallic phase compared with the recommended value of 40%.

- Rolls-Royce strongly reject the company C assertion in the addendum to company C Technical Note 05-14 that the Rolls-Royce specification is inadequate in protecting against erosion and contend that company C have drawn an erroneous conclusion from the available service data

- Rolls-Royce concludes that the repair process actually used by company C deviated from the requirements of the Rolls-Royce repair documentation.

- Rolls-Royce conclude that where erosion has occurred, there has been a variation between the spraying of components and the quality control samples; resulting in the component and the test sample or just the component, being below the required hardness range.

3.0 PART DETAILS

Part No./ Mod Std	Description	TSN	CSN	TSR	CSR	Part Con
FK20186/ SB72-E018	HPC Stage 1 Casing	2256	614	NA	NA	Scrap
FK20592/ DIS	HPC Stage 2 Casing	17488	4935	2256	614	Repairable
FK25919/ DIS	HPC Stage 3 Casing	17488	4935	2256	614	Repairable
FK22836/ DIS	HPC Stage 4 Casing	17488	4935	2256	614	Scrap
FK22837/ DIS	HPC Stage 5 Casing	17488	4935	2256	614	Scrap
FK18642/ DIS	HPC Stage 6 Casing	17488	4935	2256	614	Scrap

4.0 ROTOR PATH LINING DETAILS

Stage 1 - Sherritt Gordon Omat 3/91 (73-76%Ni – <0.8%Co– Remainder C)
A Nickel-Graphite coating (Powder particles comprise a graphite “seed” surrounded by a shell of nickel)
R-R quality standard guidelines for the coating are 50% Nickel – 25% Graphite – 25% Porosity.

Stages 2-6 – Metco 314 Omat 3/202 (5-30% Bentonite – 1-6%Al – 1-6% Cr – Remainder Ni)
A Nickel-Chromium-Aluminium-Bentonite coating (Powder particles comprise a bentonite core with a metallic shell.
R-R quality standard guidelines for the coating are 40% Metallic phase – 20% Bentonite – 40% Porosity.

5.0 INVESTIGATION

5.1 HP COMPRESSOR LINING LABORATORY INVESIGATION

5.1.1. VISUAL EXAMINATION

Figure 1 shows the casings. The degree of abradable loss varied from stage to stage but none of the stages showed any signs of cracks in the coating or evidence of gouges from entrapped material.

The Stage 1 casing is Inco material (IN907) with a Sherritt Gordon abradable coating. The coating had been lost generally with many patches to the full depth of coating. Some light smearing of the coating from contact with the rotor blades was visible over approximately an 80º circumferential arc in a band about 5mm inboard of the rear edge of the track. The rubbing was mainly in a band 5-10mm wide and extending about halfway across the track at its maximum. Figure 2.

Stages 2 and 3 casings were manufactured from corrosion resistant steel with a Metco 314 Ni-Cr-Al – Bentonite abradable coating. The majority of the coating was still in place with fairly even wear around the entire circumference, the wear was deepest in the central region of the coating. The surface of the stage 3 abradable was smeared within the wear track around the full circumference. Figure 2

Stage 4 – IN907 casing, Metco 314 abradable. The coating was evenly worn across the liner with no circumferential variation. There had been a substantial loss of abradable coating, generally down to the bond coat. Surface smearing caused by rotor blade material transfer was present around an approximately 150º arc across the whole wear track. Figure 2. The severity of rubbing decreased markedly over a further 90º arc and was very slight to virtually non-existent over the remaining approximately 120º arc.

Stage 5 – IN907 casing, Metco 314 abradable. The wear was similar to stage 4 with almost total loss of abradable coating down to the bond coat. The surface of the abradable was smeared over a 30º arc, Figure 2, with light smearing over a further approximately 70º arc.

Stage 6 - IN907 casing, Metco 314 abradable. Abradable loss was similar in appearance to the stage 1 loss with many patches where the full thickness of coating has been lost. There was no evidence of abradable de-bond i.e. no delamination.

5.1.2 EVALUATION (REPLICATION) OF ABRADABLE LOSS AND WEAR PROFILE

Synthetic rubber replication medium was used to obtain casts of the abradable rotor path liner from stages 1 and 6 to estimate the volume of material loss and from stages 2, 3, 4 and 5 to measure the wear profile.

For the volume loss evaluations the rubber compound was applied over a 90º arc of the abradable, using the edges of the metal casing at the sides of the rotor path as guides for smoothing the liquid rubber to the level assumed for the originally machined abradable surface. The volume of the solid rubber replica was measured using equipment which accurately weighed the replica in air and then when submerged in water. The volume loss of material calculated for stages 1 and 6 are given in the table below.

Replicas of the rotor path abradable lining were made at 120º intervals around stages 2-5 and sectioned to show the cross-section. In addition, a depth micrometer was also used to cross-check the depth of abradable loss. The values of abradable thickness loss are given in the table below.

Typical cross-sections through stages 2 to 5 are shown in Figures 3 to 7. Superimposed on the cross-sections are the assumed position of the as-sprayed surface, Engine Manual limits for wear (0,25 mm) and the bondcoat / abradable interface position. The width of the blade at cold build is also indicated for stages 3 to 6 but the rubbed track on the abradable will be wider than this.

The depth of wear on all of the stages exceeds Engine Manual limits and coating has been lost outside the anticipated blade contact area particularly for stages 4, 5 and 6. The replicas show that on stages 4 and 5 almost all of the coating has been lost down to the bondcoat, confirming the measurements made with the depth micrometer.

Table showing abradable coating measurements

Stage	Design Thickness (mm)	Wear Depth (mm)	Abradable Volume Loss	
			cm^3	% of total
1	2,39	1,43 max	78.5	35
2	1,17	0,77 typical		~40*
3	1,17	0,65 typical		~35*
4	1,17	1,07 typical		~80*
5	1,17	1,06 typical		~80*
6	2,39	2,29 max	58.1	35

* calculation based on a combination of the typical thickness of the abradable lost and cross-sections taken through abradable replicas

5.1.3 METALLOGRAPHY EXAMINATION

Stages 1 and 6 together with Stages 4 and 5 were sectioned to allow the abradable coating to be examined. Stages 2 and 3 were kept intact to allow them to be reworked following this investigation. Initially it was hoped that fragments of coating could be removed from stages 2, 3 and 4 to allow the abradable coating microstructure to be assessed but attempting to chisel off coating from these stages resulted only in fine particles being produced.

Stage 1

Figure 8 shows a typical cross-section through the Sherritt Gordon coating and the slightly increased porosity in the corner at the edge of the wear track, which is usual because of the increased turbulence arising in this region when depositing the coating. The general structure of the coating conforms to the Rolls-Royce quality acceptance standard (Ref 9.0), containing acceptable proportions of metallic phase, graphite and porosity.

Stage 4

Virtually all of the abradable coating had been removed from this stage with only the Ni-Al bondcoat and isolated fragments of abradable left, Figure 9 (a) and (b). As mentioned above, the coating at the corner position may not be representative of the rest of the coating because of the curvature of the corner leading to turbulence during spraying. Image analysis software calculated that the metallic phase content was 40 % but the limited material available for analysis renders this result unreliable. The guideline figure for the coating, as stated in the Rolls-Royce quality acceptance standard (Ref 9.0), is 40%. The coating contained unmelted particles in the abradable whilst the bondcoat also contained unmelts and internal oxides to a higher degree than usual. The bondcoat thickness was within specification at 0,1mm. A small amount of bondcoat / substrate interface oxidation was present. This oxidation was also present on the rest of the casing surface

Stage 5

As with stage 4, the vast majority of the abradable coating was missing with only a small volume of material remaining at the forward edge of the rotor path, Figure 10 (a) and (b). The structure of the coating and the bondcoat was similar to stage 4 and while the metallic phase content was measured at 28.7% the reservations applied to stage 4 as to the reliability of this value apply. An increased amount of bondcoat/substrate interface oxidation compared to stage 4 was present (Figure 10b) together with similar oxidation to the rest of the casing surface. Fingers of oxidation extended into the IN907 (casing) caused by accelerated oxidation at grain boundaries. Beneath the coating, cracks were present normal to the substrate surface within the oxide some of which extended into the bondcoat similar to stage 6 as shown in Figure 11.

Stage 6
Again, the abradable coating contained unmelted particles i.e. powder particles whose metallic shell was relatively undisturbed, and image analysis indicated a metallic phase content of 29.1%. The bondcoat thickness was within specification (0,08-0,13mm) but contained a high number of unmelts and porosity. An even greater amount of oxidation was present than seen on stage 5. An increased number of fine cracks within the oxide were present which extended up into the bondcoat compared to Stage 5, Figure 11.

As mentioned above the oxidation seen at the bondcoat-substrate interface was present on all of the exposed surfaces of the casings. On these exposed surfaces the depth of oxidation increased progressively from stage 4 (40µm) to stage 5 (110µm) to stage 6 (170µm) similar to the bondcoat-substrate interface oxidation. This implies that the oxidation has increased as the temperature to which the material has been operating increased. If the oxidation arose because of an operation during the refurbishment of the coating it would be reasonable to expect it to be reasonably uniform in depth on all three casings. No surface oxidation was visible on the stage 1 casing which was also manufactured from IN907 which further suggests it occurs because of the temperature experienced in service. Stage 1 will experience ~300C while stage 6 temperature is ~600C.

Company B Sprayed Test Samples

The quality specification (ref 9.0) requires that a test sample is sprayed at the same time as the casings, this is used to assess the spray quality of each lining, and each sample is hardness checked. The samples for the stage 2 – 6 casing being investigated were supplied by company B for investigation.

Cross-sections taken through the test samples were examined. The Metco 314 samples showed a higher metallic phase content (38.5%) with a greater degree of melting such that a more substantial metallic network was formed compared to the rotor path linings, Figure 12. The bondcoat test sample was also different to the rotor path bondcoats with less unmelted particles and less porosity, which was more in line with the specification coating standard. Figure 13.

Figure 14 summarises the phase distribution in the Metco 314. The first and second bars show the metallic content / porosity and bentonite ratio for the Rolls-Royce and company B quality standards respectively, the third bar shows the ratio for the test samples provided by company B and the 3rd, 4th and 5th bars show the ratio for the stage 4, 5 and 6 casings examined.

5.1.4 SCANNING ELECTRON MICROSCOPY

Chemical analysis of both the abradable and bondcoat materials, using electron microscopy, confirmed that the chemical elements present were consistent with the Metco 314 and the Ni-Al bondcoat respectively.

Chemical analysis of the oxidation visible at the bondcoat-IN907 substrate interface (e.g. in Figure 11(b)) found iron oxide i.e. this was a result of oxidation of the IN907 substrate. Clear paths through the remaining abradable and bondcoat were visible, which would allow air easy access to the IN907 substrate, accounting for the oxidation seen. Oxidation at the particle interface boundaries within the bondcoat was predominantly nickel oxide.

Smeared material on the surface of stages 3 and 4 was removed. Chemical analysis identified it as rotor blade material (IN718).

5.2 COMPANY B PROCESS INVESTIGATION

As part of the overall investigation, company B provided the information requested by Rolls-Royce (listed in 5.2.1 below) in order to carry out a remote audit of their spraying process. The objective of this exercise was to identify any deficiencies in the process that could have lead to lining quality issue.

5.2.1 COMPANY B SPRAYING PRACTICE

Company B operated within the overhaul facility using their own equipment, methods and quality standards. The following information was supplied by Praxair for stages 2 to 6 casings:-

1 Standard Practice Instruction SPI 943653.01, which details the spraying method for the Metco 314 abradable on stages 2-6.
2 Job Instruction RR-D207-1 for stage 6. This covers inspection of incoming part, masking, grit blasting, spraying (including bend specimens and hardness specimens) and final inspection. Similar instructions apply to stages 2 to 5.
3 Standard Practice Instruction SPI 330.0, for spraying the spray test samples.
4 Praxair Quality Control Instruction QCI 943653 that lists the parameters against which cross-sections taken through test samples should be assessed. It also details the practice to be followed for mounting and surface preparation. The criteria against which the coatings are to be assessed are identical to those in the R-R quality standard for spraying new components.
5 Praxair Quality Control Instruction QCI G-222 that covers the procedure for Rockwell $R_{15}Y$ specimen preparation and testing.
6 The Job Router Cards showing the steps taken in the processing of each stage with inspectors stamps confirming each had passed the inspection criteria.
7 Portions of the relevant test samples. Identified as follows:-

Stage	2	3	4	5	6
Test Sample Identification	696	699	660	669	668

8 Hardness test results for each stage (see section 5.2.5 below)
9 Metco 314 and Metco 450 powder batch details used in spraying stages 2 to 6.

5.2.2 SPRAYING METHOD

Rolls-Royce employ different spray equipment to company B so detailed comment on the spray parameters is not possible but from the Praxair document SPI 943653.01 it was noted that:-

a) No pre-heating of the components prior to spraying the top coat was specified. Pre-heating the components is considered to be beneficial to bondcoat adherence. Since bondcoat adherence has not been a contributory factor to the coating loss the absence of a preheat operation has not been significant.

b) Cooling the part with siphon jets was not specified. Subsequently Praxair has stated that Job Instructions specified the use of two compressed air jets (which cooled the outer diameter of the coating and not the coating) and that operator was to stop every 10 passes and check the part temperature with a contact thermometer. A maximum part temperature of 170ºC was specified, which is comparable to Rolls-Royce’s control of this variable, but the measurements were not recorded. Damage to the coating and/or casing is possible if the part is not cooled.

c) A slightly higher deposition rate than R-R employ was specified – but the difference is not considered significant.

5.2.3 SPRAYING OF ENGINE 51067 HP COMPRESSOR CASINGS

Praxair confirmed that to the best of their knowledge nothing unusual occurred during the spraying of the parts i.e. confirming the absence of any comments to this effect on the job router cards. Also no changes to spray equipment, operating personnel, tooling, spray procedures or consumable specification and sourcing had taken place at the relevant times at which the parts were sprayed.

5.2.4 SPRAYING OF TEST AND HARDNESS SAMPLES

Praxair stated that the test samples were sprayed in exactly the same manner as the parts. Job Instruction R-R-D207 states the samples should either be mounted with the parts or mounted on the turntable to simulate actual parts. This should ensure similarity of the coating on parts and test pieces and should ensure that no differences arise because of spraying in a different pattern for example. The method for preparing the surface prior to hardness testing can influence the result obtained. The practice specified by Praxair in QCI G-222 was in line with that used by R-R i.e. abrade the surface with 120 to 220 grit silicon carbide paper to produce a surface uniform in appearance.

5.2.5 HARDNESS TESTING

Hardness testing of the abradables on any of the stages was not possible because of insufficient material. The Sherritt Gordon stage 1 as-sprayed hardness recorded by R-R Hillington was 48 $R_{15}Y$ i.e. within the R-R quality standard guidelines of 30-50 $R_{15}Y$.

The $R_{15}Y$ hardness values measured by company B on the Metco 314 test samples they sprayed for stages 2 to 6 were within the required range:-

Stage 2	**Stage 3**	**Stage 4**	**Stage 5**	**Stage 6**	**R-R and company B Quality Limits**
51.8	51.7	48.8	48.6	49.4	45-55

6.0 HP COMPRESSOR ROTOR BLADE CONDITION

The HP compressor rotor blades were visibly in good condition. The stage 2 blades exhibited surface corrosion but these blades are steel and their condition is considered to be normal. There was no evidence of blueing (over-heat) or distress to any of the blade tips (Figure 17). Figure 16 shows an example of blade tip blueing from another engine.

6.1 HP COMPRESSOR ROTOR BLADE TIP MEASUREMENTS

Table showing rotor blade tip measurements v's engine manual limits

STAGE	ENGINE MANUAL BLADE TIP RADII GRINDING LIMITS (mm)		ENGINE MANUAL BLADE TIP RADII WORN LIMITS (mm)		ESN51067's ACTUAL BLADE TIP RADII MEASUREMENTS (mm)		
	A	B	C	D	E	F	G
	MAX	MIN	MAX WORN	AVE WORN	MAX	MIN	AVE
1	361.615	361.525	361.373	361.412	361.518	361.386	361.485
2	359.48	359.39	359.237	359.275	359.555	359.413	359.489
3	358.254	358.164	358.049	358.087	358.158	358.092	358.14
4	357.539	357.449	357.335	357.373	357.508	357.452	357.459
5	357.361	357.271	357.157	357.195	357.375	357.274	357.327

6	356.869	356.959	356.756	356.794	357.017	356.895	356.956

Columns A and B under the ENGINE MANUAL BLADE TIP RADII GRINDING LIMITS heading are the dimensions used for HP compressor rotors at new engine build and for full performance restoration engines at overhaul. Columns C and D under the ENGINE MANUAL BLADE TIP RADII WORN LIMITS heading are the maximum worn and average limits for check and repair engines at overhaul.

Columns E, F and G under the ACTUAL BLADE TIP RADII heading are the maximum, minimum and average actual blade tip radius dimensions for the HP compressor from 51067. The dimensions shown in red are below the minimum grinding limit stated in column B, although they are within the max and average worn dimensions shown in column C and D.

See Table in section 9.1 for comparison of the above HP compressor rotor blade tip measurements with those from other engines

7.0 DIGITAL FLIGHT DATA RECORDER (DFDR) ANALYSIS

Fig 15 shows the DFDR take-off data for the event on 25 August 2004, the following data are plotted:

LP shaft speed N1 (%)
HP shaft speed N3 (%)
Throttle angle (degrees)
TGT (degrees)
P30 (psi)

The data shows that the engine surges approx 33 seconds after applying max take-off power. This is a known pinch point, where HP compressor blade tip clearances are at their largest. This is due to faster thermal growth of the HP compressor casings relative to the thermal growth of the discs in the HP rotor, due to the mass differential

.

The surge is identified by the pressure drop and TGT rise. There is also an uncommanded rise in N3 speed, which suggests a HP compressor stall. The throttle angle is reduced 60 seconds after the initial surge and the engine recovers from the surge and is operating normally, but at a reduced power. The engine is shut down approximately 20 seconds after the engine recovered. On the basis that the engine was stable following the power reduction, the engine potentially need not have been shut-down.

The data also shows there was no increase in N1 speed prior to the core surge, indicative of a fan stall. This suggests that the core fairing release was secondary. It is considered that if the fairing release had been primary it would only have affected the fan working line and lead to a fan stall. The fairing release would not have caused the large tip clearances to then cause the core surge. As a significant amount of fairing material was found on the runway, it is more likely that the fairing released during the initial surge event at rotation.

8.0 LH UPPER FAIRING RELEASE

The left hand upper composite fairing was found to have released from it’s fixing points (figure 18 and 19) when the ‘C’ ducts were opened up to carry out a visual inspection of the VSV stage 1 and 2 levers was requested during on-ground inspection checks. All bolts remained in position but no torque values are available. The ATSB are carrying out their own investigation on the fairing release, which will be reported separately.

9.0 DISCUSSION

9.1 HP ROTOR BLADES.

Table showing Trent 800 HP compressor blade tip measurements as measured at overhaul

	REASON FOR REMOVAL	STAGE 1	STAGE 2	STAGE 3	STAGE 4	STAGE 5	STAGE 6
LINING MATERIAL		**SHERRITT GORDON**	**METCO 314**	**METCO 314**	**METCO 314**	**METCO 314**	**METCO 314**
EM MIN		**361.525**	**359.39**	**358.164**	**357.449**	**357.271**	**356.869**
51067	ENGINE SURGE / DETERIORATION	361.386	359.413	358.092	357.452	357.274	356.895
51135	ENGINE SURGE ON TEST	361.526	359.481	358.216	357.401	357.33	356.578
51172	ENGINE SURGE / ICE INGESTION	361.554	359.090	357.904	357.485	357.256	356.822
51017	ENGINE SURGE/ HPC STAGE 6 BLADE DAMAGE	361.424	358.940	357.657	356.753	356.418	356.057
51021	HPC STAGE 5-6 DRUM LIFE	361.551	359.372	357.894	356.890	356.761	356.296
51046	IPC DAMAGE	361.526	359.395	357.871	357.467	357.243	356.466
51148	DETERIORATION	361.414	359.308	357.530	356.852	357.106	356.182
51105	HIGH LIFE	361.62	359.477	358.128	357.542	357.057	356.787
51238	ENGINE SURGE / DETERIORATION	361.526	359.024	357.901	357.038	356.789	356.428

* Measurements below engine manual grinding limits are shown in red.

The HP compressor rotor blade tip measurements for 51067 are considered to be unusual. The HP compressor rotor blade tip measurements for a number of Trent 800 engines, in the table above, supports this statement. It can be seen that the blade tip measurements for 51067, with the exception of stage 1 blades, which runs in Sherritt Gordon lining material, only stage 3 blades are only marginally undersize. In comparison, most of the blades running in Metco 314 for the other engines are undersize.

In addition to rotor blade tip wear, under certain conditions, it is possible to cause blueing (over-heating due to heavy rubbing) and distress to the blade tips. An example is shown in figure 16. There was no such blueing or distress to the blades from 51067 (figure 17).

9.2 HP COMPRESSOR ROTOR BLADE TIP CLEARANCES

Table showing HP compressor rotor blade tip clearances

ESN	REASON FOR REMOVAL	STAGE 1	STAGE 2	STAGE 3	STAGE 4	STAGE 5	STAGE 6
COLD BUILD CLEARANCE		1.32	1.02	0.99	1.02	1.19	1.37
51067	ENGINE SURGE/ DETERIORATION	*3.21	2.02	1.95	2.33	2.48	*3.86
51238	ENGINE SURGE/ DETERIORATION	2.54	1.96	1.88	2.00	2.13	2.24
51105	HIGH LIFE	1.75	1.45	1.25	1.42	1.91	1.63

* Patchy lining loss

Engine 51238 surged at high power due to large HP compressor rotor blade tip clearances. Analysis of the data showed that the tip clearance effect on surge margin to be approx 10 % greater than that expected for an engine removed from service due to performance deterioration. It can seen that engine 51067's tip clearances are larger than those measured and analysed for 51238 (albeit the lining loss on stage 1 and 6 was patchy). It is therefore possible to conclude that the engine surged at high power due to the large tip clearances at the rear stages of the HP compressor.

9.3 ROTOR PATH LININGS

The stage 1 casing lining microstructure was satisfactory, however lining loss was experienced. Service experience with Sherritt Gordon indicates that a number of engines typically lose some areas of lining, the extent on 51067 is greater than normal. Sherritt Gordon can suffer from age softening and thermal fatigue, leading to lining loss. Loss of front stage linings on Trent 800 engine causes poor starting and does not cause high power surges.

There is no evidence of abradable coating delamination in the Metco 314 linings. This type of failure mechanism leads to wholesale abradable coating loss in large sections. This is characterised by cracking running from the edge of the casing at the abradable / bondcoat interface. It is considered that these linings eroded over a period of time until they were large enough to cause the engine to surge. At the point of surge the casings deflected heavily causing the smearing evident on the linings. Note the smearing i.e. the transfer of blade tip material to the lining material can only be light due to the light wear to the blades.

The lining has been lost progressively by an erosion mechanism caused by the low metallic phase and high proportion of bentonite and porosity. This is supported by the fact that no wear has taken place to the HPC rotor blade tips. Normally Metco 314 is abradable initially but quickly becomes abrasive due to the lining hardening. Rubs depths of 0,25 mm are considered normal. Metco 314 lining are used in the rear stages of all RB211 and Trent engines service experience has been excellent with lining loss events being very rare.

The HP compressor efficiency analysis, carried out post the event, shows it begins a downward trend around 250 cycles after returning to service following refurbishment and continued to deteriorate until the surge event 360 cycles later. This is consistent with progressive lining loss increasing the tip clearance in the HP compressor, reducing the efficiency. The IP compressor efficiency remained unaffected.

9.4 SPRAY PROCESS INVESTIGATION

The reasons for the casings being sprayed with an abradable below the normal standard and this escaping detection by the supplier are unclear. While there were no aspects of the spraying procedure and parameters which were obviously at fault there was evidence of a lack of the required degree of melting and particle cohesion in both the abradable and the bondcoat indicating that the spray parameters have not been within ideal limits. The quality control samples indicated that the coatings would be to the quality desired but there was variation between the test samples and components in both the abradable and the bondcoat, suggesting that they had not been sprayed in the same manner.

company B relined HP compressor casings in the period October 2002 to March 2004. These casings are fitted to 53 engines across the Trent 800 fleet and 1 Trent 700 engine.

Since the 51067 event, two other engines have been identified as having exceeded the TGT deterioration limit through engine health monitoring alerts, subsequently found to partly or wholly due to HP compressor lining loss. ESN 51058 was found to have lost HP compressor stage 6 linings on engine strip. Rolls-Royce is currently carrying out an investigation on this casing, which had been relined by company B. ESN 51076 was actually removed for HP compressor blade damage but was also found to have lining loss on engine strip. Again, the casings had been relined by company B.

The overhaul facility terminated business with company B in March of this year. Since March, HPC casings have been resprayed by alternative sub-contractors.

9.5 SERVICE MANAGEMENT

The engine health monitoring (EHM) monitoring carried out by DS&S monitors both absolute and step changes in TGT. If either TGT limit is exceeded, an alert will be issued.

An EHM alert was issued on 4 August 2004 for 51067 due to a step change in TGT margin being noted. Troubleshooting was carried out on the engine in accordance with the fault isolation manual (FIM), reference chapter 71-05, task 828. A borescope inspection of the HP compressor was carried out as part of the troubleshooting and minor damage (within AMM acceptance limits) to a small number of HPC stage 6 blades was reported The engine was allowed to continue in service.

Since this event, EHM procedures have been changed. If an EHM alert is issued and troubleshooting reveals no findings to explain the observed trend change, Rolls-Royce will review engine parameter data in more detail. This may lead to a recommendation that the engine is removed, particularly where the HP casings have been resprayed by company B.

The Boeing AMM will be updated to include an inspection check of the condition of the rotor path lining immediately adjacent to the borescope port hole and to contact Rolls-Royce if no evidence of lining loss (ref request for manual revision document number 5008).

Rolls-Royce has also developed an algorithm to alert changes of HP compressor efficiency as part of the suite of automatically generated alerts produced by DS&S for EHM purposes.

10.0 REFERENCES

CME 5033/2/E1 – Engineering Coating Standards for Thermal Spray Coatings - Generic

11.0 GLOSSARY OF TERMS

AMM -	Aircraft maintenance manual
ATSB -	Australian Transport Safety Bureau
DS&S -	Data Systems and Solutions
EHM -	Engine health monitoring
FIM -	Fault isolation manual
HAESL -	Hong Kong Aero Engines Services
HP -	High Pressure
IP -	Intermediate Pressure
LH -	Left Hand
QC -	Quality Control
TGT -	Turbine gas temperature
T30 -	HP Compressor Outlet Temperature

12.0 ADDENDUM

12.1 COMPANY C'S INVESTIGATIONS

12.1.1 ESN51067 – SECTION OF HP COMPRESSOR STAGE 6 CASING

A section of stage 6 casing from 51067 was requested by company C to support their investigation. About this time company C realised that the QC samples submitted to Rolls-Royce for the 51067 casings were not the correct samples. Eventually the correct samples were identified and examined by company C.

The investigation concluded that the micro structure of QC sample No.466 for the 51067 HP compressor stage 6 had a metallic content of 40.5% which is similar to the Rolls-Royce quality standard recommendation of 40%. The measured hardness of 51.7 was also within the Rolls-Royce quality recommendation of 45-55 $R_{15}Y$. Examination of the section of stage 6 casing confirmed a low metallic content of 27%.

12.1.2 ESN51363 – HP COMPRESSOR STAGE 6 CASING

The Data Systems and Support Group identified an increasing TGT trend on ESN51363 and a loss of HP compressor efficiency relative to the 'sister ' engine. Following confirmation that the stage 6 casing had been relined by company B a decision was taken to remove the engine.

Strip of the HP compressor revealed patchy lining loss from the HP compressor stage 6 casing similar to that seen on 51067 and 51058's stage 6 casings. The stage 5 casing, which had not been relined by company B, did not exhibit lining loss. Rolls-Royce were supplied with photographs (fig 20 and 21) and the lining hardness values of the stage 5 and 6 casings but declined to have them returned for investigation.

Company C did however conduct an extensive investigation into the stage 6 lining failure examining micro structures and phase distribution, chemical analysis of the bulk coating and contaminants, oxidation, coefficient of thermal expansion, erosion resistance and CMAS contamination.

Company C's examination of the microstructure concluded direct comparison of the QC sample (No.864) and the casing. The metallic content of this QC sample was found to be 40.9% and the sample removed from the casing was found to be 43.1%, both samples were therefore acceptable against the Rolls-Royce quality standard recommendations of 40%.

12.1.3 FOLLOW-UP INVESTIGATION BY ROLLS-ROYCE

On completion of their own investigation, company C sent the correct quality control samples from 51067 and the QC samples and fragments of the coating from the stage 6 casing from ESN51363 to Rolls-Royce.

12.1.3.1 EXAMINATION OF CORRECT QUALITY CONTROL SAMPLES FROM 51067

Examination of the correct set of QC samples from 51067 revealed similarity with the first incorrect set of QC samples, in terms of metallic content and reacted particles. This goes no further towards highlighting any inadequacies with the company B manufacturing process.

12.1.3.2 PHASE DISTRIBUTION OF STAGE 6 COATING MICRO STRUCTURE FROM 51363

Image analysis was used to determine the phase distribution of the QC samples and fragments of coating chipped from 51363 stage 6 coating. The results from the investigation indicated the metallic content in both the QC sample and the chipped coatings from the stage 6 casing were similar to the Rolls-Royce quality standard.

12.1.4 FOLLOW-UP INVESTIGATION DISCUSSION

Rolls-Royce concluded that the coating in the HP compressor stage 6 casing from ESN51067 had a low metallic content and, consequently, a higher proportion of bentonite and porosity compared to the Rolls-Royce acceptance standard. Also, there were a high number of particles, which had not been fully melted. This caused the coating to be more friable than normal, leading to the erosion during service operation.

Following their own investigation, company C concluded that the QC sample was the same as the coating in the casing as it left the company B coating cell in August 2003. The company C report does not offer a reason for the high number of unmelted particles but concludes that the low metallic content was due to the loss of particles from deep within the coating structure during operation.

Company C also concluded that the erosion was not caused by low metallic content in the coating, but rather by severe oxidation of the coating as a consequence of engine operating conditions. Company C suggested that the operation may have been above the recommended operating temperature for the lining and hence could have caused the excessive oxidation of both the coating and substrate.

Rolls-Royce does not accept Praxair's conclusions for the cause of lining loss. The take-off performance data for 51067 for the last 400 cycles prior to the event shows that the engine had been operating normally. As stated previously, DS&S issued an alert on 04 August 2004 following a step change in TGT, the engine still had 10 °C margin just before it surged. The maximum temperature capability of Metco 314 is around 815 °C, so the suggestion that the engine may have been above the recommended operating temperature for the lining can be ruled out.

Rolls-Royce has carried out an investigation to assess the degree of abradable coating oxidation on HP compressor stage 5 and 6 casings from 51058. The stage 5 casing, which had not been relined by company B, did not exhibit lining loss (see fig 22). The stage 6 casing, which had been relined by company B, did exhibit lining loss (see fig 23). Electron microscope images were taken from micro samples prepared from the sectioned casings and the percent oxidation measured using image analysis software. The results from the investigation showed the oxidation content on stage 5 casing to be 20.6% compared to 10.4% for the eroded stage 6 casing. This suggests oxidation was not the primary driver for erosion.

Hardness measurements have been taken from the engine stage 5 and 6 casings from 51058 and 51363, post engine running (see table below). Again, the stage 5 casing from 51363 had not been relined by company B but the stage 6 casing had.

The hardness requirement for 'as sprayed' Metco 314 is 45 to 55 $R_{15}Y$. Metco 314 hardens during engine running, therefore, the hardness values for engine run components should be greater than the 'as sprayed' hardness values. It can be seen from the table that the coating hardness measurements for stage 5 casings are harder than for the stage 6 casings. This is particularly evident on the casings from 51058, further supporting a problem with the company B sprayed linings.

No attempt was made to determine the hardness of the linings in any of the HP compressor casings from 51067 due to the amount of lining loss. However, wear normally occurs to the HP compressor blade tips due to the 'hard' Metco 314 lining. The table in 6.1 shows the HP compressor blade tip measurements from 51067 as measured post the event. This reveals that all stages of blades rubbing against Metco 314, with the exception of the stage 3, are still within engine manual grinding limits after 2256 hours and 614 cycles of engine running. This is unusual and is considered to be a result of the blades rubbing against a ‘soft’ lining. This is supported by more typical blade wear, as shown in the table in 9.1, for other Trent 800 engines.

Table showing the hardness values obtained for the linings from engine run casings

ESN	Casing Stage	Sprayed by company B	Hardness value ($R_{15}Y$)	Source
51363	5	No	62.1	Company A
	6	Yes	51	Company C
51058	5	No	80	Rolls-Royce
	6	Yes	35	Rolls-Royce

The differences between the quality QC sample and the coating in the stage 6 casing from ESN51067 cannot be explained. Also, no explanation can be given for the apparent acceptable quality of the QC sample and the stage 6 casing from ESN51363. However, the most compelling evidence for contesting Praxair’s conclusions is the Metco 314 service history in Trent 800 engines.

Praxair suggested the thermal expansion coefficient mismatch between the coating and the substrate may have initiated the coating loss. The Trent 800 entered into service in 1995. There are now 450+ Trent 800 engines in service, which have accrued more than 7 million hours of service operation. In this time, only five engines have been removed from service for loss of TGT margin and HP compressor efficiency, which subsequently was found to be due to Metco 314 lining loss. In each case, the casing that had lost Metco 314 lining had been relining by company B at the previous shop visit. Prior to the ESN51067 event date, Rolls-Royce has no history of Metco 314 lining loss, either as sprayed from new manufacture or resprayed at overhaul.

Further, company B had set up their spraying facility within company A. Following termination of the company A / company B contract in March 2004, company A purchased the cell equipment ‘as is’ from them later that year. The company B spraying process and ‘areas for improvement’ are stated in 5.2.1 and 5.2.2 respectively. company A made the following changes to equipment / process to improve the quality of component spraying:

- Introduced automated grit blasting process to ensure consistent preparation of the surface.
- Introduced additional cooling air to cool the component during spraying
- Plasma gun changed from a FP73 type to a 9MB type, as specified in the engine manual.
- Introduced new tooling and fixtures to hold the components properly during spraying no ensure no heat distortion
- Measure the flame spray hardness on the actual component
- Improved house-keeping
    - Distilled water now changed every quarter
    - Grit blast media now changed every two weeks
    - Powder hoppers moved from outside to inside the spray booth

For the reasons stated above, Rolls-Royce reject the conclusions made by Company C as to the cause of the lining loss

13.0 ADDENDUM 2

13.1 Company C'S Addendum to Technical Note 05-14

Following issue 2 of this report Company C have added an addendum to Company C Technical Note 05-14, this addendum states the following:

"Despite the evidence for erosion in service, the specification for the acceptable quality of the coating contains no evaluation for erosion' and the current R-R specification for the LCA-314 coatings is not adequate to insure the desired erosion resistance that the coating may experience in some service exposures.

Company C *suggested a particle erosion test or a tensile bond test should be considered. The bond test would give the average adhesion strength between particles within the coating. This 3-way analysis of the quality panels would thus verify acceptable hardness and metal content and particle adhesion strength of the coating."*

13.2 Rolls-Royce response to Company C statement in 13.1

Rolls-Royce strongly rejects the assertion that the Rolls-Royce specification is inadequate in protecting against erosion and contends that company C have drawn an erroneous conclusion from the available service data. The evidence for this is presented below.

13.3 Rolls-Royce controlling documentation

The RR documentation controlling the repair to the HPC casing at the time they were sprayed was TSD594 OP704. This document states the quality control sample must be attached to the part (see extract below);

"Where the indentation test cannot be effected on the part an 'integral' test piece must be used, i.e. a test piece which is attached to the part and sprayed with the part. The test piece should be of steel, measuring approximately 6,35 x 20,32 x 50,8 mm. (0.250 x 0.800 x 2.000in.)"

It is normal for subcontract companies to put in place internal local working procedures that comply with the Original Engine Manufacture's (OEM) repair documentation.

When originally questioned on the procedure used by company B to generate and measure the hardness of the quality control samples Praxair submitted (28th Oct 04) Job Instruction R-R-D207-1, for HP Compressor Stage 6 Case. on generation of the hardness quality control sample;

"R-R-D207-1 Operation N°40 – flame Coat

Procedure 9.
Mount Macro Hardness Test Coupon together with the parts if possible or mount the coupon on Turntable to simulate actual parts.
Procedure 10.
Spray top coat (Metco 314 NS) on the test coupon and the actual (For test coupon mounted together with the parts) as per SPI N° 943653.01 to achieve dimension as per Table 3A. Remove the test coupon when the coating thickness is more than 0.050"
Procedure 11.
For coupon on simulated parts, spray the coupon to 0.050" min; follow by spraying the actual part to size as shown in Table 3A."

This procedure allows the test sample to be mounted and sprayed separately to the actual casing ring. This process therefore does not comply with the stated Rolls-Royce repair scheme.

In addition to this information a fax from Fred Mundt (6th Oct 04) confirmed the component was sprayed to the Praxair Standard Practice Instruction 330.00 with the following comments;

"The parts and samples were coated at separate times (of necessity) but each representative sample set coated immediately before / after the part in the same coating centre set-up, using the same equipment and material."

The separate spraying of the test piece is considered by Rolls-Royce to be significant. When the test piece is sprayed independently of the casing, it is possible for the quality control sample to have a different hardness value to the actual casing. Rolls-Royce has previous evidence of this (see section 13.5).

The Rolls-Royce development and service evidence demonstrates that provided the hardness value of the casing matches the hardness value of the test coupon and both are within the required hardness specification, then the lining will not erode during the planned time between overhauls. Therefore, when all repair documentation requirements are complied with, there is no deficiency in the Rolls-Royce specification.

13.4 Service Evidence of Lining Issues

Metco 314 is used in all Trent HP compressor casings and has an excellent 'in service' record. In the 10 years of operation, the Trent 800 engine has accrued over 8.8 million hours of service.

With the exception of Metco 314 erosion found in casings sprayed by company B, Rolls-Royce experience is that there has not been a single occurrence of Metco 314 lining loss through erosion. This is true for HP compressor casings as sprayed during new manufacture or by vendors other than company B at overhaul. It is also true for all operators despite them operating their engines at different engine ratings and in different environments.

13.5 Previous Experience of Quality Control Test Samples

There is known experience of variation between spraying components and quality control samples resulting in the component being out of the required hardness range. RB211-535E4B engines suffered from engine surges and consequently unscheduled engine removals around March 2002. Boroscope inspection of these engines highlighted partial loss of the Metco 320 HPC stage 3 rotor path lining. All affected parts had been reworked in one particular overhaul base, with the introduction of Metco 320.

An investigation was launched to determine the root cause of the failure. The findings from the investigation highlighted the following point; Metco 320 test coupons hardness coating structure and component coating structure (and therefore hardness value) could differ if the quality control sample was not sprayed with the component.

13.6 Why have the repair documents been amended since company C casings were sprayed?

As part of Repair and Surface Engineering Process Excellence activities launched to support the robust repair of Al/Si based abradable coatings, it was deemed best practice to incorporate the additional quality requirements stipulated in the new manufacture standard (CME 5033 2 / E1) to the repair standard (TSD 594).

This "best practice "activity was read-across to all abradable coatings regardless of the service experience. In order to do this document and procedure amendments were required. These changes were made as part of on-going process improvement and not because of any deficiency in the original procedures / documents, relating to spraying Metco 314 to repair HPC casings.

13.7 Addendum 2 - Conclusions

Based on the above evidence Rolls-Royce strongly reject the assertion that the Rolls-Royce specification is inadequate in protecting against erosion and contend that company C have drawn an erroneous conclusion from the available service data

Rolls-Royce conclude that where erosion has occurred, there has been a variation between the spraying of components and the quality control samples; resulting in the component and the test sample or just the component, being below the required hardness range.

Additional Statement

Nothing in this report shall be deemed to be an admission by Rolls-Royce plc of any liability whatsoever, however arising in respect of any loss, damage, death or injury.

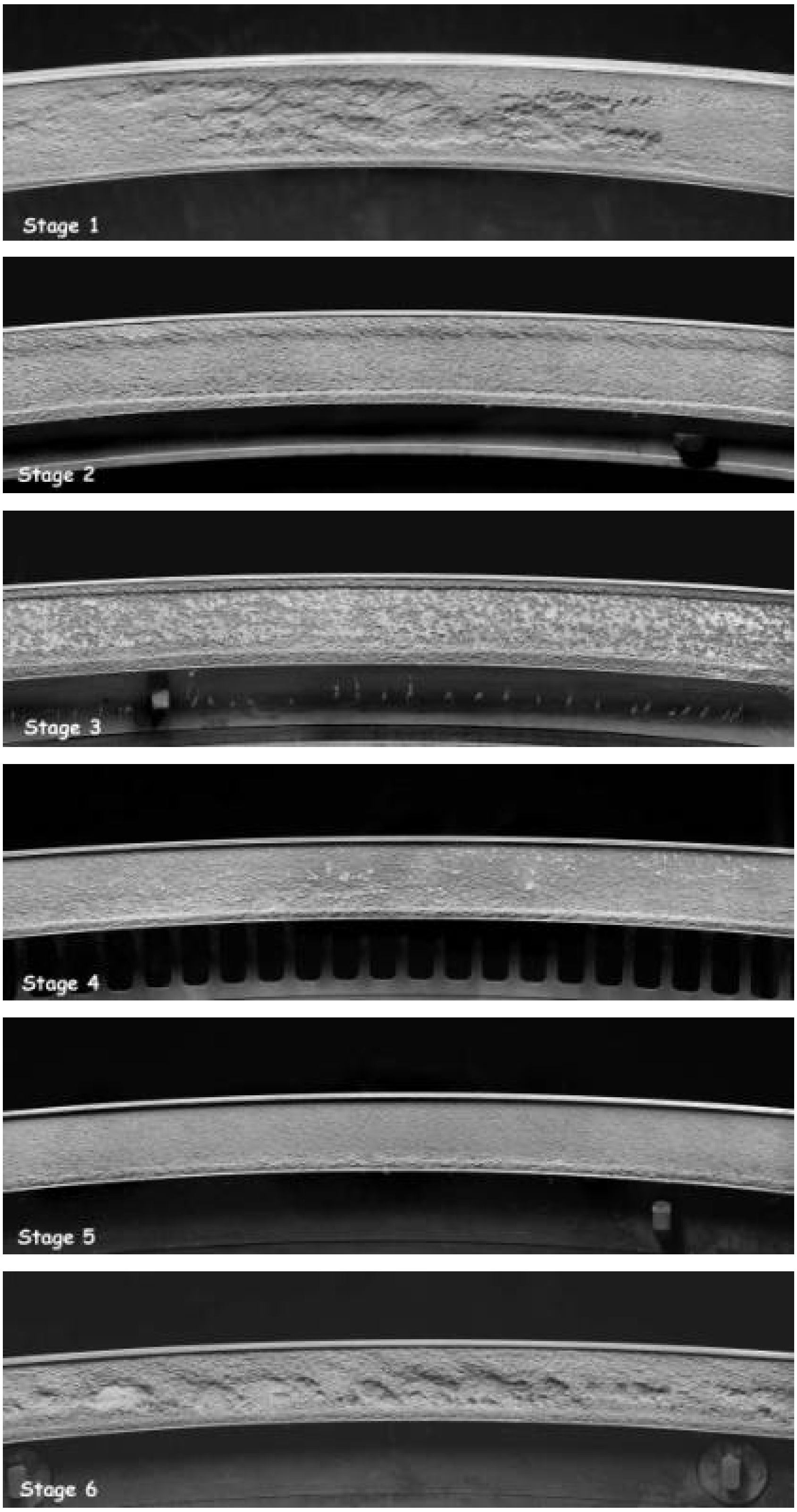
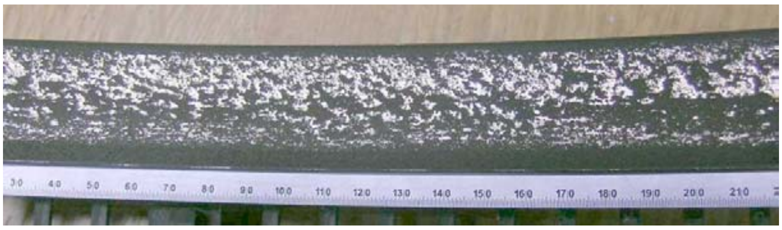


Figure 1 General view of the HPC casings

Smearing on the Stage 1 abradable surface

Stage 3 smearing

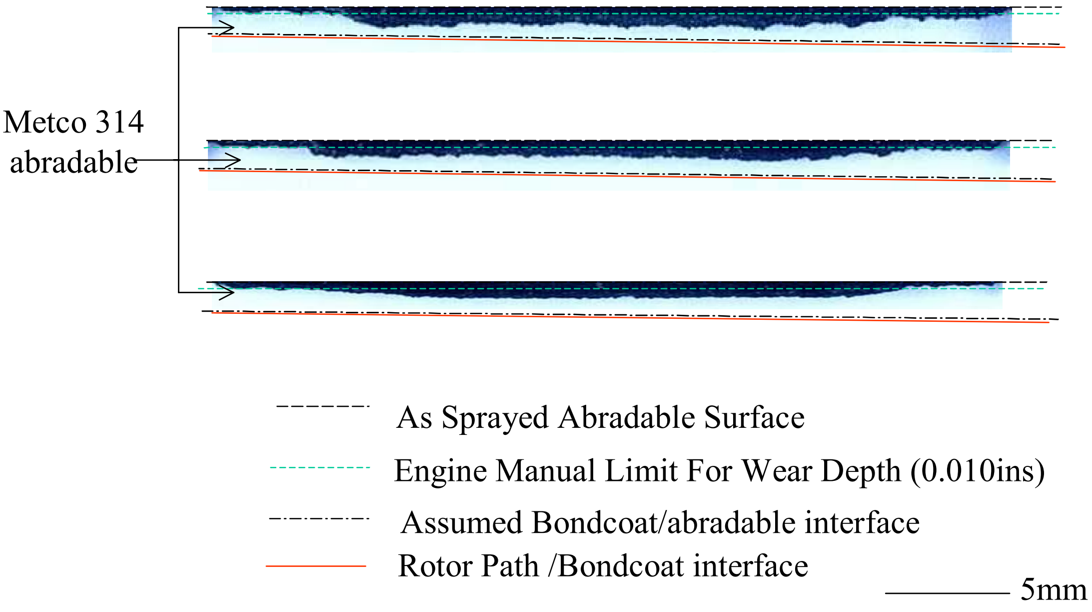


Stage 4 smearing

Stage 5 smearing

Figure 2 Examples of the smearing on stages 1, 3, 4 and 5

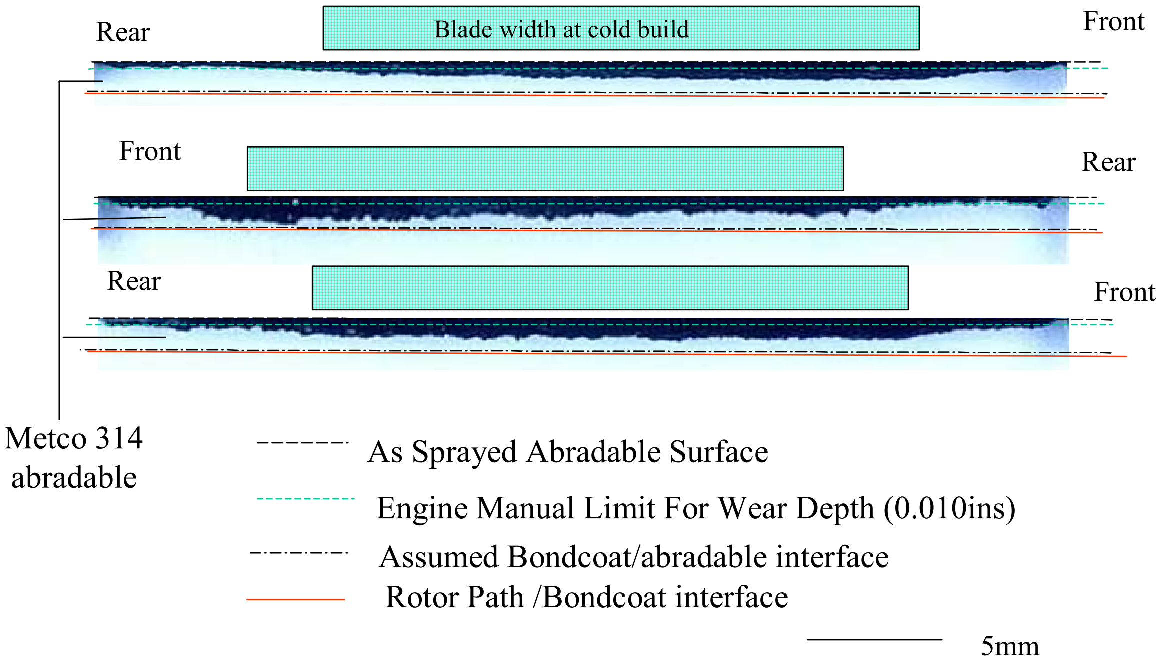
Stage 2 Rotor Path Replica Cross-Sections



The dark regions in the three views above are cross-sections through the synthetic rubber replicas of the abradable rotor path liner surface at three positions 120° apart. They therefore represent what is missing from the abradable liner. The light regions labelled Metco 314 abradable are therefore what remains of the abradable

Figure 3

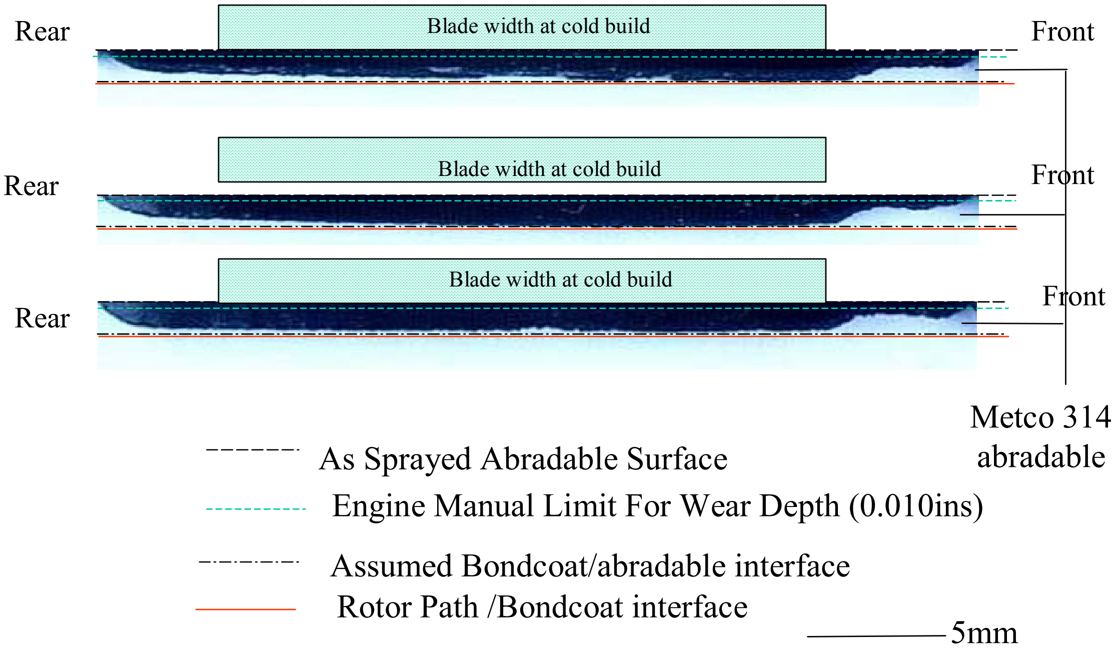
Stage 3 Rotor Path Replica Cross-Sections



The dark regions in the three views above are cross-sections through the synthetic rubber replicas of the abradable rotor path liner surface at three positions 120° apart. They therefore represent what is missing from the abradable liner. The light regions labelled Metco 314 abradable are therefore what remains of the abradable.

Figure 4

Stage 4 Rotor Path Replica Cross-Sections



The dark regions in the three views above are cross-sections through the synthetic rubber replicas of the abradable rotor path liner surface at three positions 120° apart. They therefore represent what is missing from the abradable liner. The light regions labelled Metco 314 abradable are therefore what remains of the abradable.

Figure 5

Stage 5 Rotor Path –Typical Cross-Section

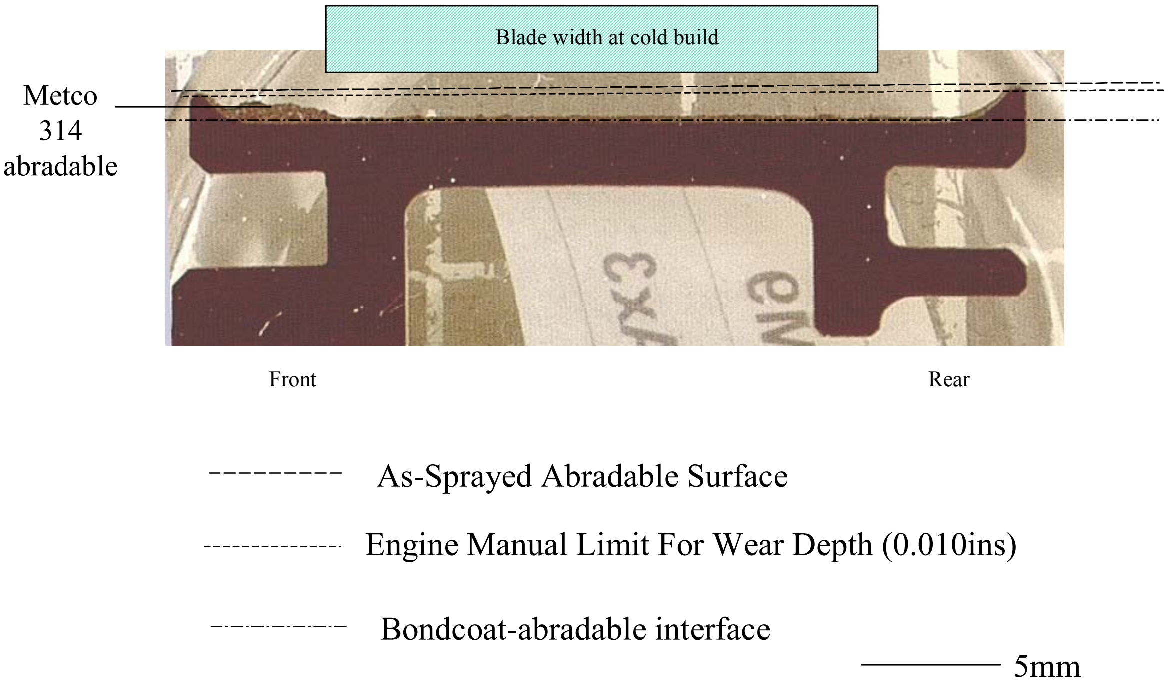


Figure 6

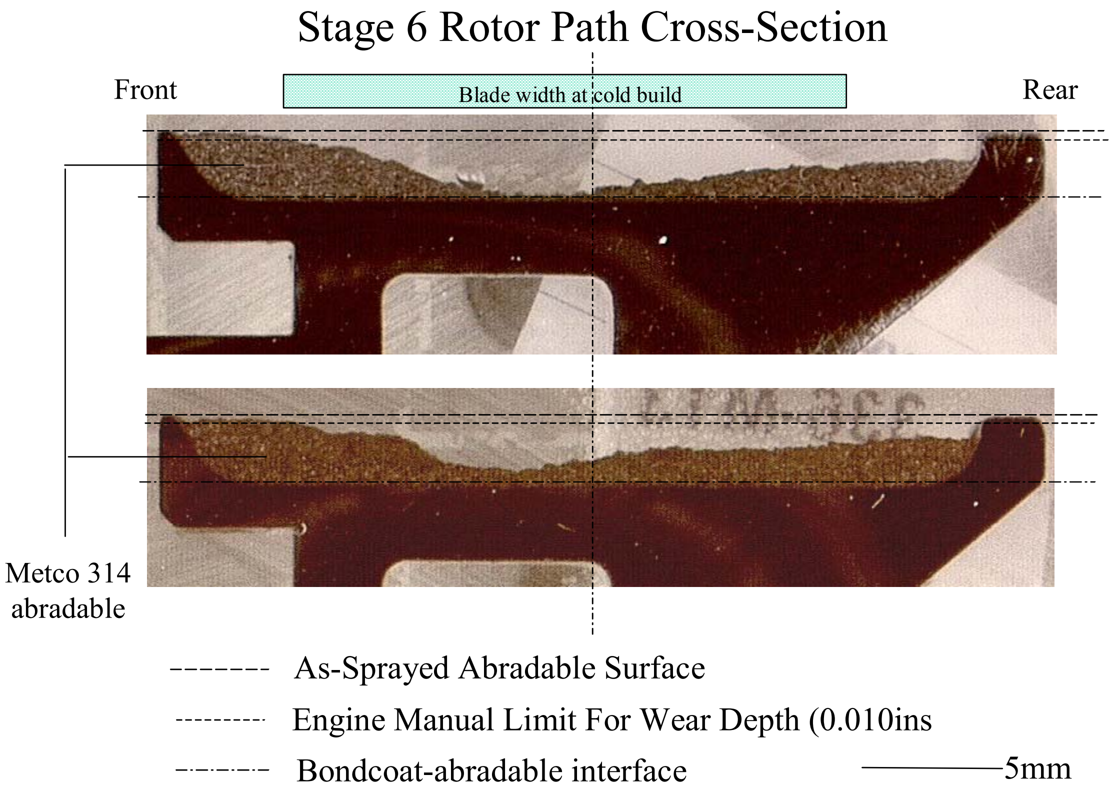
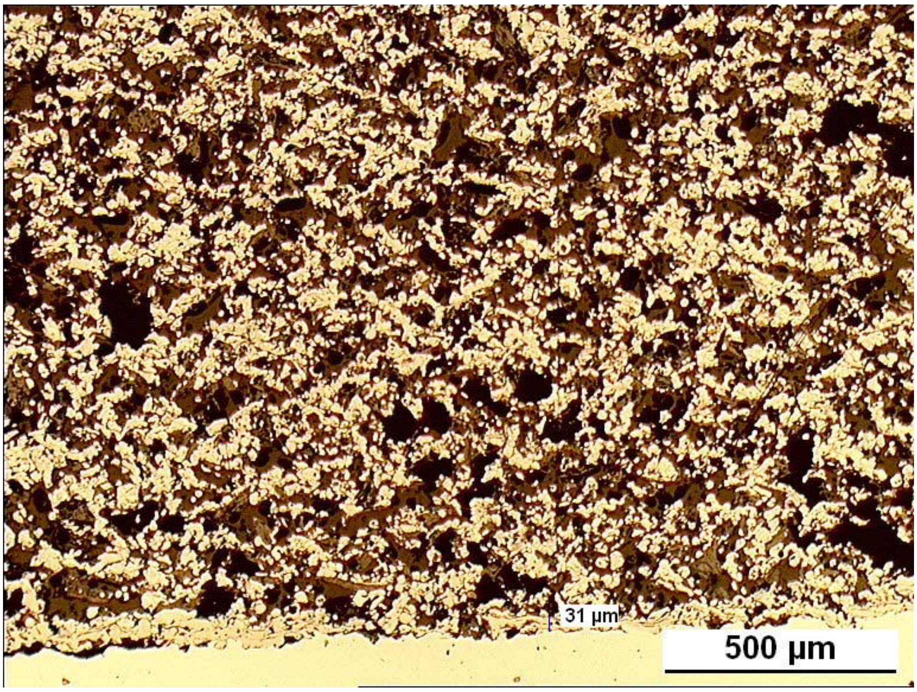
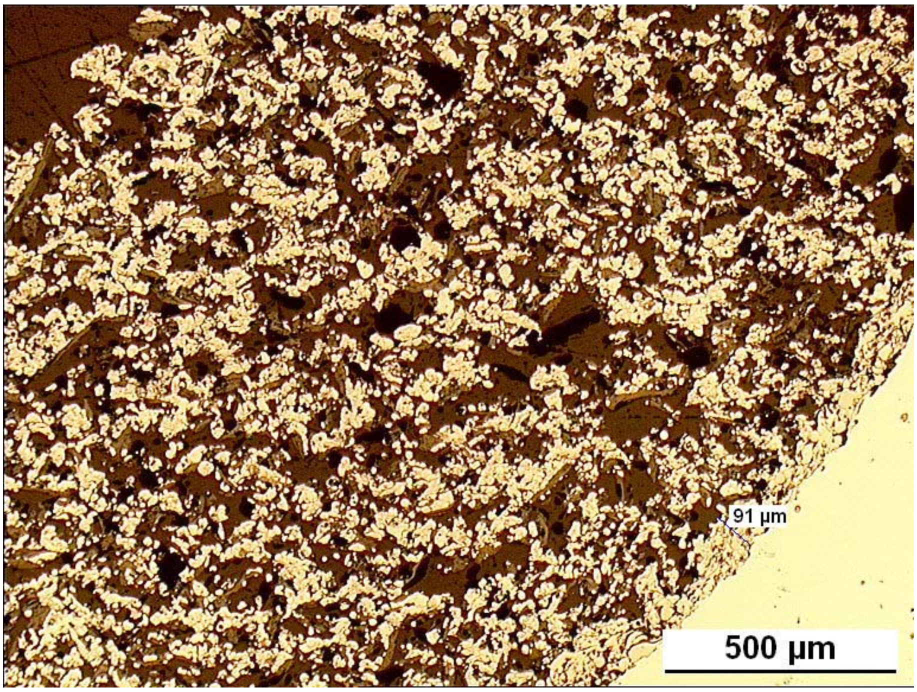

Stage 6 Rotor Path Cross-Section
Front
Blade width at cold build
Rear
Metco 314 abradable
------- As-Sprayed Abradable Surface
--------- Engine Manual Limit For Wear Depth (0.010ins
-·-·-·- Bondcoat-abradable interface
5mm

Figure 7

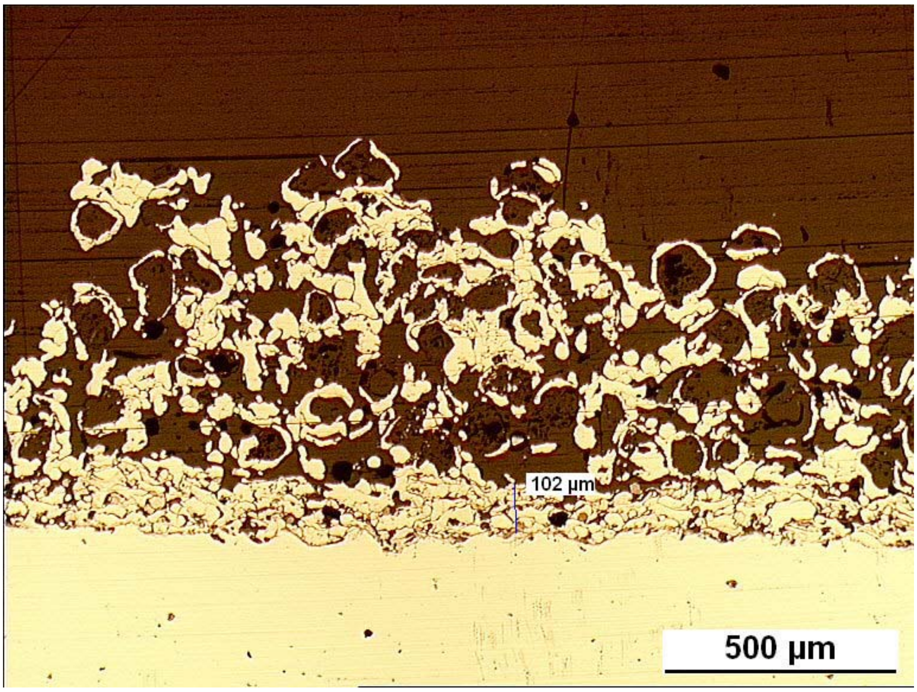


a)– Axial cross-section - typical microstructure

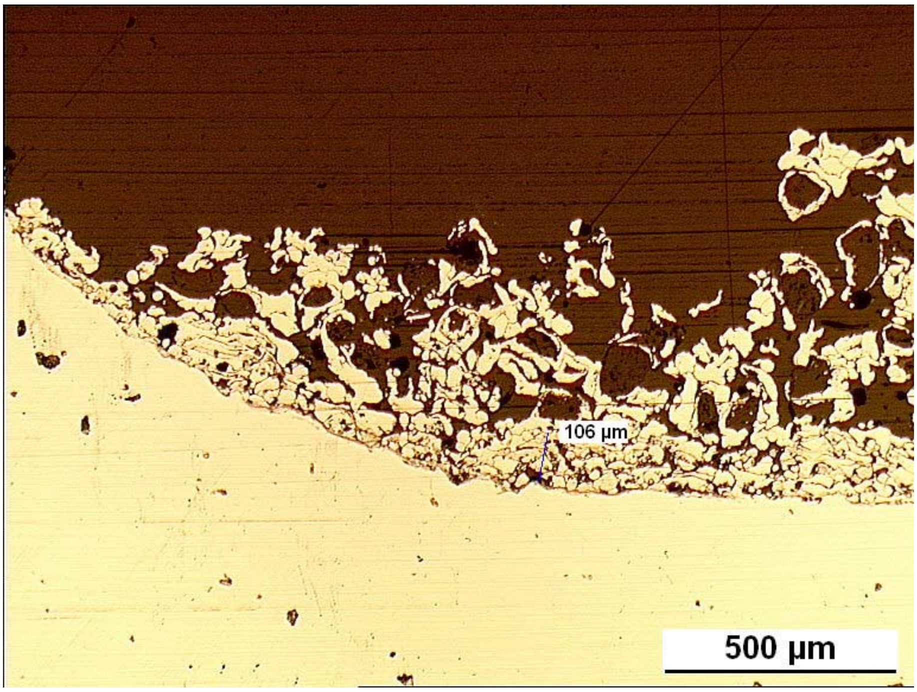


b) The Sherrit Gordon Coating in the curved corner at the edge of the casing

Figure 8 Stage 1 Sherritt Gordon Coating

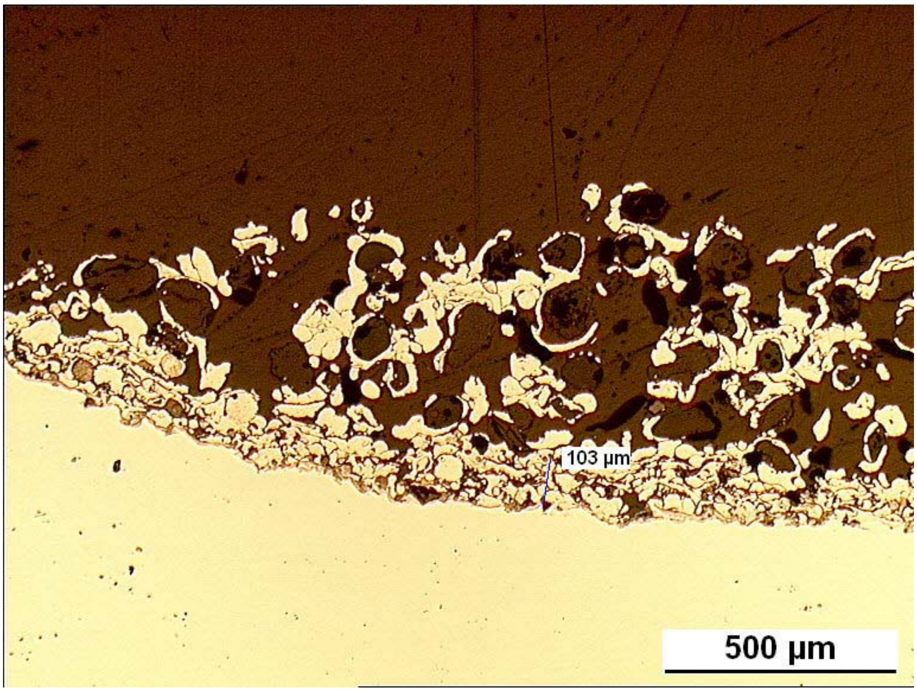


a) Axial section through the abradable coating towards the middle of the casing. The bondcoat Is 0,1mm thick (specified range is 0.08 to 0,13mm)

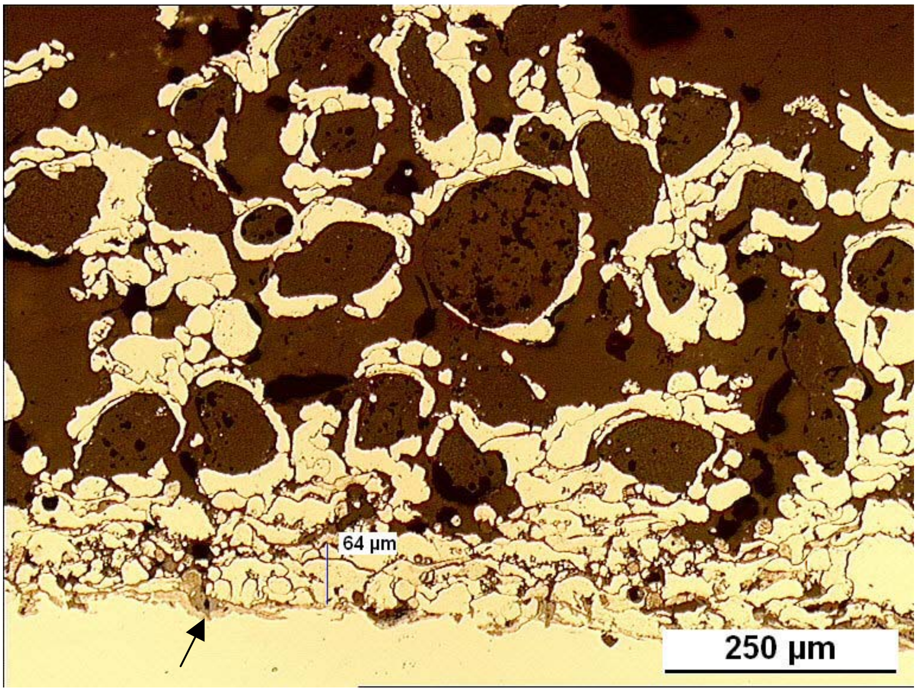


b) Axial section through the abradable coating at the edge of the casing

Figure 9 Stage 4 Abradable Coating

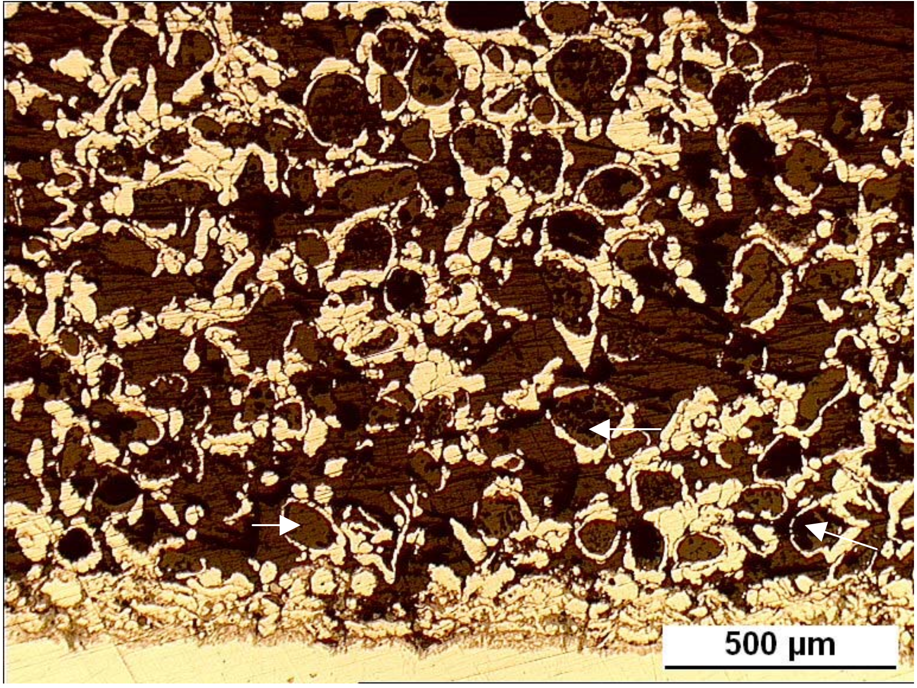


a) Axial cross-section through the abradable at the edge of the casing

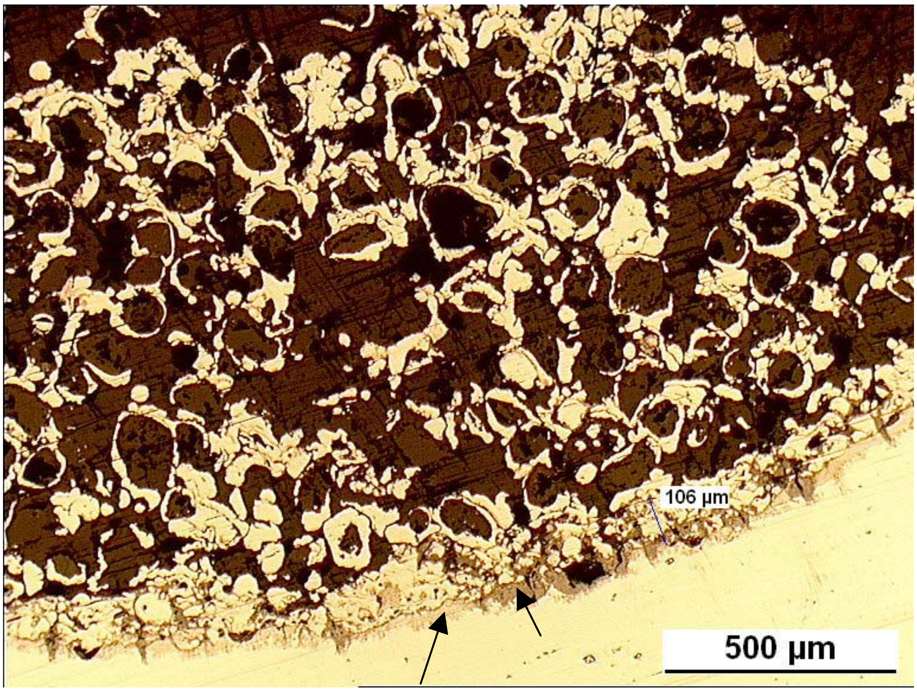


b) Axial cross-section through the abradable showing the bondcoat-IN907 substrate oxidation. Where oxidation is heaviest there are cracks within the oxide (arrowed)

Figure 10 Stage 5 Abradable Coating



a)Axial cross-section through the coating towards the centre of the casing. Powder particles which have not fused well to contribute to the formation of a metallic network within the coating are arrowed



b) Axial cross-section through the coating at the corner of the casing. Possibly more porosity than in a) because of turbulence during spraying caused by the corner geometry. Bondcoat-IN907 substrated interface oxidation arrowed

Figure 11 Stage 6 Abradable Coating

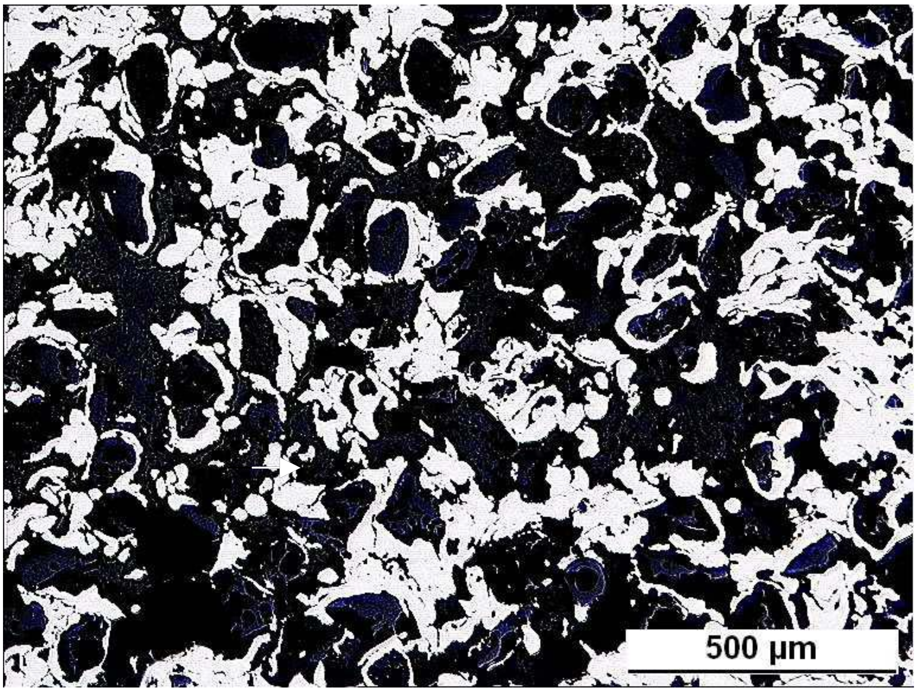


Figure 12 company B Metco 314 Test Sample (~40% metal content)

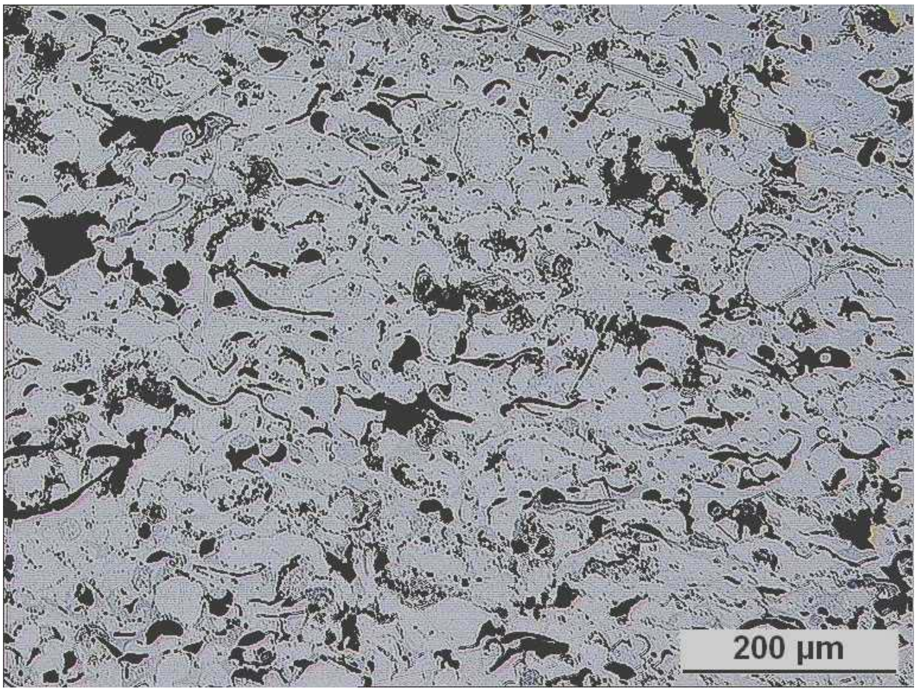


Figure 13 company B Bondcoat Test sample. Isolated unmelted particles are visible and porosity
is reduced compared to the HPC casings

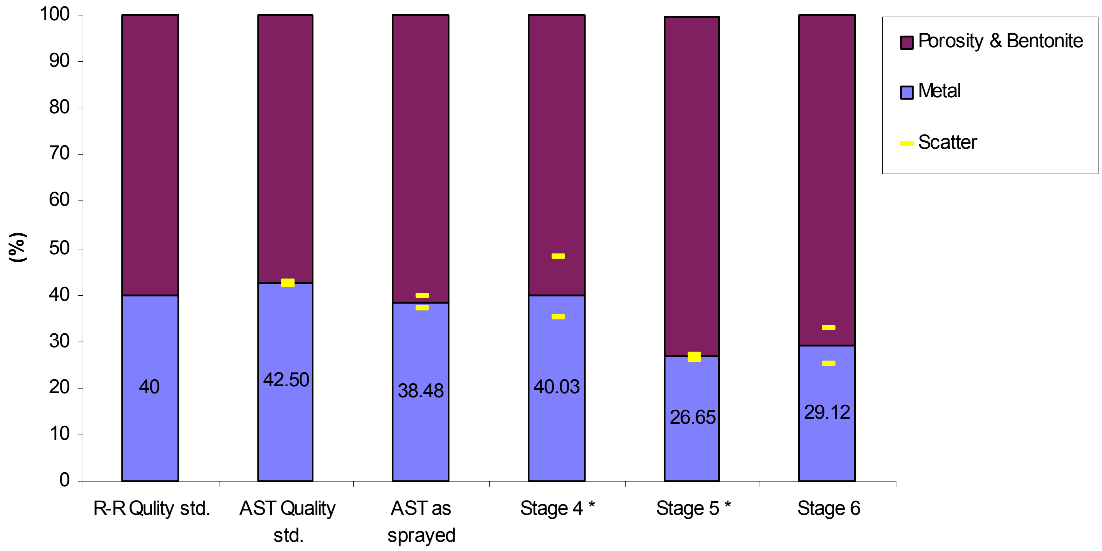


Figure 14 Metco 314 Coating Phase Distribution

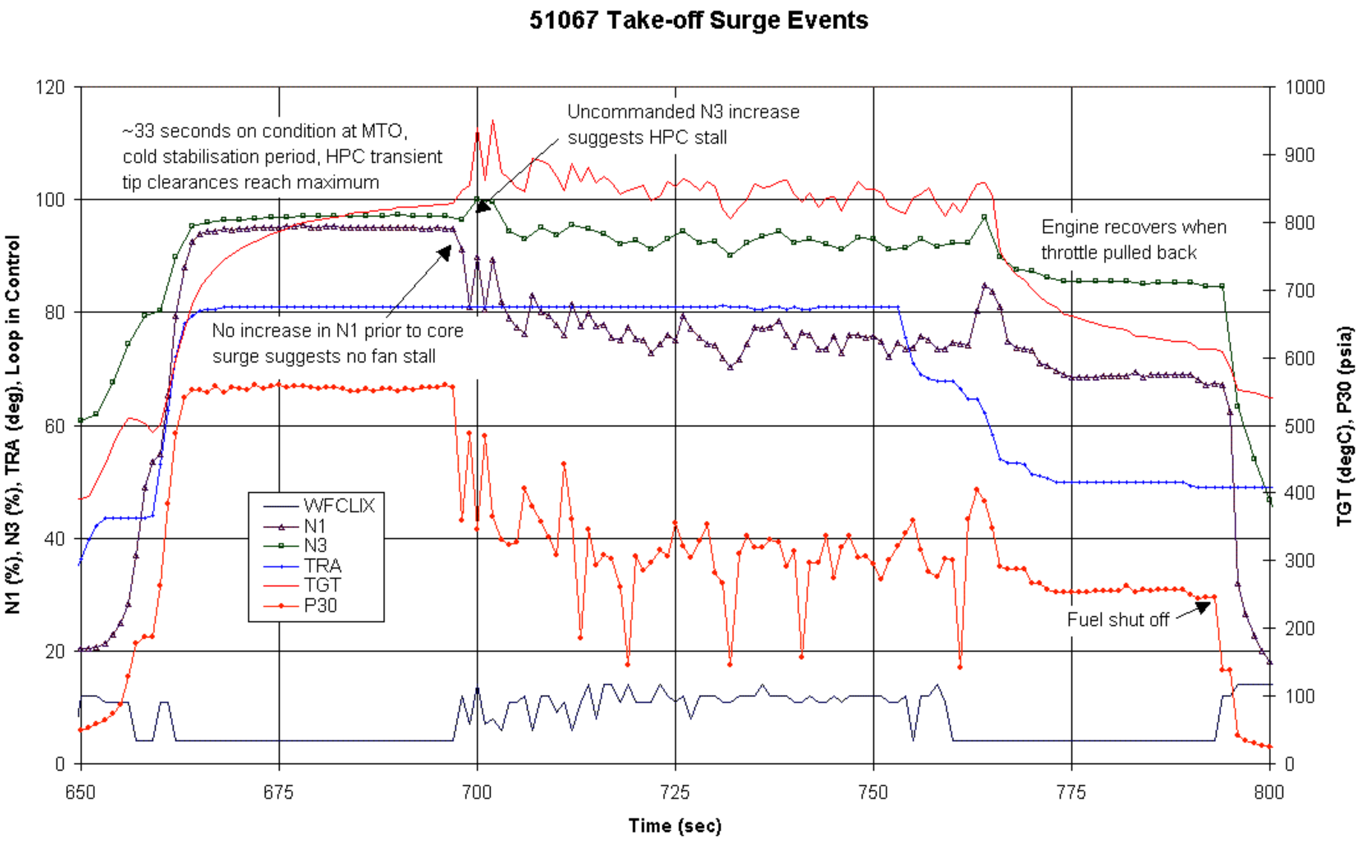


Fig 15 Take-off data taken from the DFDR

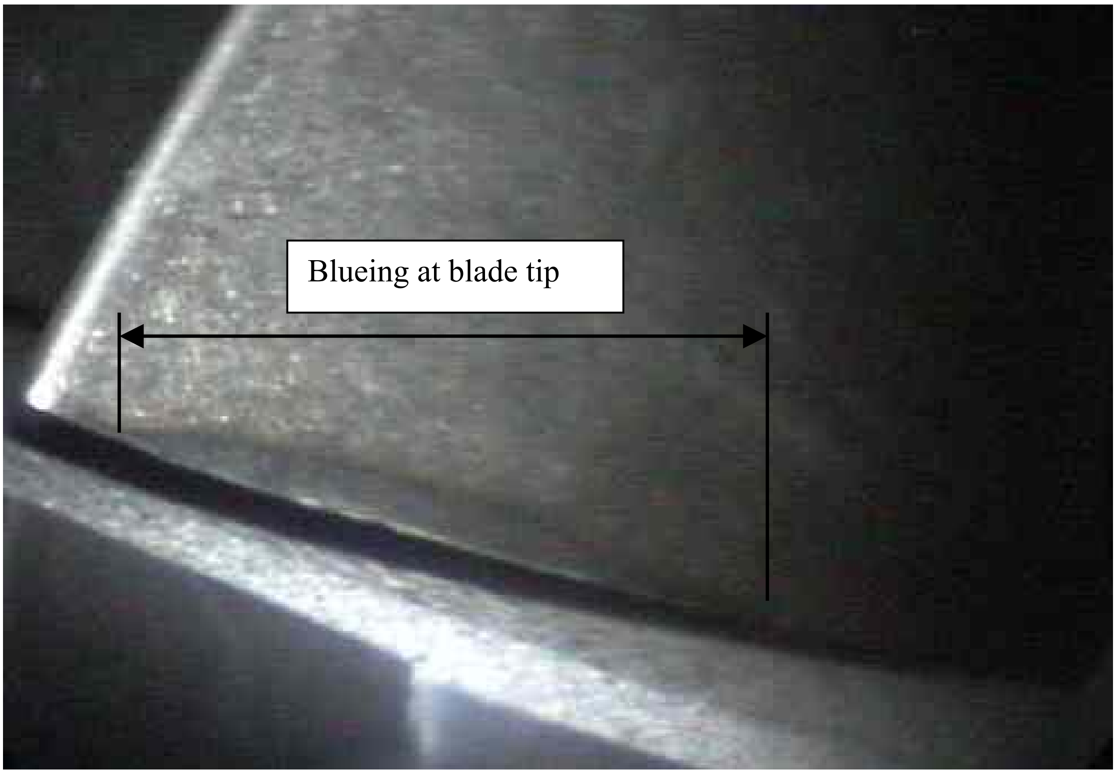


Figure 16 shows an example of a HP compressor stage 3 blade with blueing at the tip

Figure 17 shows no discolouration on the HP compressor stage 2 and 3 blade tips from ESN51067

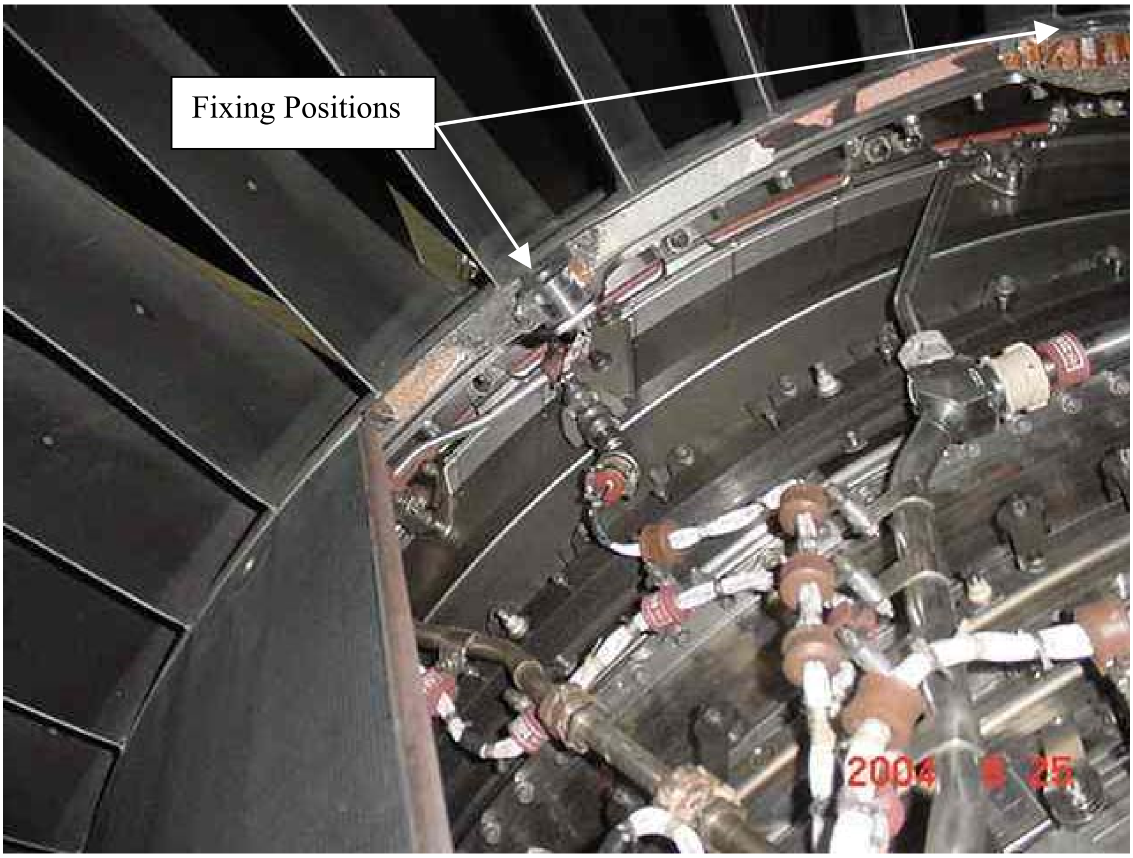


Fig 18 showing remains of the LH Upper Fairing (front)

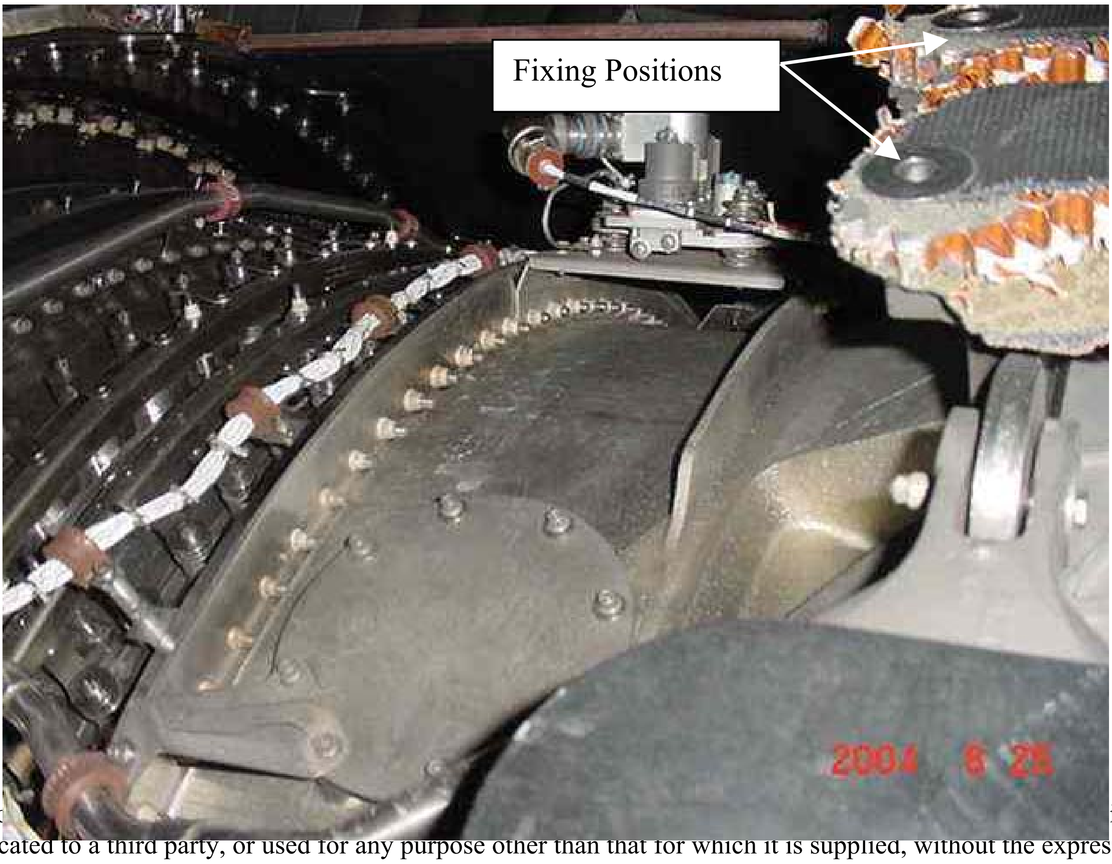


Fig 19 showing remains of the LH Upper Fairing (rear)

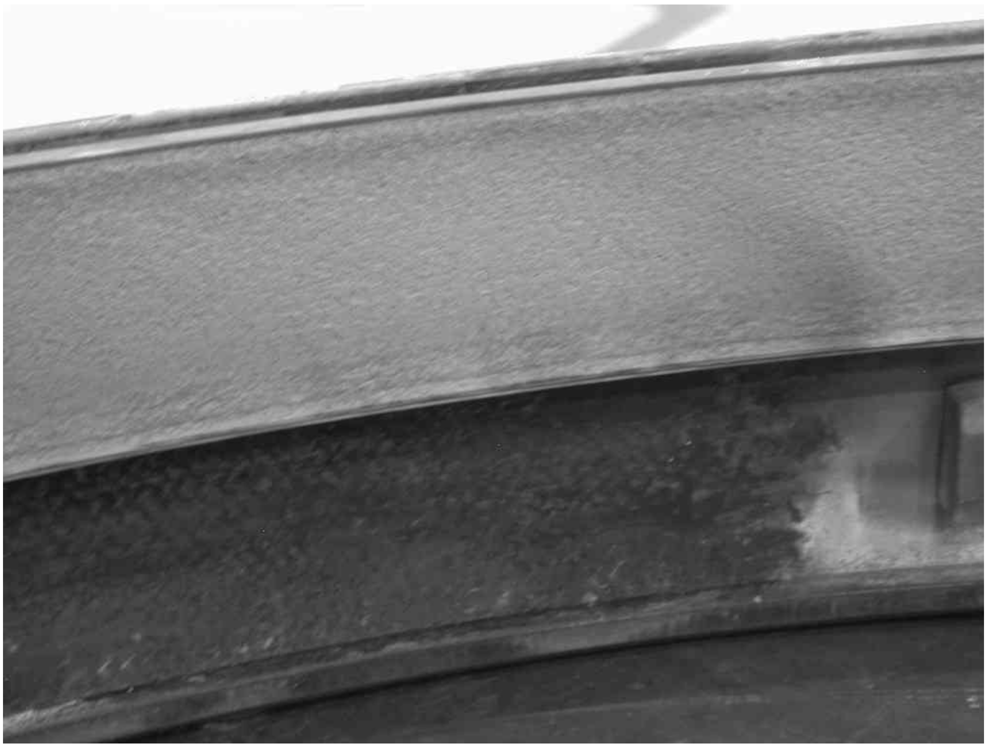


Fig 20 showing condition of the HP compressor stage 5 lining from ESN51363 (not sprayed by company B)

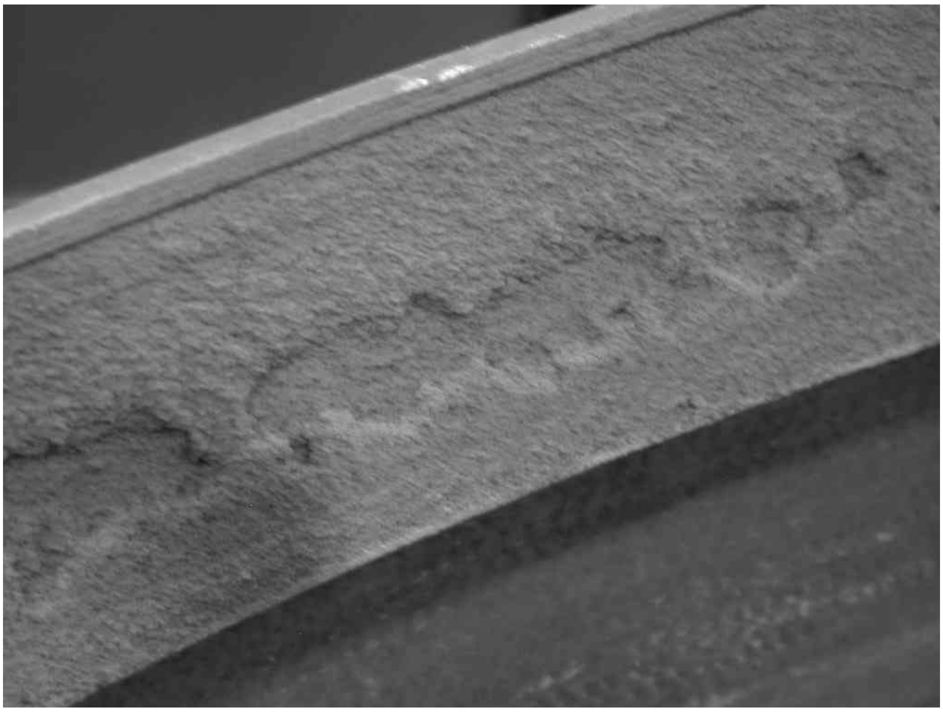


Fig 21 showing condition of the HP compressor stage 6 lining from ESN51363 (sprayed by company B)

Fig 22 showing condition of the HP compressor stage 5 lining from ESN51058 (not sprayed by company B)

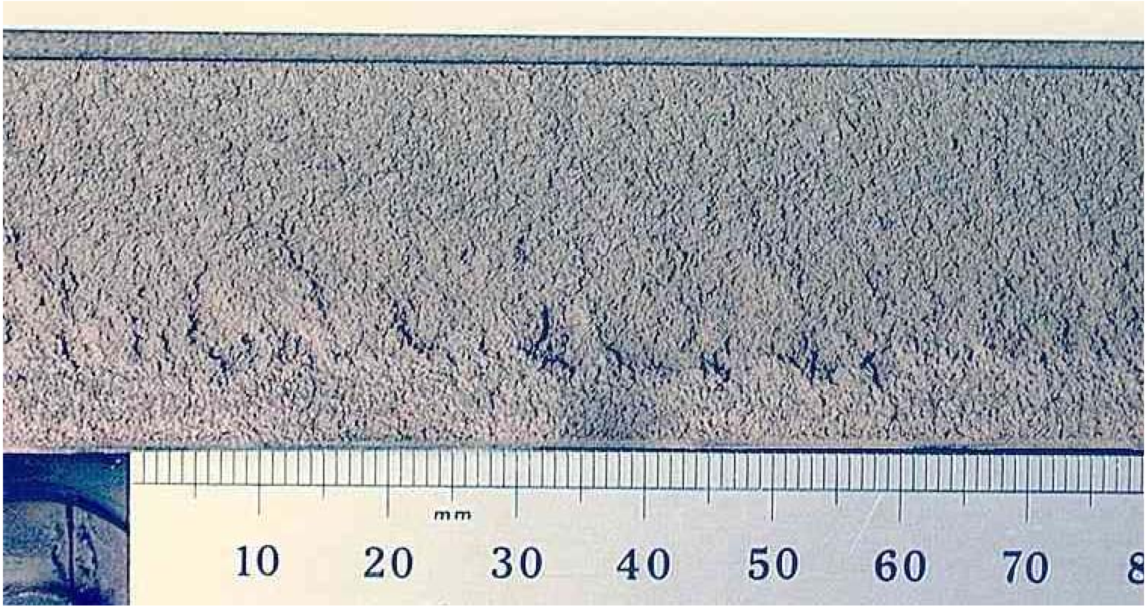


Fig 23 showing condition of the HP compressor stage 6 lining from ESN51058 (sprayed by company B)

TECHNICAL NOTE NO. 05-14
TECHNOLOGY DEPARTMENT

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TITLE:

Evaluation of NiCrAl-Bentonite (LCA-314) Coatings by AST on Trent 800 Stage 6 Compressor Rings after Flight Exposure.

Praxair Surface Technologies, Inc
1500 Polco Street
Indianapolis, IN 46224

Report Outline

Note : On the numerous SEM micrographs included here, the actual magnification is given in the caption, or can be estimated from the micron bar. The magnification on the micrograph is not for the final printed size shown here.

Background of LCA-314 Coating by AST

The compressor abradable coating of NiCrAl-Bentonite (LCA-314) has been applied to Trent 800 ring substrates by Asian Surface Technologies (AST) for several years. The coating is applied by the flame-spray technique using PST Standard Process Instruction 943653.01, and Job Instruction RR-D207-1, which is specific to the stage 6 total operation. The powder is obtained from Sulzer-Metco (Metco 314NS), and has the nominal composition of Ni-4Cr–4Al and 15-30 Bentonite (wt. %) and a typical particle size range of 45 to 150 microns. Bentonite is a clay, nominally 5SiO2.Al2O3 (silica – 25 wt.% alumina). The powder is composed of a clay particle jacketed with about a 0.4 mil (10 microns) thick layer of NiCrAl. For the Trent rings, Rolls-Royce Engine Manual Section EM: Task 72-41-41-300-021, referred to Engine Overhaul Process Manual (TSD594J) OP 704 is followed. Per this instruction the quality of the coating for overhaul work is judged only by its hardness. The average acceptable hardness on the R15Y scale is 45 to 55, with a minimum individual hardness reading of 40 and a maximum individual reading of 60.

In the overhaul coating of NiCrAl-Bentonite, AST has gone well beyond the hardness measurement to control quality. PST Quality Control Instruction (QCI No. 943653) evaluates the metallographic structure as well, using a sample that is sprayed just before the ring itself is coated with exactly the same process conditions. Normally, such detail analysis would only be required for OEM coatings. This QCI, approved by PST and created in compliance with RR CME Specifications, is included in the Appendix. The QCI makes a visual evaluation of porosity and metal content in comparison to the two polished section micrographs of this coating (LCA-314). The R15Y hardness data for each part and the polished metallographic sample for each coating qualification are maintained, and cross-linked with identification number, date, ring stage and incoming RR engine number.

The procedure for overhaul coating of compressor rings was that SAESL would dis-assemble the engine, remove old abradable coating from the compressor rings using a high pressure waterjet, do a dimensional analysis, inspect for cracks, degrease, and then turn the rings over to AST who operated a coating cell on the SAESL site in Singapore. AST would then mask areas not to be coated, grit blast the recessed channel and coat with Metco 450 bondcoat (Praxair FP-450NS, SPI 943652.01, QCI 943652) then with LCA-314. The coating of LCA-314 was done by using a TAFA FP-73 flame spray device operating on oxygen and acetylene gases. Due to the modest thermal mass of the stage 6 compressor ring, and the requirement by the RR Overhaul Manual to not exceed 150 ^{o}C substrate temperature, the coating was stopped every 10 torch passes to check that substrate temperature was within bounds. An air cooling jet was directed on the OD of the ring, while the ID was coated. About 80-90 torch cycles are needed for the stage 6 ring to obtain the coating thickness required. Further, due to the powder capacity of the TAFA Model 1264 dispenser and the rate of powder usage, the coating cycle was stopped once for powder addition, a common industry practice. The masking and any overspray would be removed, and the part would be inspected for being within the required dimensions. The coated ring was then sent back to SAESL for final machining of the LCA-314 coating surface.

Two compressor stage 6 rings have been brought to the attention of AST and are the subject of this evaluation report by PST. The rings are identified by the Trent 800 engine number, and the quality control coating sample made at the same time by AST is assigned an archive number as well. These QC samples are held by Asian Surface Technologies, Singapore. It has always been the practice to record the QC sample number in relation to the engine number from which the compressor ring has just been removed and the prior coating having been stripped. Thus the newly coated ring will be documented with a (prior) engine number, compressor stage number, and the AST associated QC number. In some cases, the SAESL overhaul group may not put the original ring back in the original engine. If that is done, there is a disconnect between the AST QC number and the (future) ring engine number, but that linkage is recorded by SAESL for their records. In the present case, this change of engine build was done for one ring, and was identified by the diligence of AST.

During the period of coating LCA-314 at AST, at least 53 stage 6 Trent 800 compressor rings were coated. Ultimate customers included Thai Airlines, Malaysian Airlines and Singapore Airlines, all through the AST – SAESL cooperative venture. Only the two rings are discussed here, both from Singapore Airlines, using a sample or the whole ring provided for PST analysis. Recently, two other rings (from engines # 51058 and #51076) have been reported to have experienced unexpected loss of the compressor abradable coating, both from Singapore Airlines. PST has no further details on these latter two rings.

Flight Exposure of Two Compressor Rings

The two stage 6 compressor rings discussed here were from Trent 800 engines 51067 and 51363, which were used in different Boeing 777 aircraft, operated by Singapore Airlines (SIA). The SIA aircraft using these engines typically had flight paths believed to be in the southeast Asia region.

Engine 51067 surged on 25 August 2004 just after take-off from Melbourne, Australia, enroute to Singapore. The engine was shut down and the aircraft returned to the ground. Upon dis-assembly the six stages of the compressor section all showed degrees of loss of abradable coating, more severe toward the rear stages. Stage 1 was a new part coated with a Sherritt Gordon coating by another supplier. Stages 2 through 6 were coated with LCA-314 by AST August 2003. All compressor rings were sent to Rolls-Royce, Derby, England for evaluation. A Technical Report No. SCIR 64628 gave the RR findings. In their summary, stages 2 through 6 showed greater coating loss than normally encountered, with stages 4 to 6 showing almost total loss of the abradable down to the bondcoat. The stage 6 ring was cut for cross section evaluation. Metallographic image analysis at RR found only 29 percent metallic content of the 314 coating, where the RR OEM guideline would call for 40 % typical. A higher number of not fully melted particles were observed, compared to the RR OEM guideline. The coating loss was attributed by RR to progressive erosion, since no hard rubs with the adjacent blades were detected. The bulk of the abradable ring coating (being lost) would not give rub evidence either. The general RR report conclusion was that the AST coating on the stage 6 ring was weak in erosion due to the low metallic content, and by inference higher porosity and Bentonite phases. Yet, the QC samples supplied by AST showed proper hardness and microstructure by RR evaluation (see later for re-evaluation due to QC ID number and engine build number change not initially revealed to AST.) An 8.5-inch long segment of the stage 6 compressor ring from engine 51067 was sent by RR to Indianapolis for the PST evaluation discussed below.

Engine 51363 was recently pulled off-wing of a Boeing 777 by Singapore Airlines due to fall-off in HP compressor efficiency. AST understands from SAESL that the engine had been running for less than six months. The stage 6 case was coated by AST with the abradable in December 2003. SAESL stripped the engine down and allowed AST engineers to examine the parts. They observed what they termed “pluck-out” of the LCA-314 coating around the whole ring circumference in patches in the central part of the coated band. It was also observed that the coating had a vivid brown coloration to its surface, as well as areas of black “burn marks”, that might have been carbon deposits. AST arranged for the whole ring to be sent to PST, Indianapolis for examination. The exam included chipping out small pieces of the coating but not cutting or damaging the ring, which was sent back to AST for delivery back to SAESL for overhaul. This ring was not examined by RR so detailed pictures are included here for any future considerations.

PST Evaluation of Stage 6 Ring, Engine #51067

The AST records show that the stage 6 compressor ring from incoming RR Trent 800 engine 51067 was coated in August 2003. The bondcoat was deposited using Metco 450NS powder, Batch No. 330956, and the LCA-314 abradable was made with Metco 314NS powder, Batch No. W59114. The Sulzer Metco powder certification sheet for this 314NS lot is included in the Appendix.

RR Derby supplied PST with an 8.5-inch long segment from the compressor ring for our evaluation. Figure 1 shows the as-received ring. PST was to do four evaluations with this ring sample. Examination of the as-received surface in the scanning electron microscope (SEM) and with simultaneous chemical analysis using energy-dispersive spectroscopy (EDS) of the SEM's electron beam generated x-rays from the sample surface. Then the ring sample was cut and mounted in cross section and polished metallographically to examine the residual coating structure and ring substrate. The substrate was Inconel alloy 907 (IN 907). A piece of the uncoated part of the stage 6 ring was cut and machined to a 1-inch long sample, suitable for thermal expansion measurement of IN 907 at PST. Finally, a segment of the coated ring was cut for clean air erosion testing of the residual coating.

Surface analysis of #51067 Stage 6

Figure 2 shows the macroscopic view of the residual coating on the ring sample. There appeared to be several distinct regions in terms of surface texture, marked A through D. There was clearly more residual coating near the forward edge of the ring, some but a lesser amount in the area near the rear, but much less coating in the middle of the section. As shown on Fig. 2, area A is near the forward edge of the ring, B is back slightly to the rear, C is about mid-ring where the erosion is more extensive, and D is near the rear edge of the ring. The SEM examination of the areas A through D revealed the following.

Figure 3 (a through d) shows the respective areas identified in Figure 2, at much higher magnification. Fig. 3a shows area A as having high surface roughness of the residual LCA-314 coating. The individual NiCrAl-jacketed Bentonite particles can be resolved. Many of these particles were seen to have the NiCrAl surface skin eroded to expose the clay core. In some areas, large zones are seen that penetrate deep into the coating and show non-eroded NiCrAl particle skins. These zones are thought to have occurred due to erosion/ejection of a large block of the coating, just at the end of the final flight exposure of the engine, which precluded further NiCrAl skin erosion.

Fig. 3b shows area B, with the same observations made as in area A. Figure 3c shows the smoother appearing area C. Area C has a nodular texture, and was found by EDS to contain mainly the Metco 450 elements, which is the bondcoat used for this system. This bondcoat is sprayed to intentionally have a rough, adherent surface, and the smooth surface here is due to erosion after the last of the LCA-314 was eroded away. Fig. 3d shows the detail of area D, which is similar to areas A and B, with residual LCA-314 coating showing erosion of the NiCrAl skin on many particles and the recent loss of large blocks of coating.

While this as-received surface was in the SEM, EDS analysis of areas A and C were obtained. These results are as follows:

SEM / EDS Analyses of As-received surface of stage 6 ring, engine #51067

Element	Area A residual 314	Area C, mainly 450 bondcoat
C	15.5	11.1
O	19.0	27.2
Mg	0.5	2.9
Al	9.8	8.1
Si	3.0	5.5
P	0.1	0.3
S	0.4	1.9
Cl	0.2	0.4
K	0.2	1.0
Ca	0.3	2.0
Cr	3.6	1.4
Fe	1.4	2.6
Ni	45.4	34.0
Ti	0.2	0.6
Co	0.5	1.0

The carbon may be from soot deposits, and the oxygen will be seen to be from the Bentonite clay but also oxidation of the coating. The Cr is from the NiCrAl jacket and is seen mainly in area A, but some still with area C, which was mostly the Ni-5Al bondcoat. The Al and Si are principally with the Bentonite and are found in both areas, so some clay residue still was on the bondcoat, area C. There are several elements not expected in either the 314 or 450 compositions: Ca, Mg, K, Ti and sulfur. These are found in both areas, but more concentrated on the residual bondcoat, area C. Recall that the SEM / EDS is a near-surface analysis, receiving x-rays from perhaps only about a 1-micron surface layer (SEM and X-Ray Microanalysis, 2nd Ed., Goldstein, et al).

Cross sectional analysis of #51067 stage 6

Next the cross section of the coated ring was examined, and Figure 4 shows the macroscopic view of the mounted sample, with the forward and rearward directions noted. These directions refer to the front-to-rear directions of the engine, and with normal through-engine airflow going from front to rear.

Figure 5 shows the microscopic detail of the coating and substrate within the ring recess of Fig. 4, near the forward, center and rear edge of the ring. This view gives the indication that the forward edge of the ring protects the coating from erosion to a degree. At higher magnification, Figure 6 shows the residual LCA-314 coating near the forward edge of the ring, where erosion-thinning of the NCrAl jacket layer is predominately seen on the side of the particles facing engine airflow, and subsequent erosion of the Bentonite clay cores. Figure 7 is another area at the surface of the coating, now near the rear edge. Again, leading edge erosion of the particle jacket is seen, then allowing Bentonite erosion. Deep porous zones are seen in cross section (now filled with metallographic mounting epoxy), as was seen from the as-received surface of Fig. 3. Fig. 7 also shows that the surfaces and boundaries between NiCrAl particles are heavily oxidized.

Figure 8 shows the residual LCA-314 coating at the rear of the ring, just at the junction where the 314 coating is present and is totally removed, with only the bondcoat remaining. This would be the area of highest angle of erosion impingement. Figure 9 is the microstructure near the center of the ring recess, showing apparent complete loss of the LCA-314 coating and only bondcoat remaining. The Metco 450 bondcoat has heavy internal oxidation with oxide layers between the splats of the Ni-5Al material. These oxide layers have interrupted the cohesive bond between the 450 particles, and some particles have cracks within the oxide inter-layer. The IN 907 substrate is also heavily oxidized.

Figure 10a shows the microstructure of the Metco 450 bondcoat on the IN 907 substrate, both heavily oxidized. Nickel oxide (by EDS) layers between the 450 coating splats have allowed de-cohesion of splats due to crack formation and porosity in this oxide layer. Figure 10b also shows the 450 bondcoat on the IN 907 substrate and the effects of oxidation. Large iron oxide (by EDS) particles penetrate into the IN 907, and these particles are typically cracked normal to the IN 907 surface. There is also an inner layer of fine particle internal oxidation within the IN 907 near the surface.

Figure 11a is a cross section seen in the SEM of the LCA-314 coating near the outer surface, showing inter-particle oxide at the NiCrAl splat boundaries. Figure 11b is further detail of the inter-splat oxidation of NiCrAl and separation between splats caused by the weak oxide layer.

Figure 12 shows the uncoated, oxidized backside of the stage 6 compressor ring in cross section in the SEM. The EDS system can also obtain a wt. percent value for oxygen, and from the element ratio, the outer dark grey oxide layer is judged to be Fe_3O_4. The light grey inner layer is Ni,Co,Fe-oxide with some Nb, possible a fine internal particle oxide. Cracks are seen to form from the surface of the IN 907 oxide layer then further oxidize along the crack surfaces with a dark Fe_3O_4 scale. Crack penetration stops just at the inner layer of the oxide and does not enter the clean IN 907 substrate. One long crack is seen to run through both layers, and apparently occurred near the end of service for this ring, having little further oxidation growth on the flanks of the crack surfaces.

SEM / EDS analyses of the separate phases were also done on the polished cross section of this stage 6 ring with residual coatings. Clean IN 907, away from any surface oxide, Bentonite clay particles and the NiCrAl metallic jacket were analyzed. There were indications of carbon but this was thought to be an artifact of epoxy infiltration and the final diamond polishing step, so it was removed and the analysis normalized to 100 %. For comparison, the Bentonite clay cores of new, never-sprayed, NiCrAl-Bentonite powder was analyzed in polished cross section to remove the issue of engine contamination effects.

Polished Cross Section #51067 stage 6

IN-907 substrate

Element	Ring substrate	Book value
Si	0.3	
Nb	5.2	4.7
Ti	1.6	1.5
Fe	42.5	42
Co	13.4	13
Ni	37.0	38

So when the nominal composition is known, as in the case of IN-907, the SEM / EDS analysis is seen to be very close to the book value.

NiCrAl metallic jacket of LCA-314

Element	Residual 314 metal*	
Al	4.0	
Si	1.5	
Cr	8.1	
Fe	1.0	
Ni	85.4	*average of 2 areas

Bentonite clay particles

Element	Residual LCA-314 *	Book value	Metco 314NS powder*	
O	50.6	51.7	50.2	
Na	1.7		1.3	
Mg	1.5		2.0	
Al	10.6	13.4	12.3	
Si	26.1	34.9	29.2	
Cl	0.1			
K	0.6		0.4	
Ca	0.2		1.0	
Cr	0.7			
Fe	2.0		2.4	
Ni	5.8		1.4	*average of 3 particles

The Bentonite is reasonably close to the calculated value for 5 $SiO_2.Al_2O_3$, and would be closer if the Ni, Cr and Fe were removed (probably due to underlying NiCrAl) and the other unexpected elements were removed and the Si, Al and oxygen normalized to 100%. The same unexpected elements found earlier in the surface analysis of this same sample are now found in the Bentonite clay phase of the polished cross section. These impurities are in the Bentonite clay, possibly not an engine contaminate. The sulfur found in the surface analysis was not found in the cross section, even near the surface. This suggests that S was in a very thin layer on the surface. However, when the coating on engine #51363 stage 6 ring is analyzed (see below) the unexpected impurities will be found again in a foreign surface layer at much higher concentrations.

Cross section analysis for percent metal in residual LCA-314 coating on #51067 stage 6

The expected amount of metallic phase in the LCA-314 coating is 40%, typical. In the RR report of their sample cut from this same stage 6 ring from engine #51067, only 29 percent was found by the image analysis method. In that method, the polished cross section of the sample is analyzed in the optical microscope with computer-based software that separates the image into distinct levels of grey-scale brightness, with the metal phase being fully bright, the clay being a darker grey level and the porosity another level of grey. Only the metallic phase was of interest.

While PST has image analysis capabilities, we did not have an adequate metallic standard sample in the phase size and percentage range to calibrate the method. So an older method was used called linear intercept analysis, which is perhaps the original standard for phase analysis methods for polished cross sections. In the PST application of this method, the polished sample was imaged in the SEM, which actually takes sharper contrast and edge detail micrographs than the optical microscope. These micrographs were printed on high contrast glossy photo paper. To avoid bias in the areas selected, and to provide some idea of the area-to-area variability of the measurement, five areas were imaged, all in a line with edge-to-edge contact, each with a true area of 406 by 612 microns (16 x 24 mils). These glossy prints were photocopied on paper for subsequent drawing of seven parallel equi-spaced lines across the width of the micrograph for the linear intercept analysis. The total line length analyzed per micrograph was thus nearly 4300 microns (168 mils). The bright image of the NiCrAl phase was measured as intercept lengths along the fixed lines, summed along the line, and divided by the line length. A typical glossy micrograph is shown in Figure 13a, and its photocopy with the seven analysis lines drawn is shown in Figure 13b. In this method, the absolute magnification does not need to be known. The five areas in the coating were taken from the residual LCA-314 coating near the forward edge of the seal, where considerable 314 was still present, and at a fixed distance above the 450 bondcoat. This is more clearly seen in Figure 13c. Each of the seven lines of intercept analysis was averaged per area, and this value was recorded below.

<u>Linear intercept analysis of percent metal phase in residual LCA- 314 coating on #51067 stage 6</u>

Area	% Intercept	Std. Dev. of 7 lines
1	35.5	11.3
2	27.1	10.5
3	20.9	8.0
4	37.4	9.2
5	29.6	6.8

These five areas gave an overall average of 27.0 % metallic phase, with a five-area standard deviation of the individual averages of 9.7 % metallic phase. Thus, the PST analysis of the residual 314 on the engine-run stage 6 compressor ring of engine #51067 agrees very closely with the RR report of 29% metal on the same ring sample.

Microhardness of phases in residual LCA-314 on #51067 stage 6 sample

The final test done on this polished cross section sample of the stage 6 compressor ring from #51067 was the microhardness of the clay phase and the NiCrAl jacket, in comparison to the quality control sample made by AST. This QC sample, #668, was originally identified as the QC sample done just before the #51067 ring was coated. AST later found that it related to another engine build number, since SAESL did not return the ring from #51067 to that engine upon re-assembly. It is still representative of an as-coated LCA-314 coating for the present purpose.

The microhardness was done on a Beuhler Model 1600 microhardness machine, using a 100 g load on the clay phase and 50 g on the NiCrAl, with six readings per average reported.

	Microhardness, kg/mm^2	
	Ring coating #51067	QC sample #668
Clay phase		
Average	614	554
Std. Dev.	39	83
NiCrAl phase		
Average	265	160
Std. Dev.	81	33

Thus the clay phase has no significant difference in hardness after engine exposure, and while the NiCrAl appears harder after exposure, the difference is not statistically significant.

PST Evaluation of Stage 6 Ring, Engine #51363

After the #51067 engine ring evaluation was underway, a second stage 6 compressor ring with AST-coated LCA-314 abradable coating was brought to the attention of PST. This ring was from engine #51363 and its’ coating had several similar features and several differences compared to the first ring. There was much more coating still intact, there was no macroscopic evidence for a blade tip rub, there was a slight overall depression of the LCA-314 surface from the IN 907 edge surfaces (suggesting some general erosion), the residual LCA-314 coating had a very noticeable brown / gray surface coloration, and most noticeable was a string of spalled zones of the coating around the whole ID surface centered in the rub path. These intermittent spall patches had a width of about 1/3 of the total coated width.

Macroscopic observations of #51363 stage 6

Figure 14 shows the whole ring inside surface, taken in a series of over-lapping pictures. The strong brown coloration of the coating surface is clearly seen. The numbers on the ring are for location reference, applied by PST. The coating is in the recessed track at the top of the figures, and the very top edge is the aft direction of the ring relative to the engine. The total part width seen is 3.3 inches and the coated track is about 1.1 inches wide. The orientation of the coated track and the spall zone is similar to the #51067 ring, seen in Figure 15, where the IN 907 ring cross section is also showing. The spall zone is mostly centered over the local thin web of the IN 907 casting, which is about 0.1 inch thick. The beveled lower edge of the ring substrate of Fig. 15 identifies the rear or aft direction, per the RR report.

Figure 16 shows examples of the spall patches at about 3x magnification. It is seen that while they are quite irregular in shape and size, there is somewhat of a tendency to have a similar depth to the spall. Measurements were taken by micrometer and caliper of typical spall patch dimensions, and these are listed in Figure 17. For future reference, the AST position numbers around the ring (small tapes with numbers attached to the ring, as-received at PST) are coordinated with new position numbers added at PST in terms of angular position around the ring. The total recess depth of the track is about 0.10 inches, and this is to be filled with the LCA-314 coating. The spall depth measurements shown on Fig. 17 average about 0.05 inches (50 mils), so the spall is to about the mid-plane of the coating thickness.

The surface roughness of the upper layer of the residual LCA-314 coating was measured on the #51363 ring with a Taylor-Hobson portable roughness instrument. This was found to be in the 800 to 900 micro-inch Ra roughness range, on average. It was not possible to measure the roughness at the spall surface due to limited stylus reach.

Both AST and PST measured the superficial hardness of the LCA-314 coating on the ring. AST obtained 45.3, 52.5, 51.3 and 50.1, for an average of 49.8. At Indianapolis R&D, PST obtained 51.0 average for 10 readings, standard deviation 9.7, all on the HR15Y scale. This was a difficult measurement to make requiring two people to hold the ring vertically and take readings on the ID coating. It does show that the ring coating still had the hardness of the RR specification, even after engine exposure.

Coating chip examination from #51363 stage 6

Next, a chip of the coating was removed from the ring. Care was taken to remove material fore and aft of the chip area first, so that the chip would come off easily. These chips were analyzed for surface structure and composition with SEM / EDS, mounted in cross section for further SEM / EDS analysis, and examined by the linear intercept method described earlier for percent metal phase.

First, the percent metal measurement results. Three areas of the polished cross section of the chip were photographed at 100X in the optical microscope, and these micrographs are shown in Figure 18a. These 4 x 5-inch micrographs were enlarged on the photocopy machine to about 7 x 9 inches, and these enlargements were scribed with 7 lines along the wide direction, spaced apart by 1-inch. These were measured for metal phase intercept segment lengths using a magnifying glass and steel rule (0.01 inch resolution), as was done before for the #51067 ring. The results for this LCA-314 coating chip are as follows:

<u>Linear intercept analysis of percent metal phase in LCA-314 coating chip from #51363 stage 6</u>

Area	% Intercept	Std. Dev. of 7 lines
1	44.1	11.4
2	46.6	6.7
3	38.5	11.1

These three areas gave an overall average of 43.1 % metallic phase, with a three-area standard deviation of 4.2 % metallic phase.

The polished cross section of the #51363 stage 6 coating chip is again shown in Figure 18b, at higher optical microscope magnification. It is seen that this coating, like the remnant LCA-314 on #51067, is very oxidized. The splat interfaces of the NiCrAl phase are all decorated with oxide and instances of cracking and separation between splats are seen.

Comparison of oxidation - #51363 & # 51067, both stage 6 with QC sample #864

At this point it is useful to compare the degree of oxide within the LCA-314 coating for the two engine-run samples shown above, and the as-coated QC sample from AST which was done just prior to the #51363 stage 6 ring coating. These are shown in polished cross section at a common optical microscope magnification in Figure 18c. The as-coated #864 will be discussed further below. It was found that the as-coated LCA-314 does have slight inter-splat oxide on the NiCrAl phase, as this is an oxy-acetylene flames-sprayed coating. However, the degree of oxide is very minor. The degree of oxidation from the engine-run coatings is much more extensive, even penetrating grain boundaries within the NiCrAl particles, whereas in #864 the oxide was only on the particle surface. It further appears that #51067 is at a more advanced state of oxidation than #51363.

Surface analysis of #51363 stage 6 coating chip

Next is the surface analysis of the free-standing chip of the LCA-314 coating. Figure 19a is the SEM image of the backside of the chip, which was used for EDS analysis in comparison to the front or outer surface of the chip, Figure 19b. The front surface of the chip has two features of note, small rub patches showing bright metallic scars which are not easily visible to the eye and a fine-grained deposit on the 314 coating surface, which is the brown-colored surface of Fig. 14. It is believed that the very light rub seen in Fig. 19b occurred upon the last engine shut-down, since the rub scar surface is still bright and non-oxidized. The main interest of this sample is the surface deposit. The results of the EDS analysis are shown in Figure 20. These analyses are of the whole areas imaged in Figs. 19a and 19b, for the backside and front side of the chip. The original EDS data shows the expected backside analysis for a NiCrAl-Bentonite coating, with only a slight impurity amount of Na. The front side is quite different, with considerable Na, Mg, Ca, K and sulfur. There is some carbon indicated at a low level, and about the same on both surfaces. To emphasize the differences between the two surfaces, the original values were manipulated in two stages. As seen on Fig. 20, first the carbon was removed and the balance normalized to 100 %. Then the Ni, Cr and Fe were removed (due to the metallic jacket phase) and again normalized to 100%. The last comparison of surface to backside thus compares what normally would be just the Bentonite phase, but the front side has in addition Na, Mg, Ca, K and sulfur. These are the principal elements, perhaps as oxides, that are believed to have given the brown colored coating over the 314 coating surface.

The coating chip in polished cross section was shown in Figure 18 (optical), and now is seen in the SEM image of Figure 21a, except at higher magnification and just at the front side or surface edge. The surface deposit can now be seen in cross section, and is of variable thickness, but up to about 20 microns thick in areas. This is a finer grained material than the Bentonite, and is seen to penetrate into the LCA-314 coating. The penetration was measured to be as much as 15 mils in some areas. It penetrates into the original coating’s porosity, which by design is quite open and extensive. Figure 21b is the same area, at slightly higher magnification, but with an analysis box indicted on the micrograph. This area of the surface deposit was then analyzed by

EDS. A second, similar area of the surface deposit nearby but not indicated with a box was also analyzed, and these results are given in Figure 22. The two areas are very similar in composition. This original data was manipulated as before, to remove carbon, Ni+Cr+Fe, and now in this mounted cross section a correction for infiltrated epoxy. The pure epoxy of the same mount was analyzed to be about 80 carbon + 20 oxygen, by weight, using EDS. The final result is the average of the two areas of the surface deposit, after all these corrections, and is shown in Fig. 22.

The original surface and cross section EDS analyses of the brown-colored deposit are now compared, after the corrections to remove the LCA-314 coating and epoxy influences.

Comparison of EDS results for surface deposit on sample chip from #51363 stage 6

Element	Free chip surface	Cross section surface layer
O	51	55
Na	11.5	9
Mg	5.5	4.5
Al	17.5	7.5
Si	5.5	9.5
S	6	5.5
K	0.5	1.5
Ca	2	1.5
Ti		1.5
Zn		3.5
P		0.5

The surface deposit analysis is essentially the same for surface or cross section samples, and is probably an oxide with main constituents Na, Mg, Al, Si and Ca, with the addition of sulfur in some form.

Finally, the microhardness of the coating phases were measured and compared to the #51067 and QC data above.

Microhardness, kg/mm^2

	Ring coating #51067	QC sample #668	Ring coating #51363
Clay phase			
Average	614	554	605
Std. Dev.	39	83	23
NiCrAl phase			
Average	265	160	252
Std. Dev.	81	33	69

The phases are essentially the same hardness, whether in the ring or QC coatings. In the #51363 ring coating chip, the surface deposit was also hardness tested in the polished cross section. It was very soft, averaging 24 kg/mm^2, using only a 10 g load.

Evaluation of AST QC Sample #668

In this section, a QC coating sample of LCA-314 was analyzed for percent metallic phase. This is not required for overhaul coating work, but of interest in that the two evaluations of the #51067 engine stage 6 compressor ring coating of 314 both found it to be low on metal phase after flight service. Sample #668 was coated by AST just before the stage 6 ring that was returned from engine #51067, and thought to be the relevant QC coating. It turned out that the coated ring was put in another engine, not #51067. The actual QC sample #466 for engine #51067 was determined by AST's search of SAESL records, and that sample is evaluated below. The Metco powder lot W57192 was used for this #668 sample, and that powder certification is in the Appendix.

While the #668 sample was examined extensively, the effort was not wasted. One of the questions that arose as to why both the PST and RR evaluation of the engine-run #51067 LCA-314 coating on stage 6 compressor gave such low percent metal phase was directed at polishing methods. What was done here with the #668 QC sample was to polish it by three methods and do the linear intercept analysis on each polish for percent metal. The polish methods are considered by PST to be somewhat aggressive (Method 4), normal polish and used in our QCI for LCA-314 (Method 10) and a low stress finish method used with many TBC coatings by PST (Method 19G). These polishing methods are given in the Appendix.

The results for each polish plane on the same metallurgical mount sample (vacuum epoxy infiltrated first) are as follows:

Linear intercept analysis of percent metallic phase in #668 QC sample of LCA-314

	Area	% Intercept	Std. Dev. of 7 lines
Method 4			
	1	51.2	14.9
	2	43.9	14.8
	3	41.5	14.3
		Average	Std. Dev. of 3 areas
Overall		45.6	5.0
Method 10			
	1	49.2	14.6
	2	51.1	19.2
	3	42.8	8.1
		Average	Std. Dev. of 3 areas
Overall		47.7	4.4

Method 19G

1	44.6	7.7
2	47.6	11.2
3	42.6	13.6
	Average	Std. Dev. of 3 areas
Overall	44.9	2.5

This evaluation shows that the coating is quite robust and not subject to distortion or pullout by the variation of polish methods used here. Good vacuum epoxy infiltration may be the key element.

The superficial hardness of this same #668 sample was measured by AST and given in the RR report as 49.4 on the HR15Y scale.

Evaluation of AST QC Sample #466

The AST QC sample #466 has been identified as the quality sample coated with LCA-314 just prior to the stage 6 compressor ring for Trent engine #51067. It was coated with Metco 314NS powder, lot W59114, and that lot certification is included in the Appendix. Interestingly, comparing the two Metco powder lots, it can be seen that at least a 2 wt. percent variation exists for the amount of Bentonite present, and about 0.8 wt. percent difference in the amount of Al and Cr.

The QC sample panel #466 was tested at AST for superficial hardness and the result was 51.7 with a standard deviation for 10 readings of 3.2 units. No readings were below 44 or higher than 56.

The QC panel was sectioned at Indianapolis and mounted in vacuum impregnation epoxy and polished Method 10. The cross sectioned sample was examined in the SEM where three random areas were photographed at 200 X magnification. The images were printed on glossy photo paper at 425 X, photocopied to plain paper for the linear intercept metal phase analysis, just like all previous samples. The image analysis results are as follows:

Linear intercept analysis of percent metallic phase in #466 QC sample of LCA-314

	Area	% Intercept	Std. Dev. of 7 lines
	1	37.8	11.7
	2	38.8	9.3
	3	44.9	9.5
		Average	Std. Dev. of 3 areas
Overall		40.5	3.8

Thus, the two QC samples examined here, made at different times by AST and with different powder lots are statistically identical for both hardness and percent metal phase, and both are well within the limits established for the approved Metco-314 coating.

Evaluation of AST QC Sample #864

The AST QC hardness panel #864 is the LCA-314 coating deposited just before the #51363 stage 6 compressor ring was coated. The 10-impression R15Y average hardness value at AST was 45.7 (std. dev. = 3.9). This panel was sent to PST for metallographic examination. A slice was taken, cleaned and dried, mounted in cross section using vacuum impregnated epoxy, then polished by Method 10.

Five micrographs at 100 X magnification of the polished section were taken in an edge-to-edge series. These were enlarged 2X by photocopy, then each of the five areas were analyzed by the seven line linear intercept method used throughout this study. The result for the 5-area average percent metal phase is as follows.

<u>Linear intercept analysis of percent metallic phase in #864 QC sample of LCA-314</u>

Area	% Intercept	Std. Dev. of 7 lines
1	41.9	4.7
2	35.4	11.4
3	41.9	8.2
4	43.0	9.1
5	42.4	8.3
	Average	Std. Dev. of 5 areas
Overall	40.9	3.1

This sample is within specification for both percent metal and superficial hardness.

Oxidation Testing of IN 907

The stage 6 compressor ring from engine #51067 was oxidized during service, as seen in Fig. 12. PST does not know the average service temperature of the stage 6 compressor ring, but the RR report suggests it should be about 600 ^{o}C. PST further does not know the time the ring had been in service. The ring may have had several overhaul cycles so the total time would need to be the sum of the cycle times. This is because the oxide scale on the OD of the ring is not removed by the overhaul process, and the incoming dark grey oxide on these rings has been noted by AST. Figure 12 shows areas where the total oxide layer thickness is about 173 microns, which is composed of about 106 microns of an internal oxide layer plus about 65 microns of the outer Fe_3O_4 oxide layer.

To establish some idea of the oxidation rate at 600 ^{o}C, pieces were cut of IN 907 from the scrap stage 6 ring of #51067, roughly ground clean, and exposed in furnace oxidation in static air for different times up to 356 hours. The oxidized alloy samples were mounted in cross section and the oxide layer thicknesses were measured. Figures 23 and 24 show the layer thickness data plotted as a function of square root of time, and it is seen to be a reasonable fit for both the total oxide thickness and just the internal oxidation layer thickness.

The fit equations from this data were used to estimate the time at 600 ^{o}C it would take to generate the oxide layer thicknesses found in Fig. 12 for the bare IN 907 alloy. This calculation gives about 7700 hours using the total oxide thickness or about 10,000 hours using just internal oxide thickness results. If these times are judged to be too long relative to the engine service time, it may be that the engine exposure temperature was higher than 600 ^{o}C.

Another estimation is to examine just the internal oxidation layer under the LCA-314 / 450 coatings on the stage 6 ring sample of engine #51067. From Figs. 10, this internal oxide layer varies from 23.5 to 58.8 microns. If it is assumed that the SAESL high pressure waterjet and the AST grit blast procedures removed all pre-existing oxide on the IN 907 when the old coating was stripped, this oxide layer is then only due to the last engine run cycle. Using the equation for internal oxidation layer growth, given on Fig. 24, the measured layer thicknesses would need between 480 and 3084 hours to grow.

Oxidation Testing of NiCrAl-Bentonite Coating

The oxidation of the NiCrAl-Bentonite coating on the #51067 stage 6 ring has been shown earlier. In an attempt to duplicate such oxidation patterns, a sample of NiCrAl-Bentonite from the PST archives was exposed to static air oxidation at 600 ^{o}C, for various times up to 453 hours. The oxidation observed in the polished cross sections was minimal, so only the longest time exposure sample will be discussed here. Figure 25 shows the SEM cross section microstructure of the 453 hour sample. This micrograph can be compared to Fig. 11a of the engine-run LCA-314 coating, taken at the same magnification. In the 453 hour sample the oxide is thin and in most cases limited to the surface of the splats or splat interfaces. In the engine-run coating, the oxide layer is wider, has penetrated all inter-splat boundaries. It would appear that the engine-run 314 coating has seen either much longer time than 453 hours at 600 ^{o}C (the expected stage 6 compressor temperature) or run at a higher temperature than 600 ^{o}C.

Thermal Expansion Testing of IN 907 and NiCrAl-Bentonite

The idea to test the thermal expansion of the two materials, the ring alloy and the LCA-314 coating came about due to the observed spallation patches or “pluck-out” of the 314 seen in the middle of the coated band of #51363. Without any blade rub wear, this loss of material could be considered to be due to many cycles of mechanical stressing due to a mismatch of thermal expansion. IN 907 is known as a low expansion alloy, said to be suitable for turbine engine components by Inco (see Appendix). In 1975 PST built a thermal expansion apparatus made of single crystal sapphire support rods, and has been in near-constant use. It measures a 1-inch high sample, oriented vertically, and it has several microprocessor-controlled heating cycles to choose from. The cycle used here was to heat at 5 degrees C per minute to 1080 ^{o}C, and then cool at the same rate without a soak pause. Each sample was run twice to insure that the stabilized thermal expansion was obtained. The IN 907 showed no length change after either of the cycles. The NiCrAl-Bentonite coating had a 0.2% shrinkage on the first cycle and 0.1% on the second. The data shown here is all from the second cycle cooling curve, considered to be the best estimate of stabilized thermal expansion.

The IN 907 sample was cut from the #51067 stage 6 ring, in the uncoated flange area. The NiCrAl-Bentonite sample was not from AST, but from much earlier development studies, using a sample that was the same hardness and structure typical of LCA-314, provided by Walt Aton of PST’s Kansas City plant. In addition, a sample of IN 718 was available for comparison so it was run at this time.

The thermal expansion curves for IN 907, NiCrAl-Bentonite and IN 718 are shown in Figures 26 to 28. IN 907 is seen to have a two-stage thermal expansion curve, very low expansion up to about 450 degrees C, then a higher expansion rate above that temperature. The author believes this is due to a reversible phase change in the material. It is reproducible with multiple runs, and shows no hysteresis. The NiCrAl-Bentonite material has a slightly upward curving second order thermal expansion curve. The equation of that expansion curve was fitted and is included on the figure. It was found that the NiCrAl-Bentonite coating has larger thermal expansion than the IN 907 alloy. IN 718 also has a upward curving second order expansion behavior. It was found to have higher expansion than IN 907 at every temperature, but especially below 450 ^{o}C where the alloy might be used in turbine engines.

The mathematical differences between the thermal expansion curves of IN 907 and NiCrAl-Bentonite were found, as an indication of the mismatch between them. Figure 29 shows this difference plot, which reaches a maximum difference in the 400 – 600 ^{o}C range. However, without modulus data it is not possible to estimate the magnitude of the mismatch stress, or to know if it exceeds the fracture strength of the coating. The mismatch is about 0.2 percent, and if all the mismatch is born by the coating it could be beyond its yield point.

Erosion Testing of LCA-314 on Stage 6 Ring, Engine #51067

It was of interest to see if the residual coating on the stage 6 compressor ring was erodable in clean air. PST has no knowledge of the air velocity near stage 6 in the Trent 800, and so the results of the following test have no connection to the engine environment. In fact, they were at room temperature, and the stage 6 is estimated to be at about 600 ^{o}C in the engine. The PST test is based on the alumina particle erosion test, except in this case the unit was carefully cleaned of all alumina dust. The setup was the same in terms of standoff (3.5 inches), impingement angle (20 degrees, low angle), as shown in Figure 30. The air was run at 60 psig through a 0.185 inch diameter orifice (340 cfh) giving a calculated 500 ft./ sec. gas velocity. The impingement spot on the sample is approximately ¼-inch by a 1-inch oval. The sample was cut from the 51067 stage 6 ring, and had 1.1 x 1.1 inch of residual coated area. The weight loss was measured on a Mettler microbalance after several incremental clean air erosion exposures. The sample did erode as shown in Figure 31. After testing up to 240 seconds, the same sample was placed in a 600 ^{o}C furnace for 4 hours in air, and then tested again in the erosion test. This oxidation appeared to increase the early erosion rate, which then became somewhat constant. The appearance of the erosion sample before and after the first test is shown in Figure 32. The central section of the coating did brighten up somewhat. The main impingement area also coincides with the area where most of the coating was already lost due to engine exposure, and there may be different erosion rates found if more of the engine-exposed LCA-314 coating were in the central jet of erosion.

CMAS Background

A relatively new realization is that airborne dust can be a problem for flying (and even stationary) gas turbine engines. The dust is everywhere and can come from all sources of the earth's crust: dirt, sand, and volcanic ash. A term has even been coined for the troublesome material, CMAS. This stands for calcia-magnesia-alumina-silica, although other minor constituents may also be present. One estimate for the general composition of the earth's crust is as follows:

Oxide	Wt. % as oxide	Wt. % as metal	Wt. % oxygen
CaO	32.9	23.5	9.4
MgO	6.8	4.1	2.7

Al_2O_3	12.0	6.4	5.6
SiO_2	48.3	22.5	25.8

The sum of the oxygen with this list of compounds is 43.5 wt. percent. It will be seen that this and the metal percentages comes very close to that analyzed for a sample of volcanic ash obtained by the author and to the brown deposit on the #51363 stage 6 compressor ring.

Where does CMAS come from? It could be airborne volcanic ash, and Figure 33 shows that some areas in the Pacific are currently active. Mt. Saint Helens in Oregon was active in 1980, and may become active again. Sand and dirt are everywhere, and the fine particle fraction can easily become airborne or it can even be drawn up to the engine during runway take-off as seen in Figure 34.

The known problem for gas turbines is in the high temperature turbine section, where the material can deposit and melt onto the YSZ coatings on turbine blades. The melting point of generic CMAS is about 1250 ^{o}C. This deposit seems to fuse the columnar structure of the EB-PVD YSZ coating on turbine blades, loosing its thermal cycle compliance, and the coating spalls on cooling. One example known to PST relates to a thermally sprayed YSZ coating that has intentional vertical segmentation cracking for compliance. This coating was on outer airseals of a power generation turbine, in the turbine section. The unit was place outside a brick factory, and the silica dust from the factory was drawn into the engine, which affected the YSZ coating the same as in the EB-PVD case. At lower temperatures, as in the compressor section, the effect of CMAS is not yet clear.

Evaluation of Volcanic Dust Sample

PST has no sample or information on the volcanic ash material that might be present in the southeast Asia area. However, the author does have a sample of ash from the Mt. St. Helens eruption of 18 May 1980, which was collected in Portland, Oregon which is over 50 miles away from the eruption. For the analysis here, the ash was tamped lightly into a small DTA alumina cup then imaged in the SEM (Figure 35) and analyzed using EDS. The EDS analysis is as follows:

SEM / EDS analysis of Mt. St. Helens volcanic ash of 1980

Element	Wt. Percent
C	3.6
O	46.6
Na	3.0
Mg	1.0
Al	8.4
Si	27.8
K	1.5
Ca	3.6
Ti	0.4
Fe	4.1

While the St. Helens ash is of different compositional mixture, all the unexpected elements found in the brownish coating on the #51363 stage 6 ring coating are present. The St. Helens ash is richer in silica, while the engine deposit was richer in aluminum and sodium oxides. It is interesting that no sulfur is seen in the ash sample, but was present in the engine deposit.

Summary and Conclusions

This evaluation of why the LCA-314 coating on compressor rings in the RR Trent engines #51067 and #51363 experienced loss has focused on three aspects. One is the actual evidence of the two rings from the flight exposure, trying to understand if they are showing the same or different loss mechanisms. The second aspect is to examine the AST QC samples coated just prior to each ring in question. Third, is to do auxiliary laboratory tests to try to clarify the cause of the observations on the parts. It is understood that the laboratory studies would benefit from knowing actual engine conditions for these specific exposures, such as the stage 6 ring temperature history or the total time of engine operation. Some engine conditions could not be duplicated in the laboratory, such as the atmospheric pressure at that compressor stage, or the actual thermal cycle of the real engine.

First the properties of quality control sample #466 made just before the ring in engine #51067 was coated were measured. It was shown to have 40 % metal phase and a 51.7 average hardness. This meets the specification for that coating, exactly. Another QC sample (#668), coated by AST at a different time and with a different Metco 314 NS powder lot for a different engine (not in question), was examined. This sample had about 45 % metal phase and 49.4 hardness, both values centered exactly on the coating specification. It was further shown on sample #668 that the metal phase analysis was not affected by three different polishing methods. QC sample #864, done just before the #51363 stage 6 ring, was found to have 40.9 % metal phase and 45.7 R15Y hardness, again within specification.

Then there are the flight tested rings themselves. If the flight profile, operating environment and thermal cycle history could be shown to be similar, it could be argued that #51363 represents the early stage of coating loss and #51067 is the late stage. Both coatings have highly oxidized NiCrAl phase particles and splat boundaries. Both show cracks and separation between metal splats allowed by this interface oxidation. Yet, #51363 has much more intact coating, but with large “pluck-outs” of the LCA-314 in the center of the coated band around the whole ring. In #51067, most of the 314 coating is gone, but has a general similarity of most of the central coating being lost, with much more residual coating at the leading and trailing edges of the ring recess track. Erosion seems active for both rings, and neither had indications of hard blade tip rubs. The key observation seems to be the high state of oxidation of the coatings and the clear weakening of the cohesion between the metallic phase particles. And erosion is not just at the surface of the coating. Evidence was shown for deep pockets of missing coating, and even individual particles missing from within the coating creating more internal porosity. This could be due to some mechanism of suction or cavitation caused by an air stream at the surface. The loss of only 1 in 4 particles (with their NiCrAl jackets) from within the depths of an already intentionally porous coating, could explain the low metallic results measured for #51067 stage 6.

#51363 stage 6 also brings evidence of a foreign deposit on its surface. This same collection of CMAS type materials might be present on #51067, but was not as clearly evident. It was found that this material can penetrate into the LCA-314 coating, it is very soft, and the 5-20 micron thick layer on top of the 314 for #51363 likely gave it the vivid brown coloration. While material of this type has been shown to drastically affect the spallation life of YSZ coatings in the turbine section, where the CMAS can be heated to its melting point, it is not known if it can affect compressor abradable coatings. Lower amounts of these same compounds containing Na, Mg, Ca were also found as impurities in the Bentonite clay, even in the starting Metco 314NS powder, but not near the high level concentration as on the surface of #51363.

One of the most important results was the percent metallic phase measurement of coating chips taken from the #51363 stage 6 compressor ring. This measurement gave 43 % metallic phase. The method PST used, linear intercept analysis, was shown to agree almost exactly with RR Derby on the common sample of the residual LCA-314 coating on the #51067 ring. Further, the #51363 stage 6 ring was found to have a 51 R15Y hardness after engine running.

Then the auxiliary laboratory results. The thermal expansion measurements did find a mismatch between the higher expanding NiCrAl-Bentonite coating and the IN 907 substrate alloy. It could be argued that as the system is heated to say, 600 ^{o}C, the LCA-314 coating goes into compression, but at temperature these stresses could relax. However, on cooling the higher expansion coating would also try to contract more than the IN 907, putting the coating into tension. This could lead to vertical cracking in the coating. Repeated cycles could grow these cracks. The complex stress pattern in such a large ring during thermal cycling could also be imagined to allow horizontal cracks to branch from the vertical cracks, and the location of the horizontal crack might just be the plane within the coating where the coating operation was stopped to add powder. This is all speculation, but does suggest one scenario for the early “pluck-out” coating loss on ring #51363.

It was also found that high velocity clean air could cause erosion of the oxidized LCA-314 coating on the #51067 ring. The test temperature was 22 ^{o}C, not 600 ^{o}C, and PST has no idea of the air velocity in the engine near the stage 6 ring. While the erosion rate was slow in these tests, the metallographic cross sections showing the weak, oxidized interfaces between the NiCrAl binder phase in the engine-run samples might allow particle-by-particle loss over time.

The oxidation testing of both IN 907 and NiCrAl-Bentonite coating at 600 ^{o}C, gave rather low rates and much less oxide scale even at 300 – 400 hours than seen in the LCA-314 coating on the engine rings or of the IN 907 under the Metco 450 bondcoat. The question is, could the temperature at the stage 6 compressor ring be higher than 600 ^{o}C to explain this difference?

Conclusions

It is concluded by PST from all the evaluations cited above, that the QC samples coated prior to any given compressor ring do show the same structure and properties of the coating on the ring. This was shown by the direct comparison of QC sample #864 and it’s mating coating on the #51363 stage 6 ring, using the coating chip from that ring. The QC sample had a metal content of 40.9 percent; the coating chip from the ring had 43.1 percent. The QC sample had 45.7 R15Y hardness; the coated ring had 51.0 hardness. The QC sample #466 for #51067 stage 6 ring coating had 51.7 hardness and 40.5 percent metal phase, both within OEM specification for the Metco 314 coating. It follows that the #51067 stage 6 ring coating had the same properties as its QC sample as it left the AST coating cell in August 2003.

The low metal phase measurement obtained here of the residual LCA-314 coating on the #51067 stage 6 ring is believed due to loss of particles deep within the porous coating during engine running, leading to low metal count.

The loss of the coating, apparently mainly due to erosion in flight, was not caused by low metallic content in the coating, but rather by severe oxidation of the coating caused by operating conditions of the engine. It is not proposed that the LCA-314 coating itself is not satisfactory for the application, if run at or below its temperature capability limit. This limit is not known by PST, but the two rings evaluated here could have been run at temperature higher than the recommended use temperature by RR, or even Sulzer-Metco, as shown by what could be considered to be excessive oxidation of both coating and substrate alloy for this application.

It is only suggested that thermal expansion issues could have initiated the coating loss, which was then further carried out by erosion. This would also be exacerbated by high temperature exposure of the stage 6 component.

The foreign surface deposit, of CMAS-type composition, could have only occurred during engine running. It is not known if the routes taken by the aircraft with the present engines with compressor ring coating issues encountered volcanic ash or some other source. This material on the surface and internal to the LCA-314 coating should be further evaluated as a source of coating degradation.

It is not known what effect the substantial amount of sulfur that was found in the foreign surface coating on both compressor rings had on the LCA-314 coating longevity.

Acknowledgements

This study could not have been done without the substantial help of Richard Hill, Ken Beard, Ming Hui Kwang, Samual Tang and Fred Mundt. They supplied all the background information from AST and the Quality Department that was obtained early in the meetings at SAESL and RR Derby. They continued during this study to make sure the facts were correct. Ken Beard arranged for the #51363 stage 6 whole compressor ring to be obtained for examination, which was a key element in understanding this coating loss problem, with how the “plucked-out” zones of LCA-314 coating possibly preceded and accelerated the general erosion. At PST R&D, Brian Thompson was very helpful, and did all the digital macrophotos. The Met Lab staff of Sergio Comarella, Tom Albert and Greg Moody prepared all the critical samples for evaluation. The SEM / EDS work by Rusty Rice was very extensive, giving this project #1 priority, and provided key information to the study. Barbara Houdek scanned all the figures for inclusion here, allowing the original detail to be preserved. Walt Aton and Richard Hill carefully reviewed the final draft. Ann Bolcavage provided the figure on volcanic activity. Thanks to Thos. L. Taylor for the sample of volcanic ash.

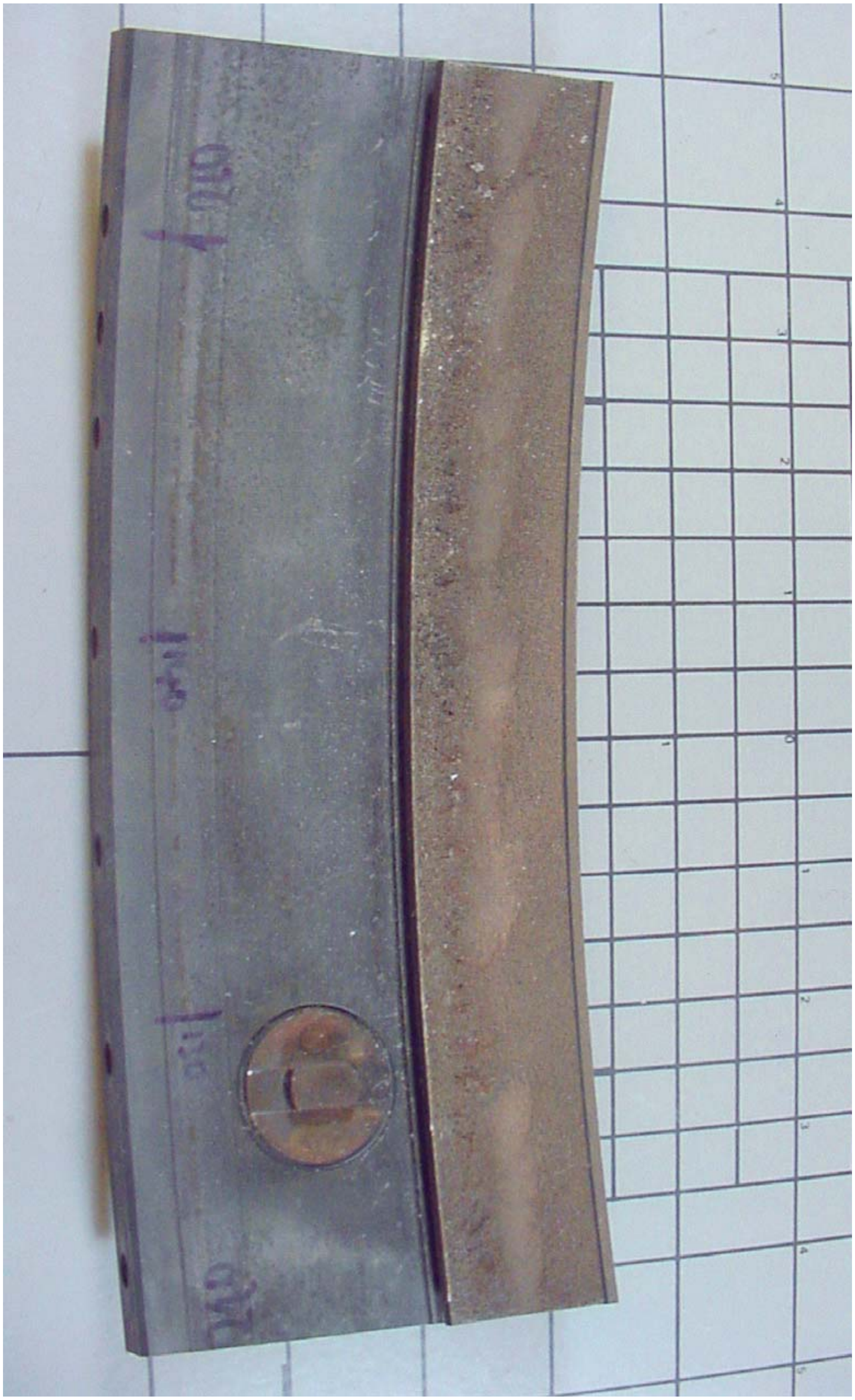


Figure 1. As-received 8.5-inch long segment of stage 6 compressor ring from #51067 Trent 800 engine after flight service with Singapore Airlines. Forward edge on left.

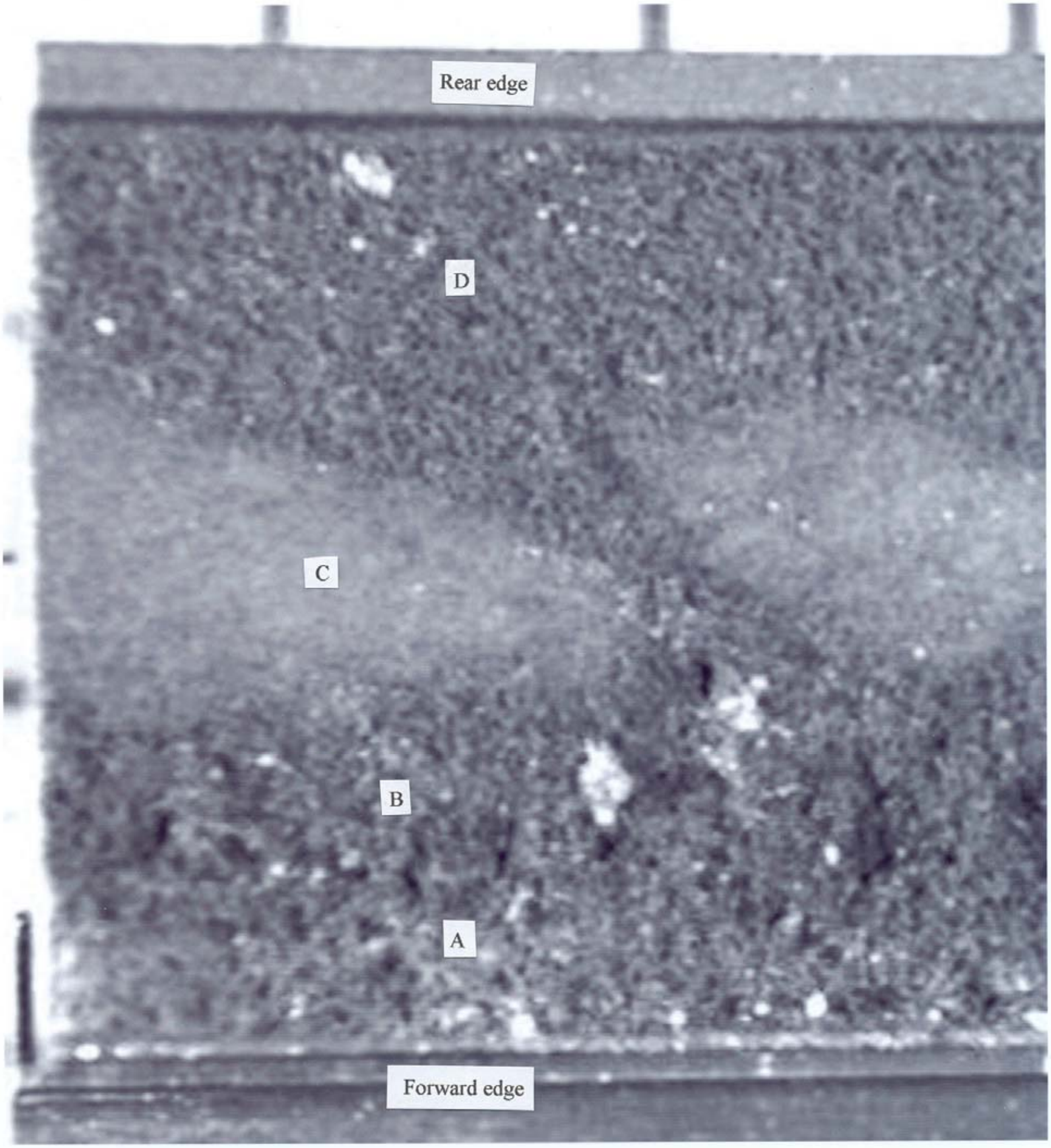


Figure 2. Macro photo of sample cut from Fig. 1 segment for SEM evaluation, showing certain areas of interest. Sample location is from upper end of Fig. 1. 5 X magnification.

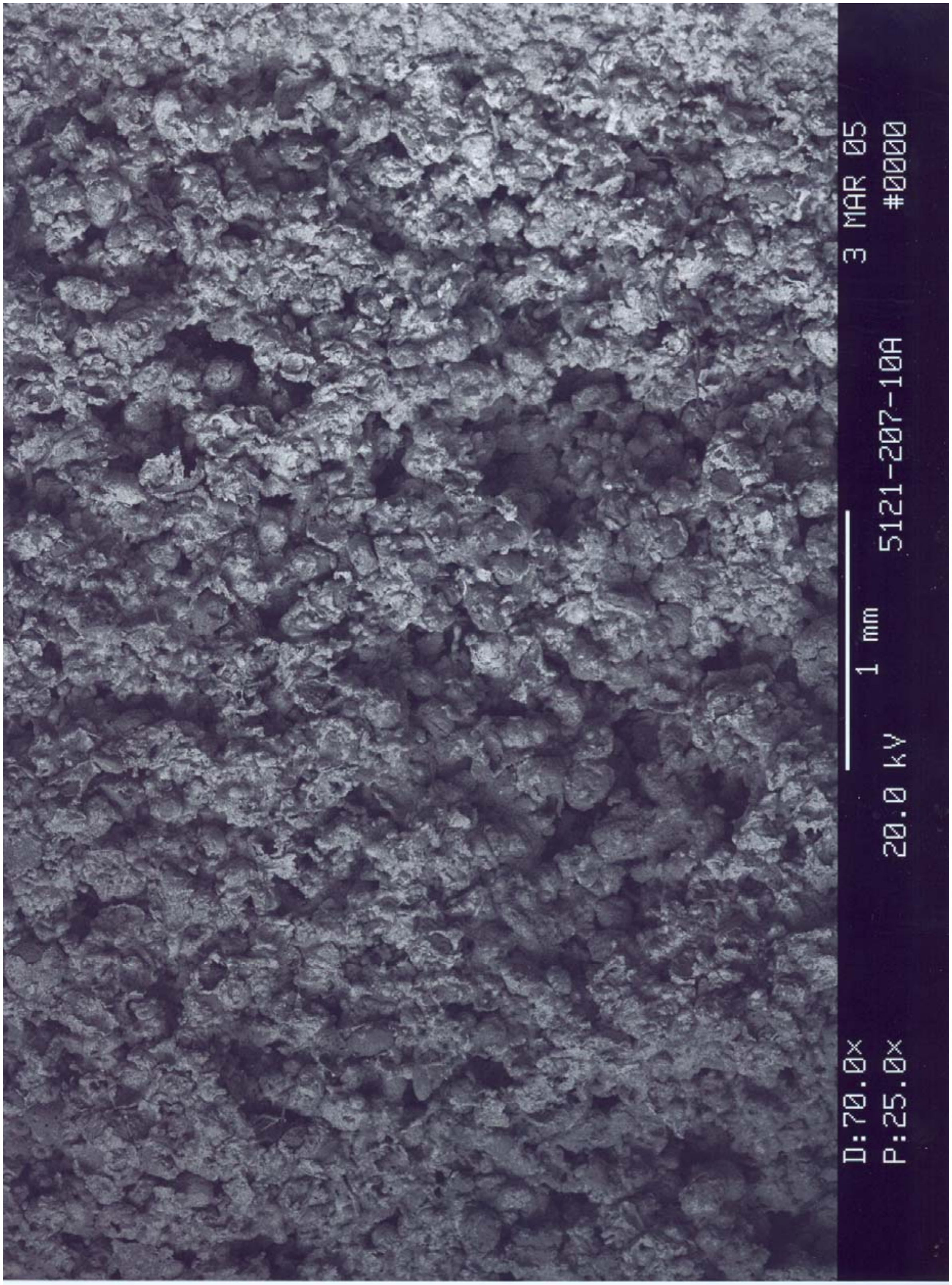


Figure 3a. SEM surface micrograph of area A, near forward edge of ring, showing high roughness and surface structure of LCA-314 particles, with NiCrAl skin eroded to expose Bentonite core, and more recent loss of areas exposing particles with no skin erosion. 42 X magnification.

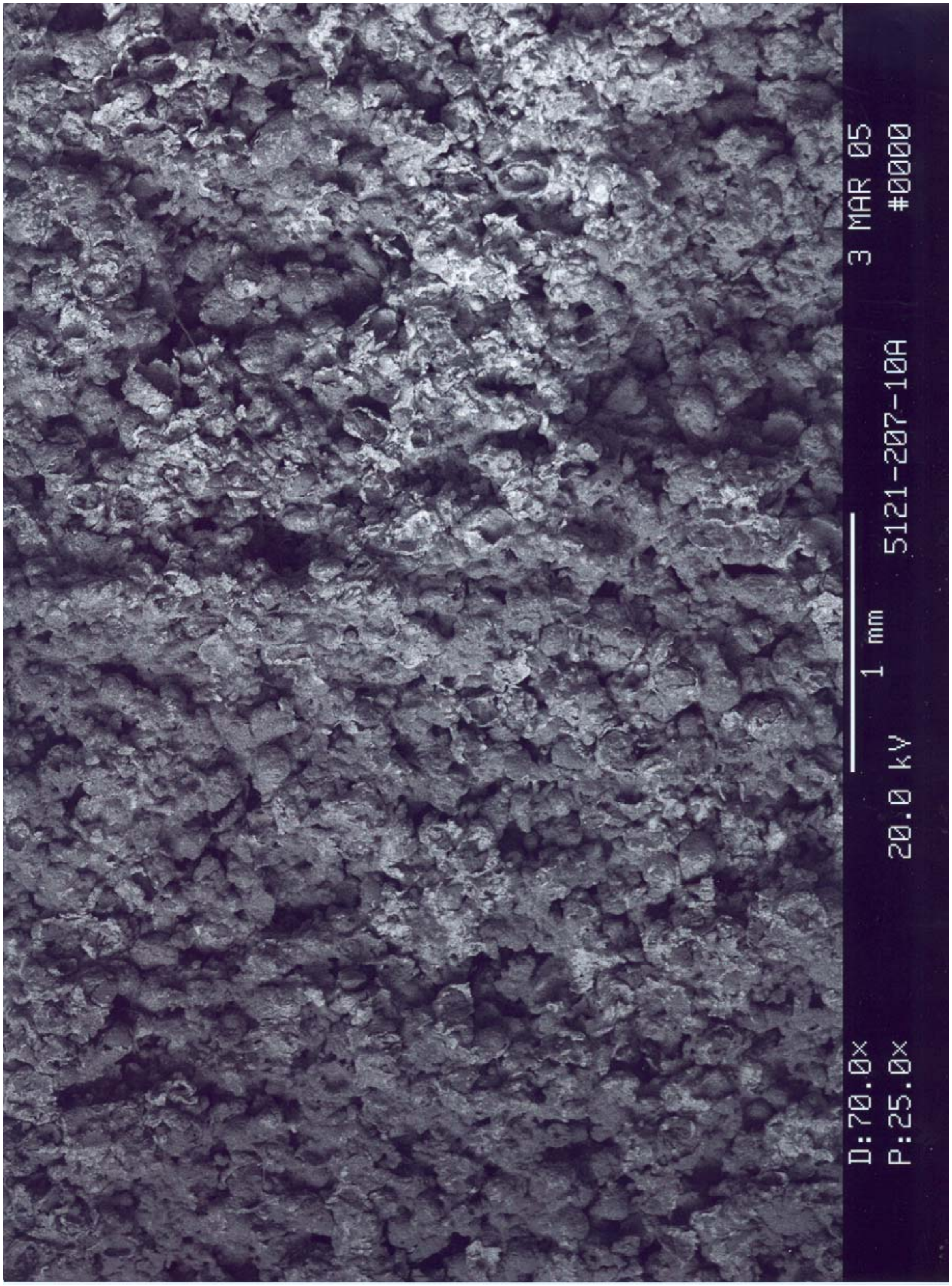


Figure 3b. SEM surface micrograph of area B, slightly rear of forward edge of ring, much like area A, showing further examples of NiCrAl skin erosion and peel-back, exposing Bentonite cores. 42 X magnification.

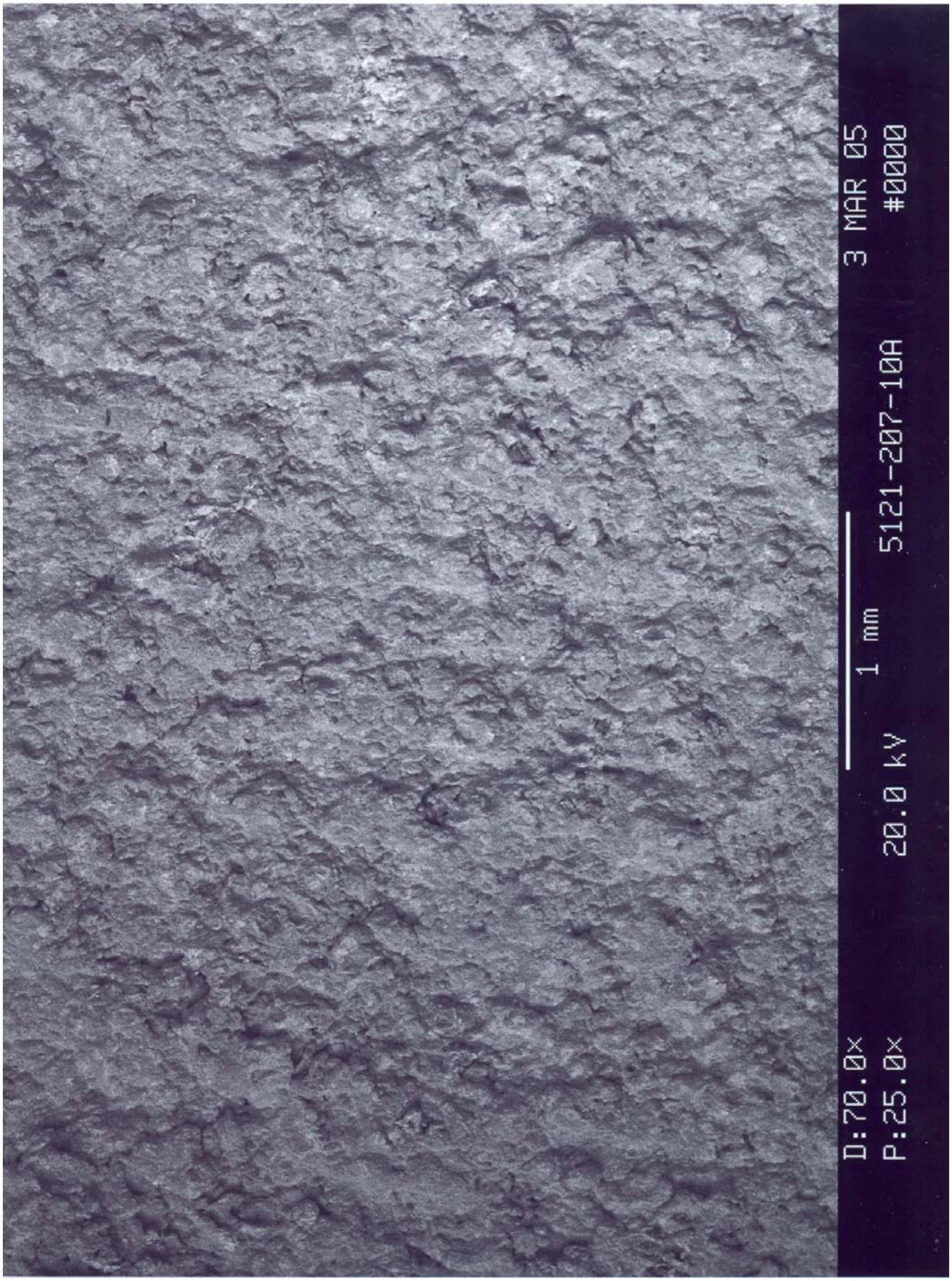


Figure 3c. SEM surface micrograph of area C, about mid-ring, showing relatively smooth, nodular surface, found by EDS to be mainly Ni-5Al bondcoat, but eroded to a smoother condition than as-coated. 42 X magnification.

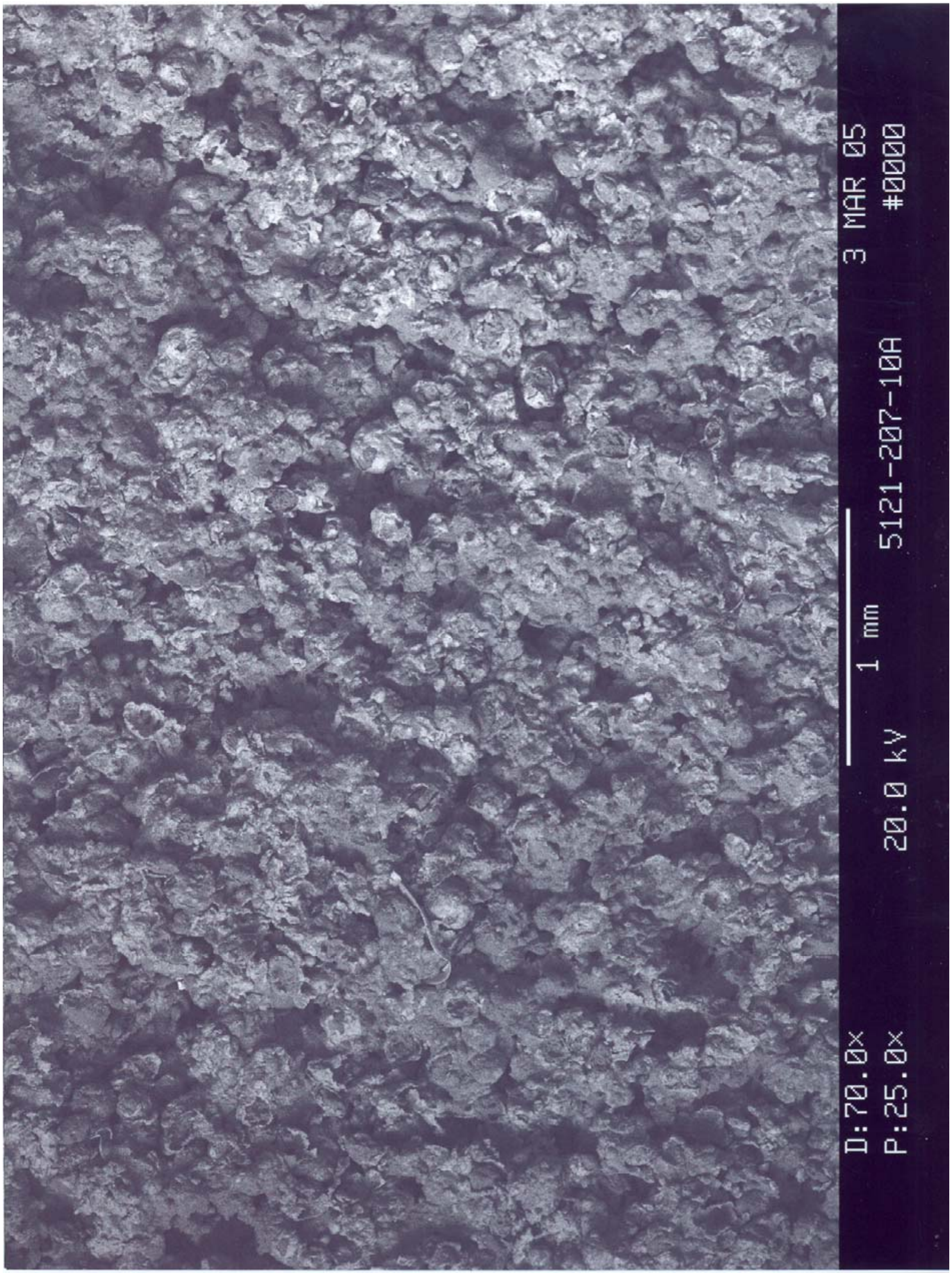


Figure 3d. SEM surface micrograph of area D, near the rear edge of ring, showing erosion mechanism details much like areas A and B. 42 X magnification.

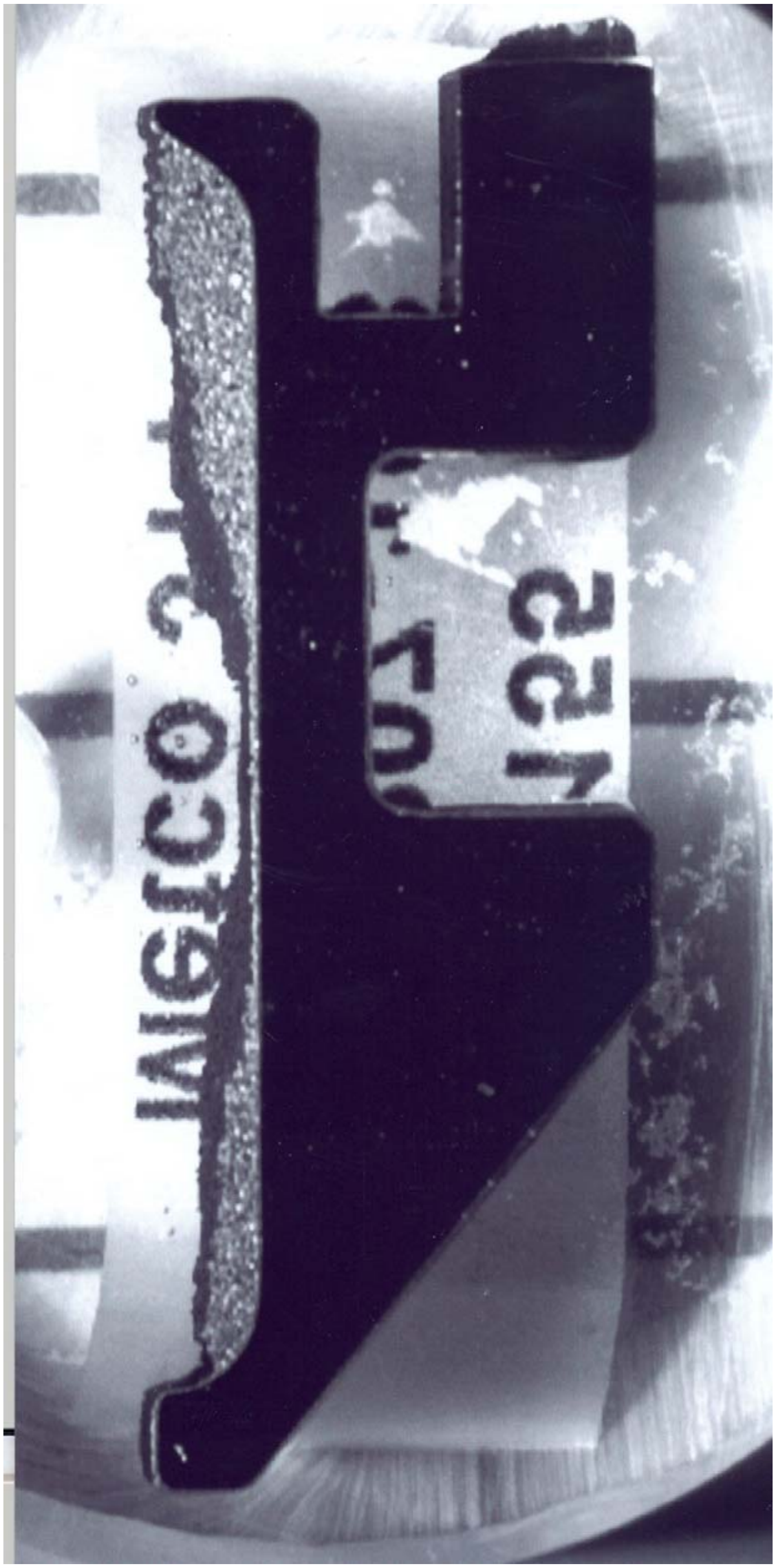


Figure 4. Macro photo of cross section slice of #51067 stage 6 ring with residual LCA-314 residing mainly on the forward edge (at top) and to the rear of center. The 314 is essentially gone in the center with only the 450 bondcoat remaining. EV 40155. 5126-207-10B. Approximately 6X magnification.

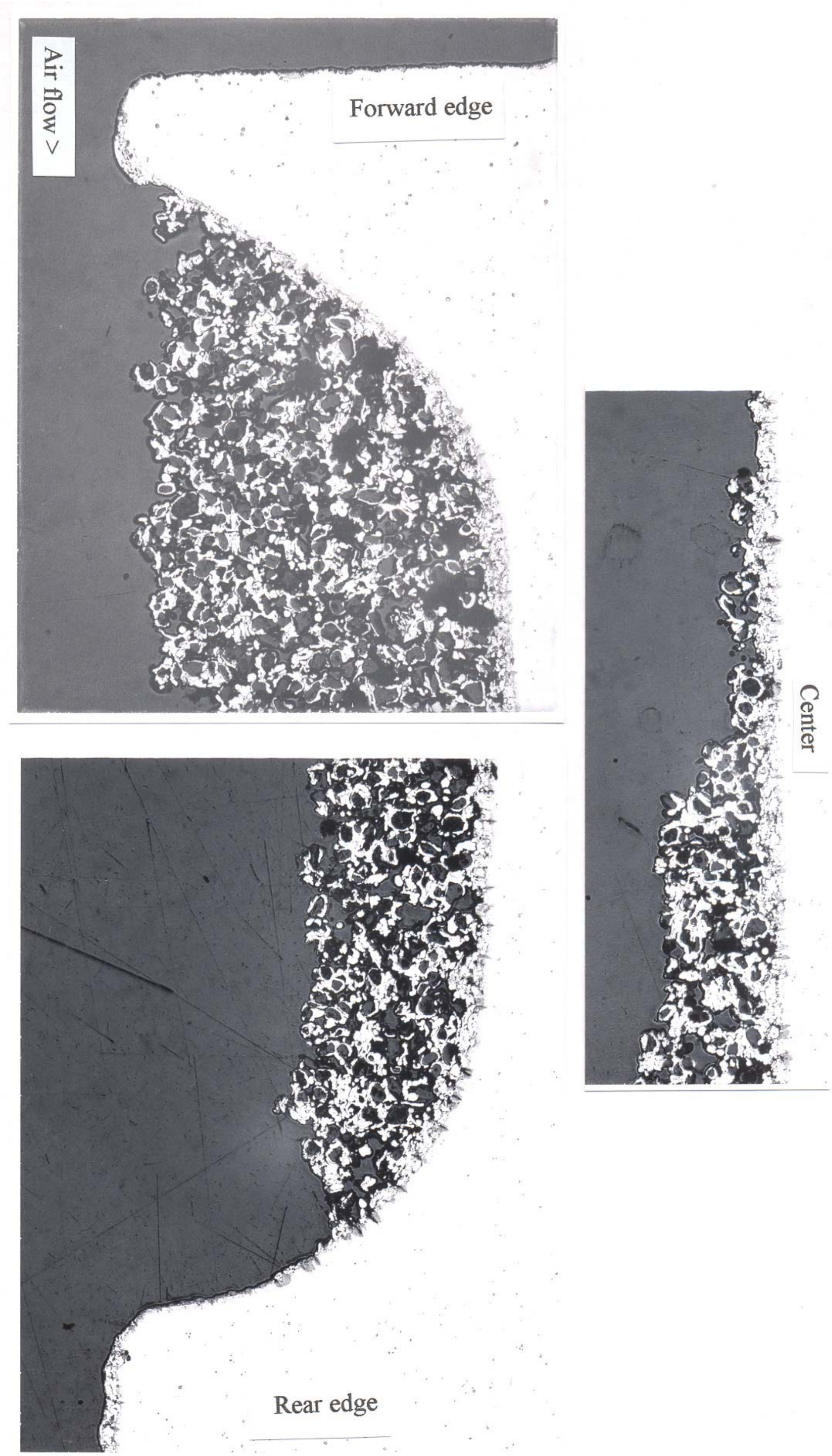


Figure 5. Microscopic cross sections of Fig. 4 sample to show detail of residual coating near forward, center and rear edge areas of the ring. Engine air flow from forward to rear as noted here. 23 X magnification.

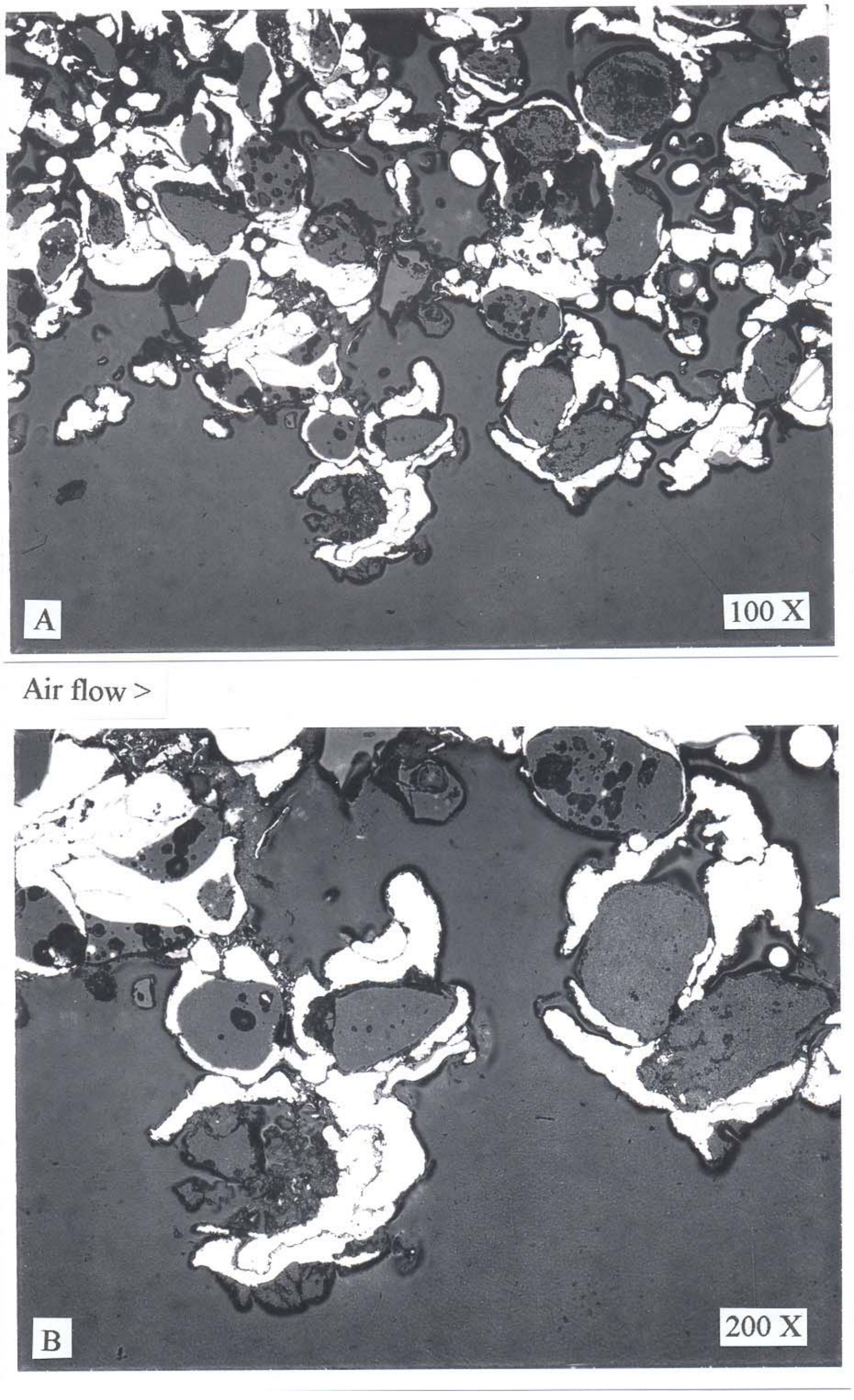


Figure 6. Cross section microstructure of residual LCA-314 coating of Fig. 5, but near forward edge of ring only. Engine air flow direction indicated. Showing erosion thinning of NiCrAl jacket layer predominately on side facing air flow, and subsequent erosion of Bentonite cores. 100 X (a) and 200 X (b) magnification.

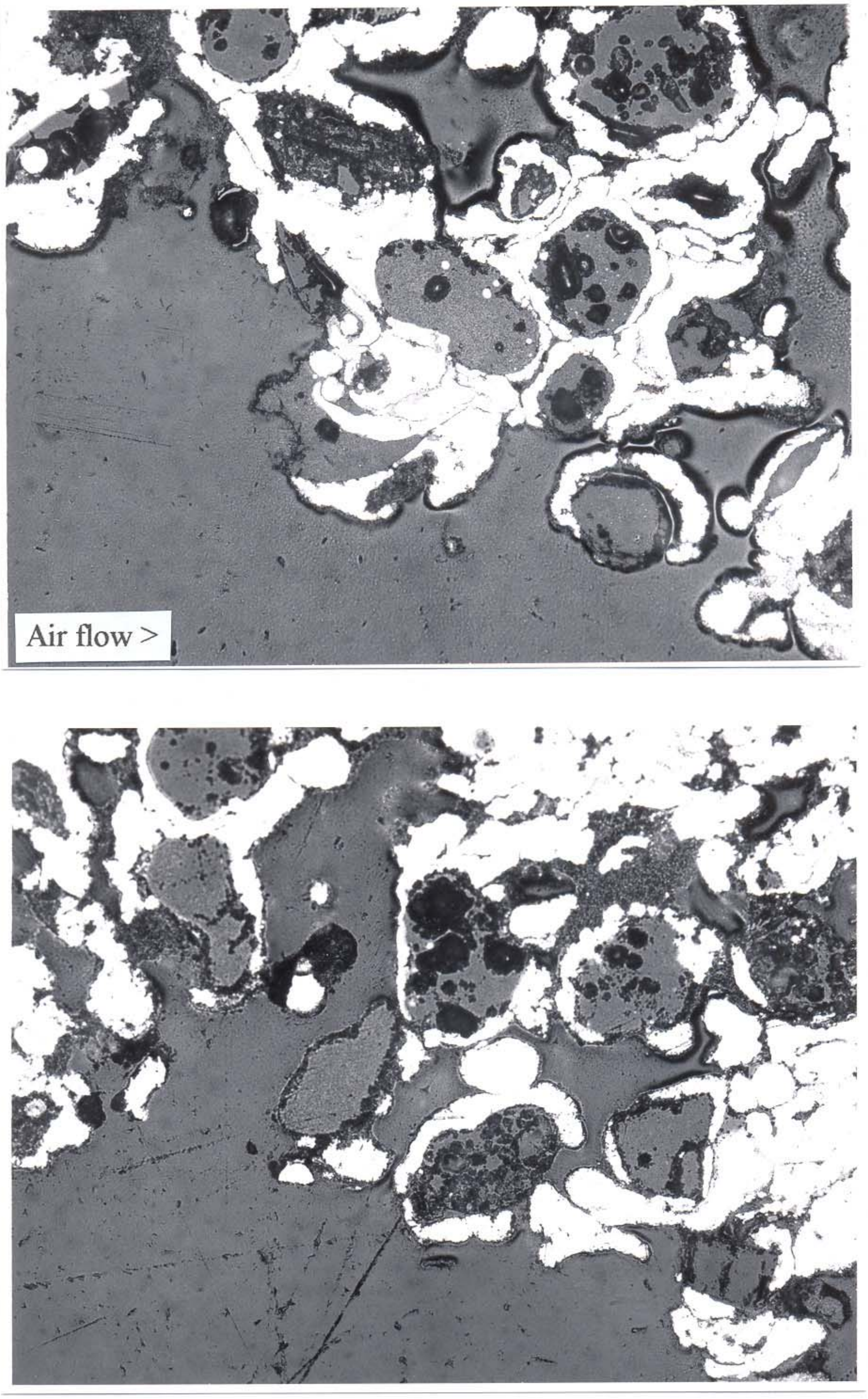


Figure 7. Cross section microstructure of residual LCA-314 near rear edge of ring, showing leading edge erosion of NiCrAl jacket and then the Bentonite core, deep porous zones devoid of all coating (now filled with epoxy), and heavily oxidized surfaces and boundaries of the NiCrAl phase. 200 X magnification.

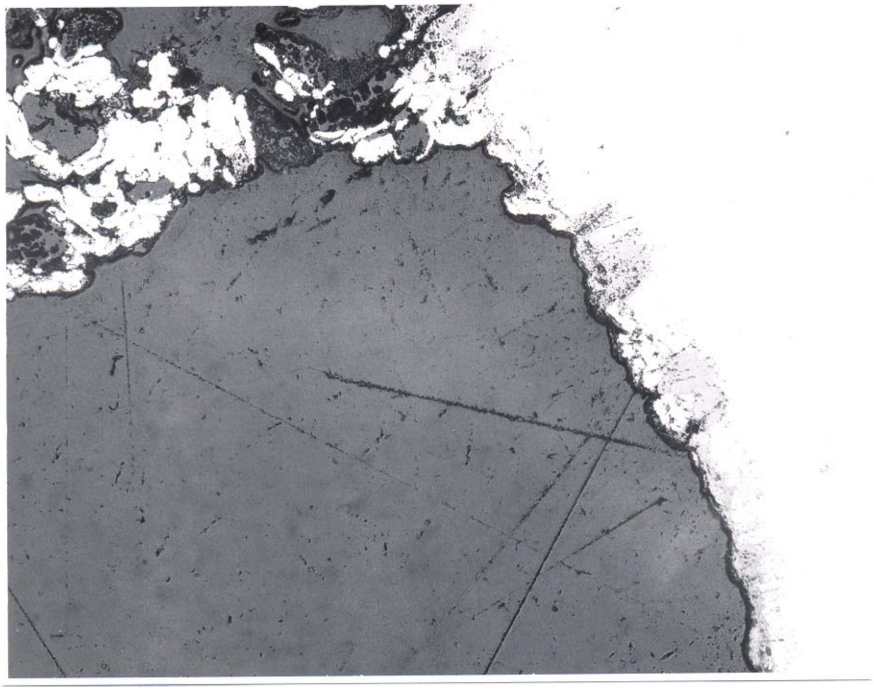


Figure 8. Cross section microstructure of residual LCA-314 coating at the rear edge of the ring, at the boundary where the coating is totally removed and only the bondcoat remains. 100 X magnification.

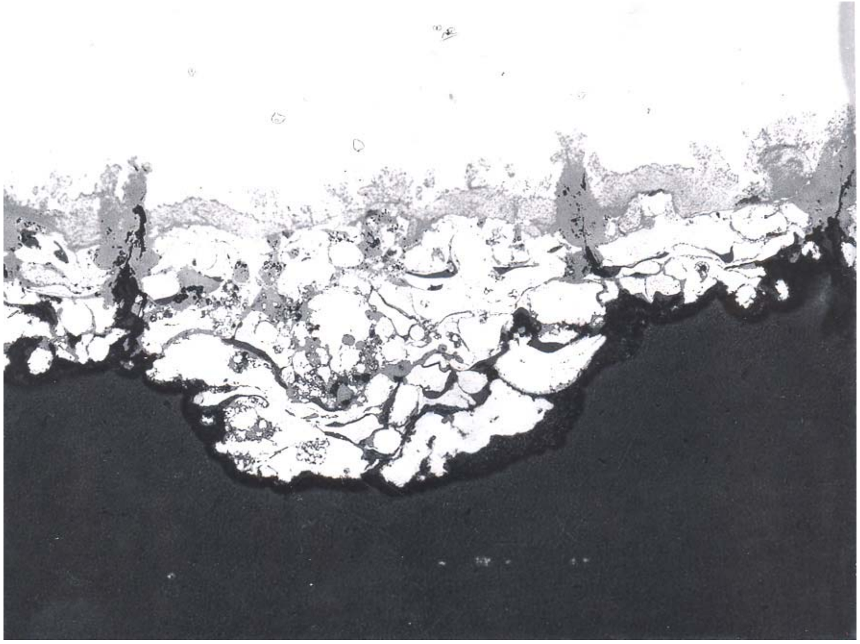


Figure 9. Cross section microstructure of residual 450 bondcoat near center of ring, showing complete loss of 314 layer, heavy internal oxidation of the 450 bondcoat and how the oxide layers between splats have allowed de-cohesion of the splats. IN 907 substrate also heavily oxidized. #51067 stage 6 ring. EV 40155. 5126-207-10B. 200 X magnification.

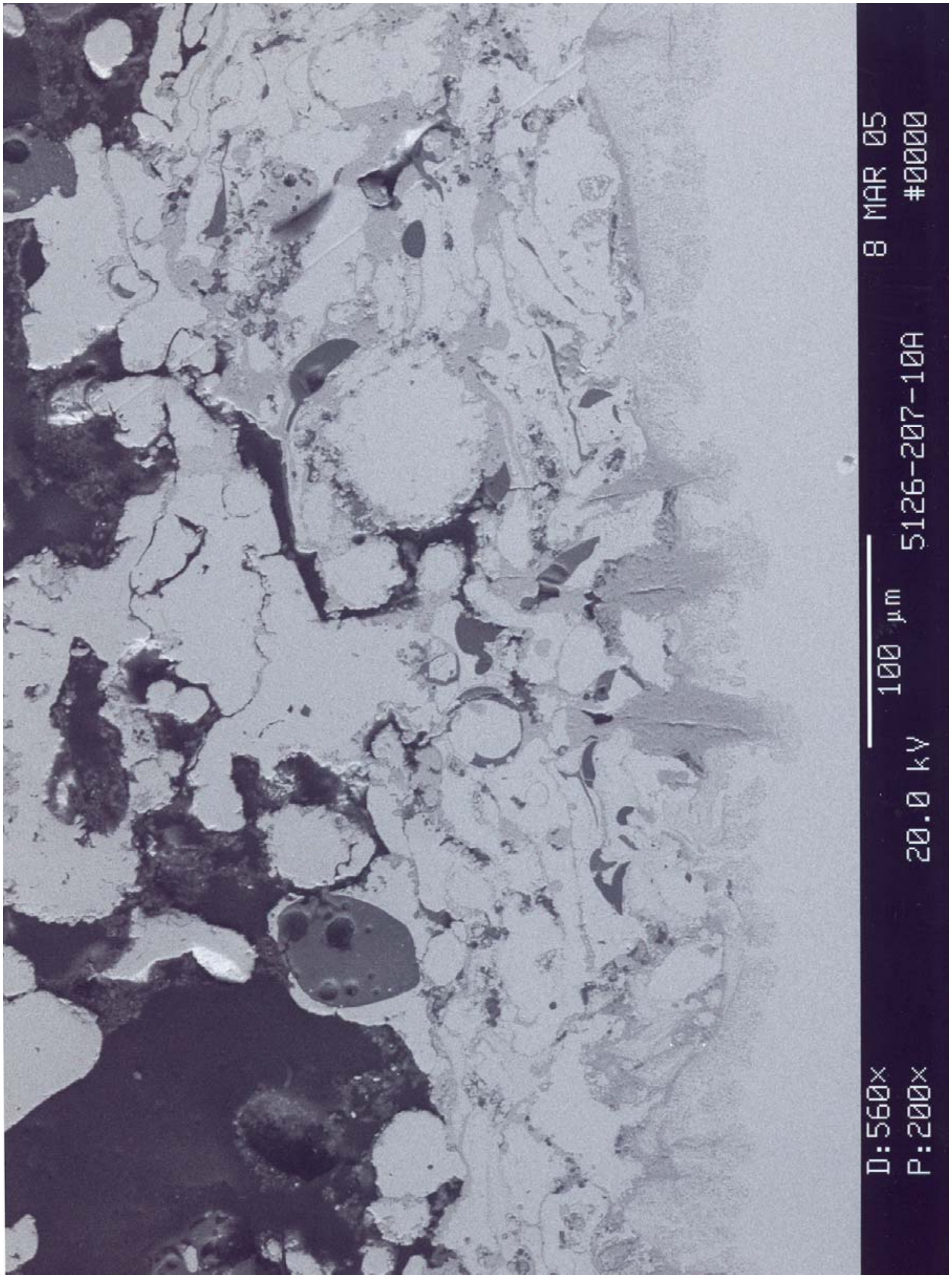


Figure 10a. SEM cross section microstructure of residual 450 bondcoat on IN 907 substrate, both heavily oxidized. Nickel oxide layers between 450 splats are allowing de-cohesion. #51067 stage 6 ring. 340 X magnification.

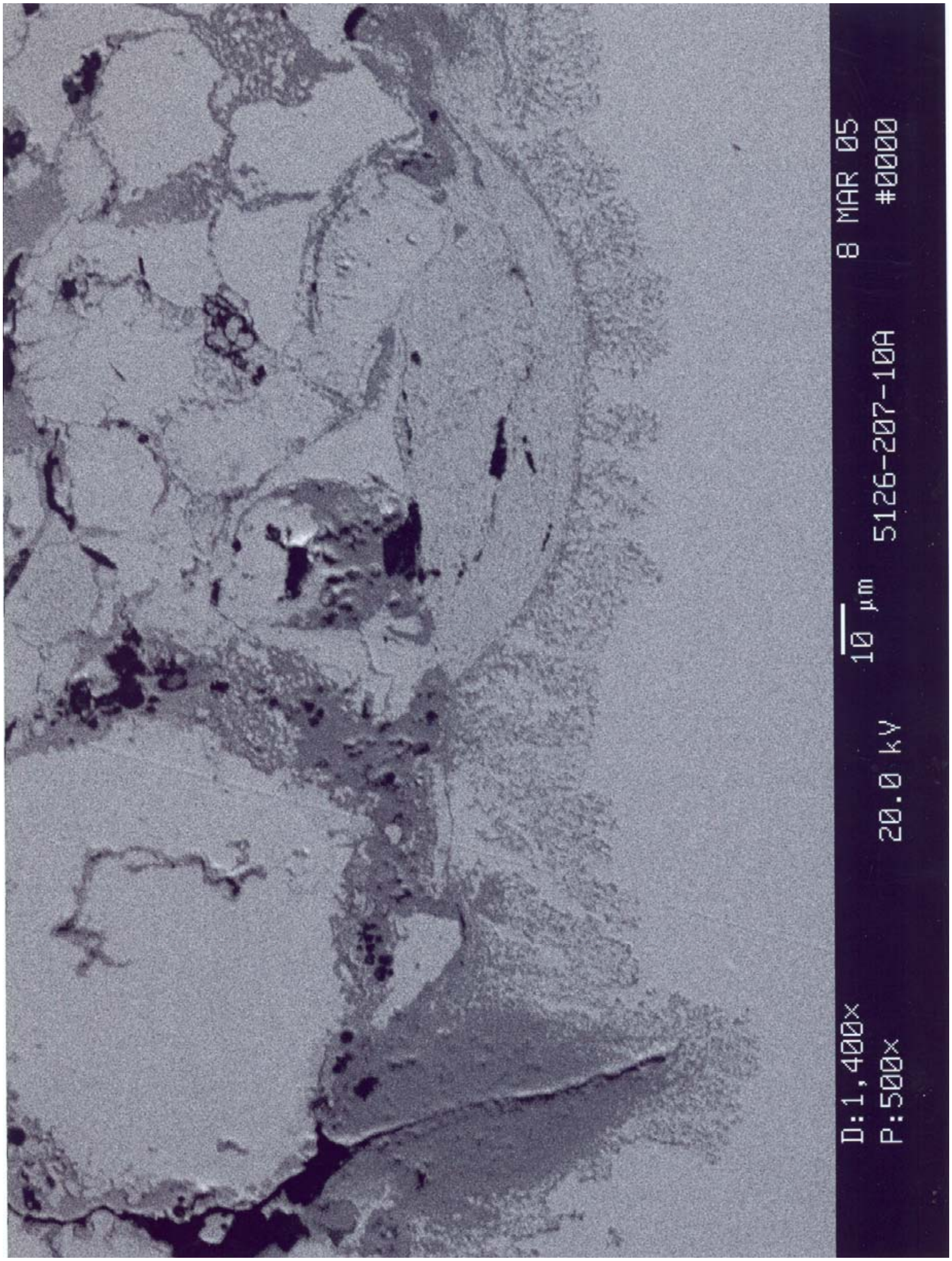


Figure 10b. SEM cross section microstructure showing detail of 450 bondcoat and IN 907 oxidation. Porosity and cracks formed in the inter-particle boundaries of 450 bondcoat. Large iron oxide particles penetrate IN 907, typically cracked, and layer of internal oxidation. 850 X magnification.

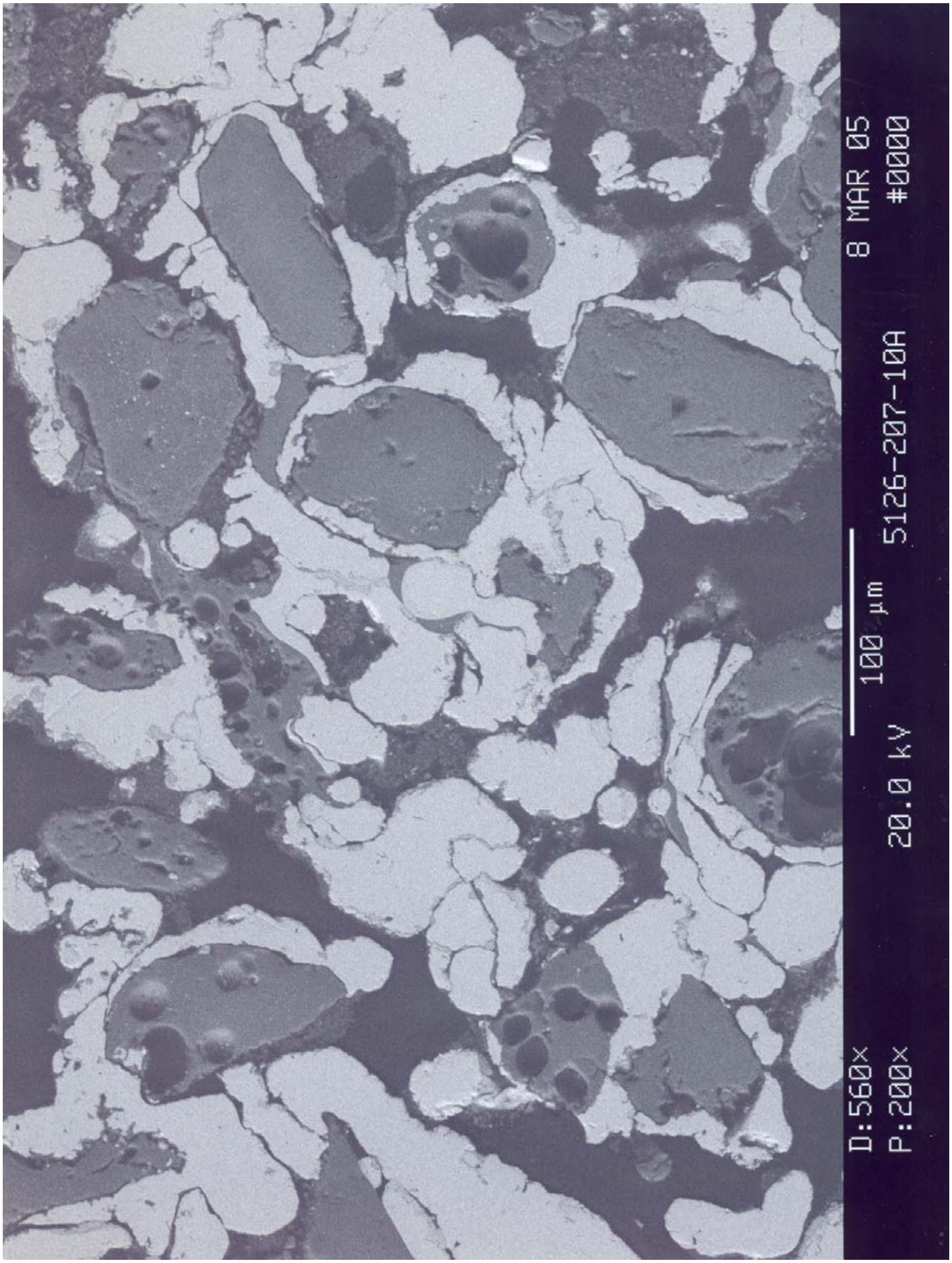


Figure 11a. SEM cross section microstructure of LCA-314 coating near upper surface, showing inter-particle oxide at NiCrAl splat boundaries. #51067 stage 6 ring. 340 X magnification.

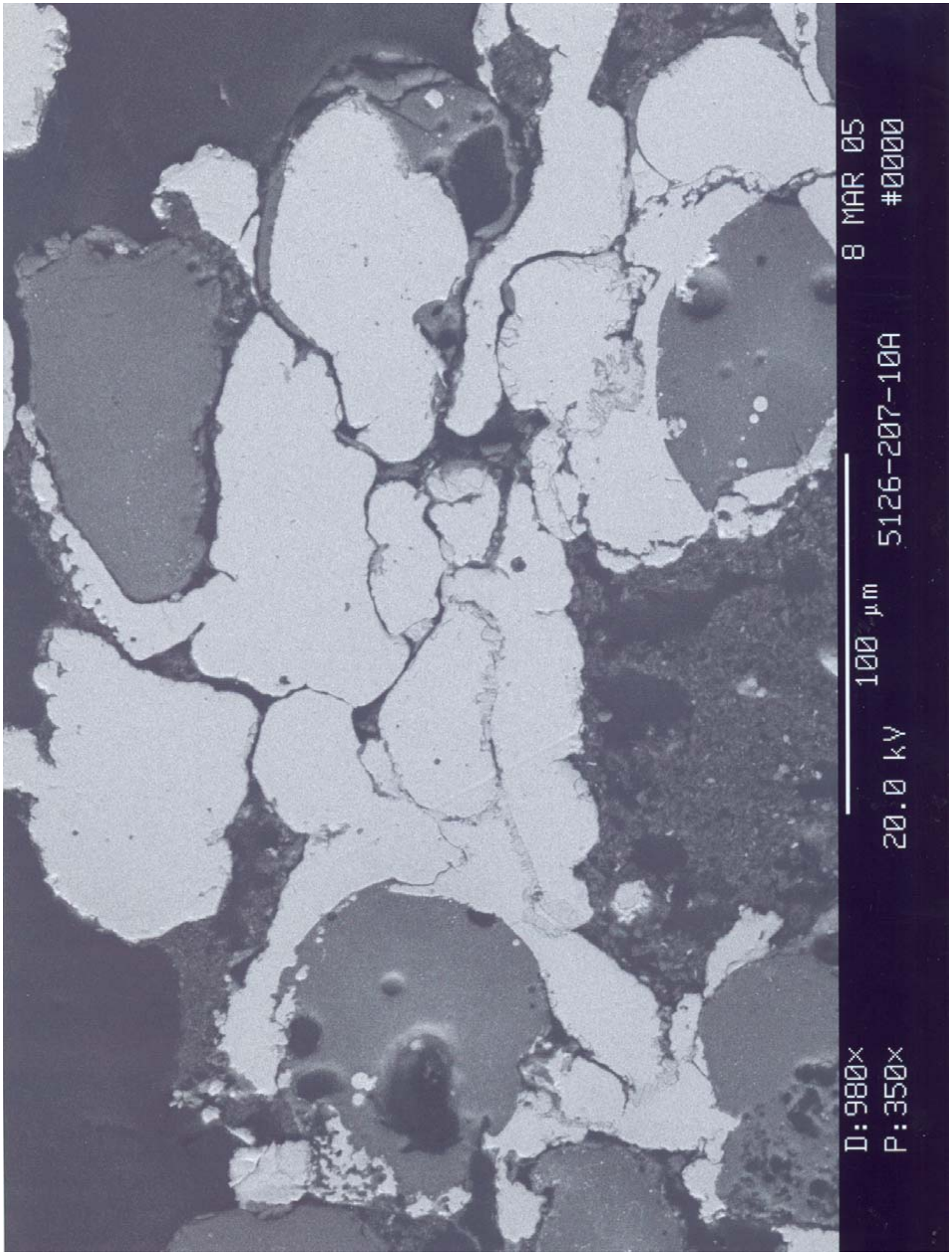


Figure 11b. SEM cross section microstructure of LCA-314 coating near upper surface, showing detail of inter-splat oxidation of NiCrAl and separation of between splats. 610 X magnification.

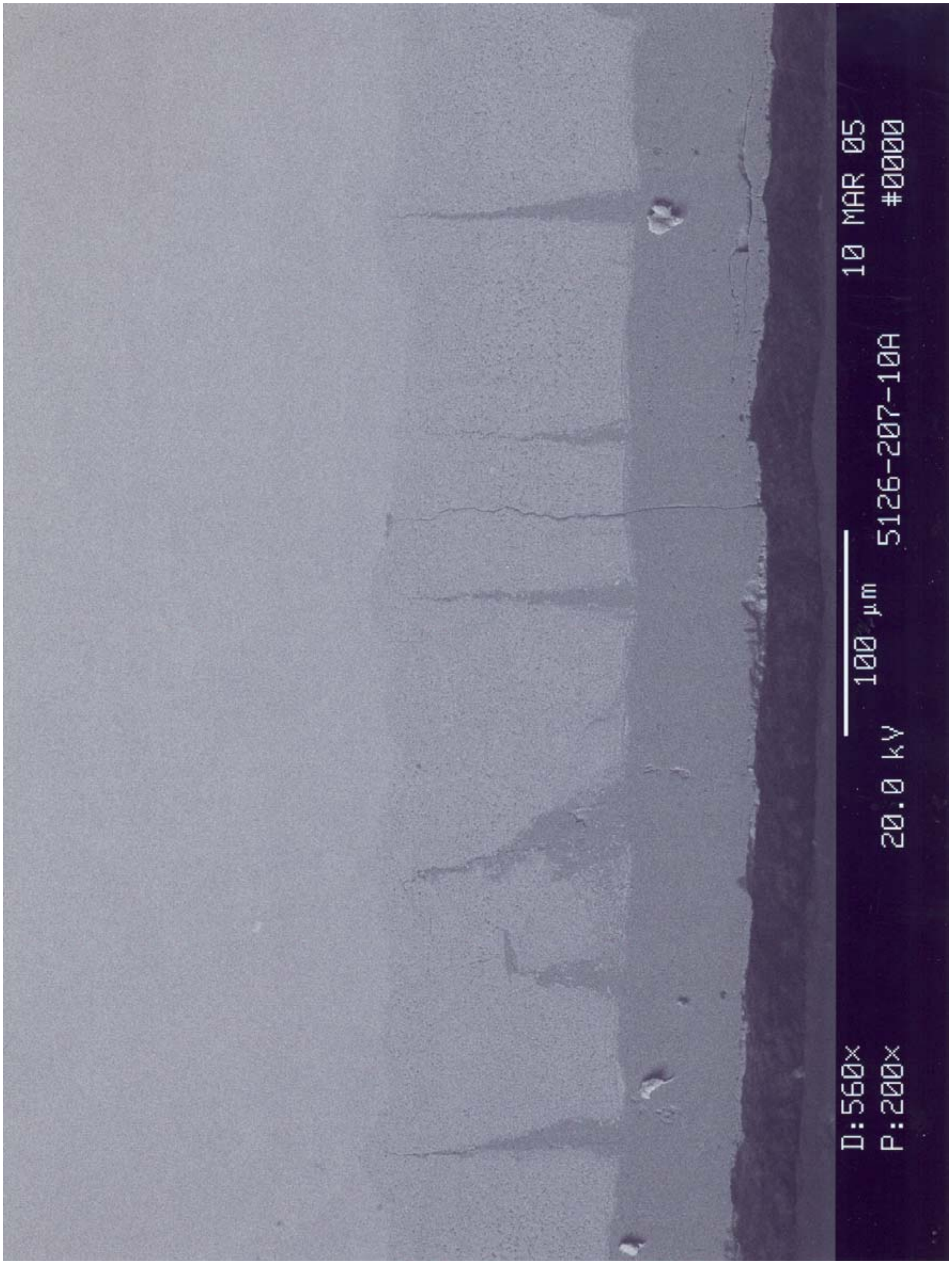


Figure 12. SEM cross section microstructure of oxide layer on (uncoated) backside of IN 907 stage 6 compressor ring. Outer dark grey layer by EDS is Fe_3O_4. Inner light grey layer is Ni,Co,Fe-oxide with some Nb, probably as a fine internal particle oxide. Cracks form at the surface of the Fe_3O_4 layer and penetrate though the inner oxide layer, stopping at the clean IN 907. Crack flanks develop Fe_3O_4 after they form. One long crack though both layers occurred near end of service for this ring, having little further crack surface oxidation. 325 X magnification.

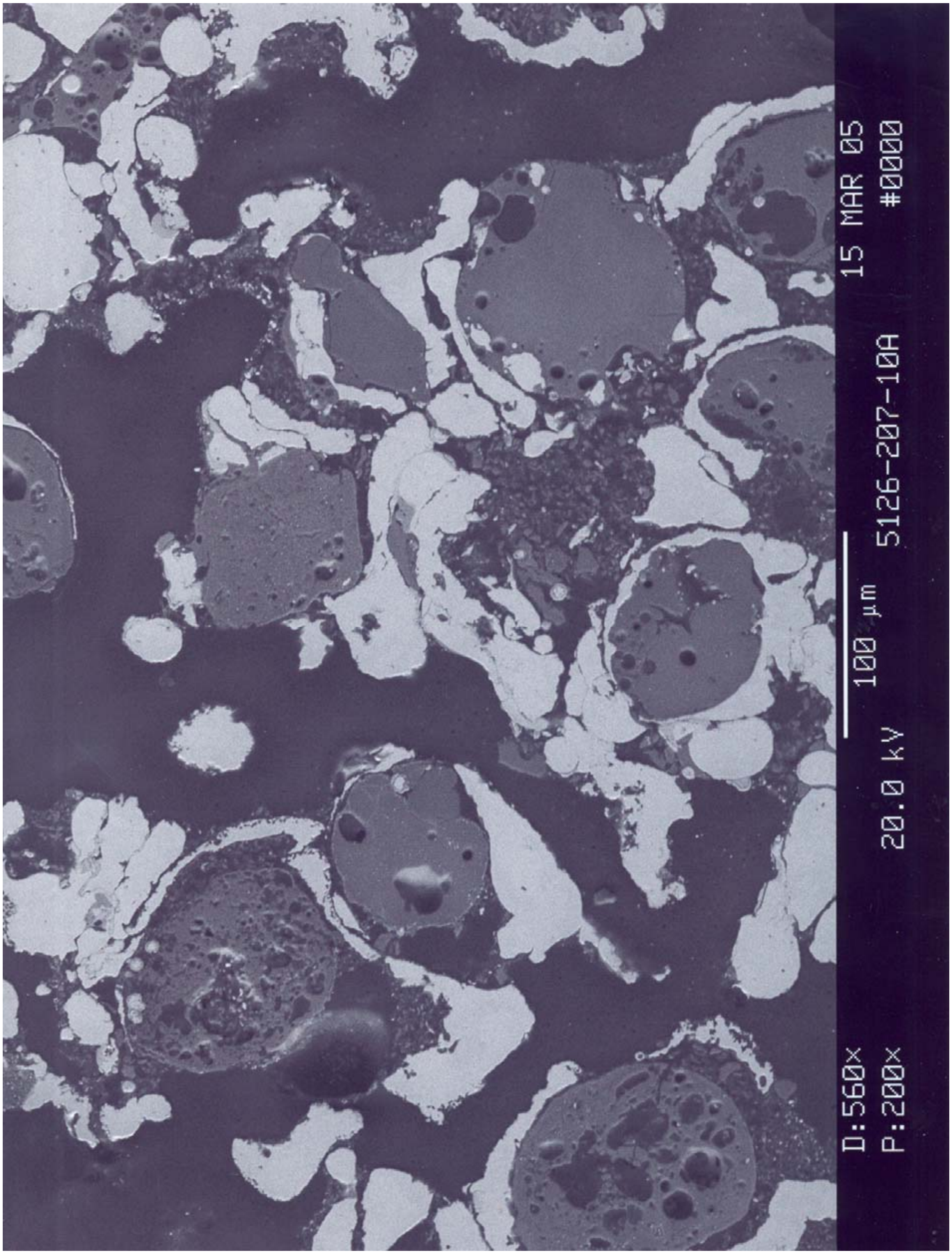


Figure 13a. SEM cross section microstructure of residual coating on #51067 stage 6 ring, “area 5”, used for measurement of percent metallic phase by the linear intercept method. EV 41020. 5126-207-10A. 340 X magnification.

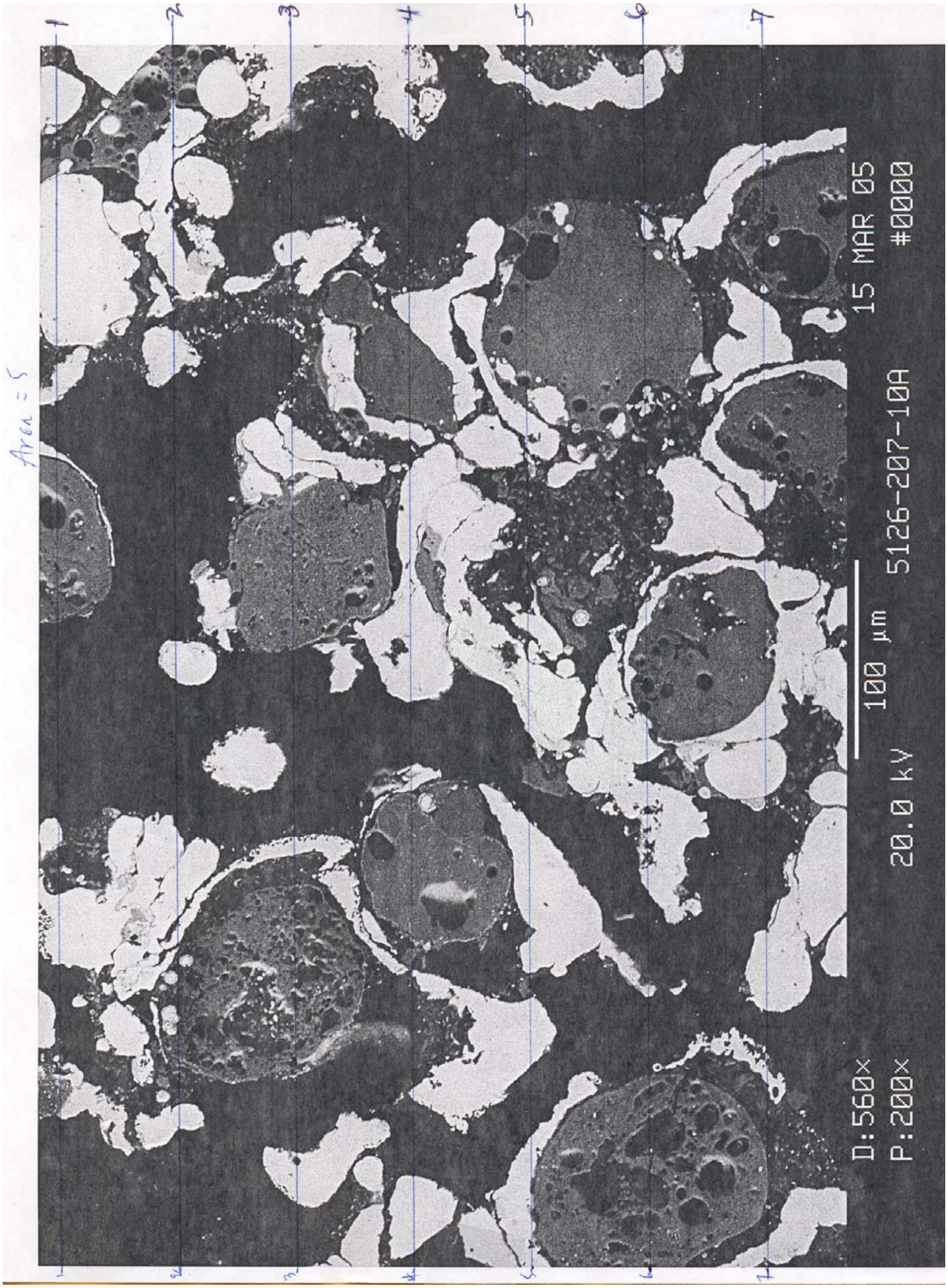


Figure 13b. Photocopy of SEM image of Fig 13a, with seven parallel lines drawn across long direction, each spaced 1-inch on original, for line-by-line measurement of metallic phase segments leading to estimate of whole-area percent metallic phase. 340 X magnification.

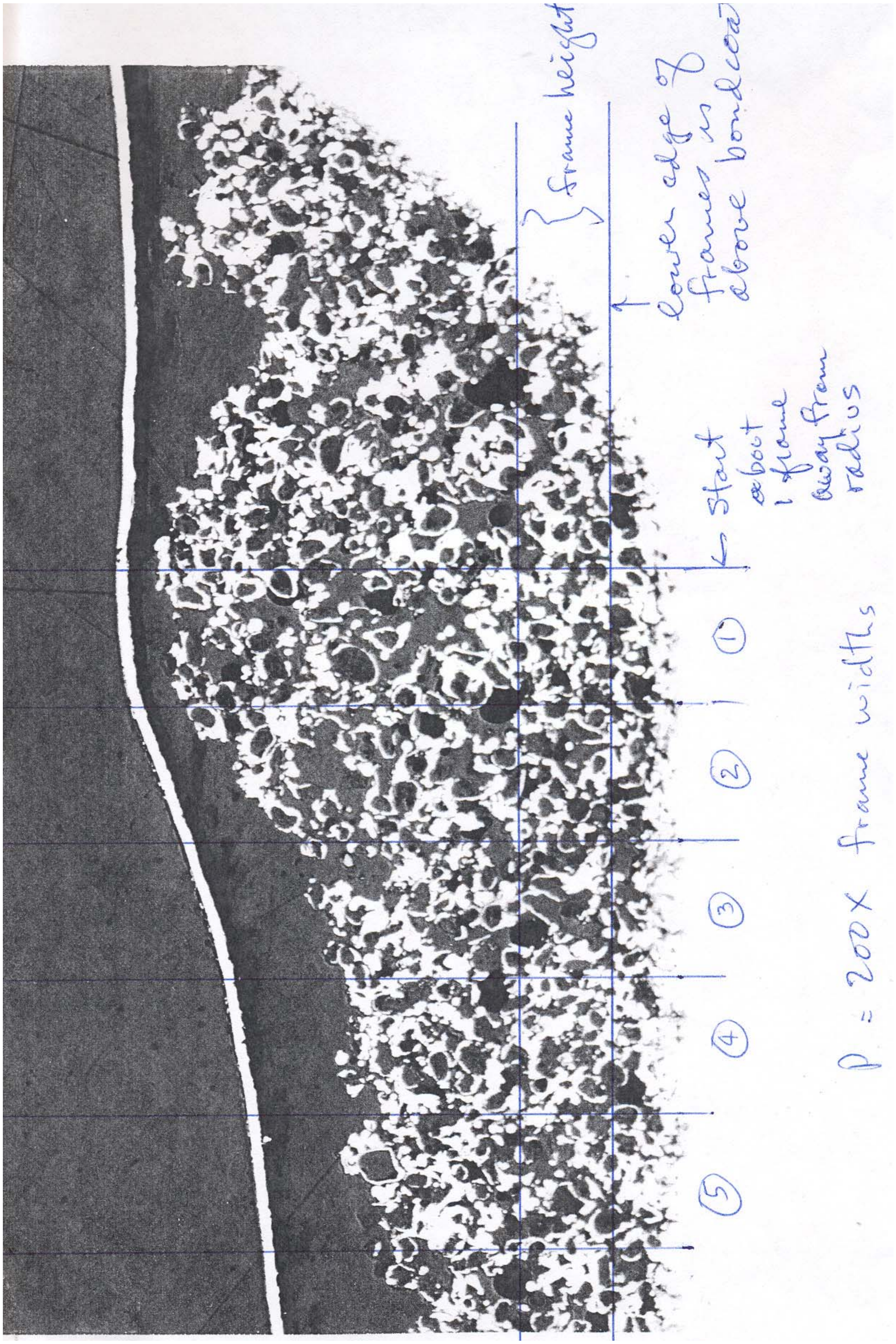


Figure 13c. Photocopy of optical microscope section of #51067 stage 6 ring, near forward edge, with drawn-on lines showing areas and frames 1 – 5 for subsequent SEM micrographs to be used in linear intercept analysis of percent metallic phase. About 50 X magnification.

Macro Photos of Coated I.D. in the "As-Received" Condition Depicting PSTI's Location Numbers
Trent 800 Compressor stage 6 ring. Engine # 51363

Figure 14. Photographic record of as-received #51363 stage 6 compressor ring with residual LCA-314 coating in upper track area. Whole ring is shown in overlapping views, with PST location numbers. “Pluck-out” of 314 and vivid brown surface coloration are both shown.

Macro Photos of Coated I.D. in the "As-Received" Condition Depicting PSTI's Location Numbers

Figure 14 (cont.)

Macro Photos of Coated I.D. in the "As-Received" Condition Depicting PSTI's Location Numbers

Figure 14 (cont.)

Macro Photos of Coated I.D. in the "As-Received" Condition Depicting PSTI's Location Numbers

Figure 14 (cont.)

Figure 15 (View 1). Macroscopic views of the #51067 stage 6 compressor ring segment under evaluation at PST. The view shows the cross section of the IN 907 ring substrate, the location of the LCA-314 coated track and the general features of the eroded 314 relative to substrate location. Full ring width is about 3.25 inches, coated track is 1.1 inches.

Figure 15 (View 2). Macroscopic views of the #51067 stage 6 compressor ring segment under evaluation at PST. The view shows the cross section of the IN 907 ring substrate, the location of the LCA-314 coated track and the general features of the eroded 314 relative to substrate location. Full ring width is about 3.25 inches, coated track is 1.1 inches.

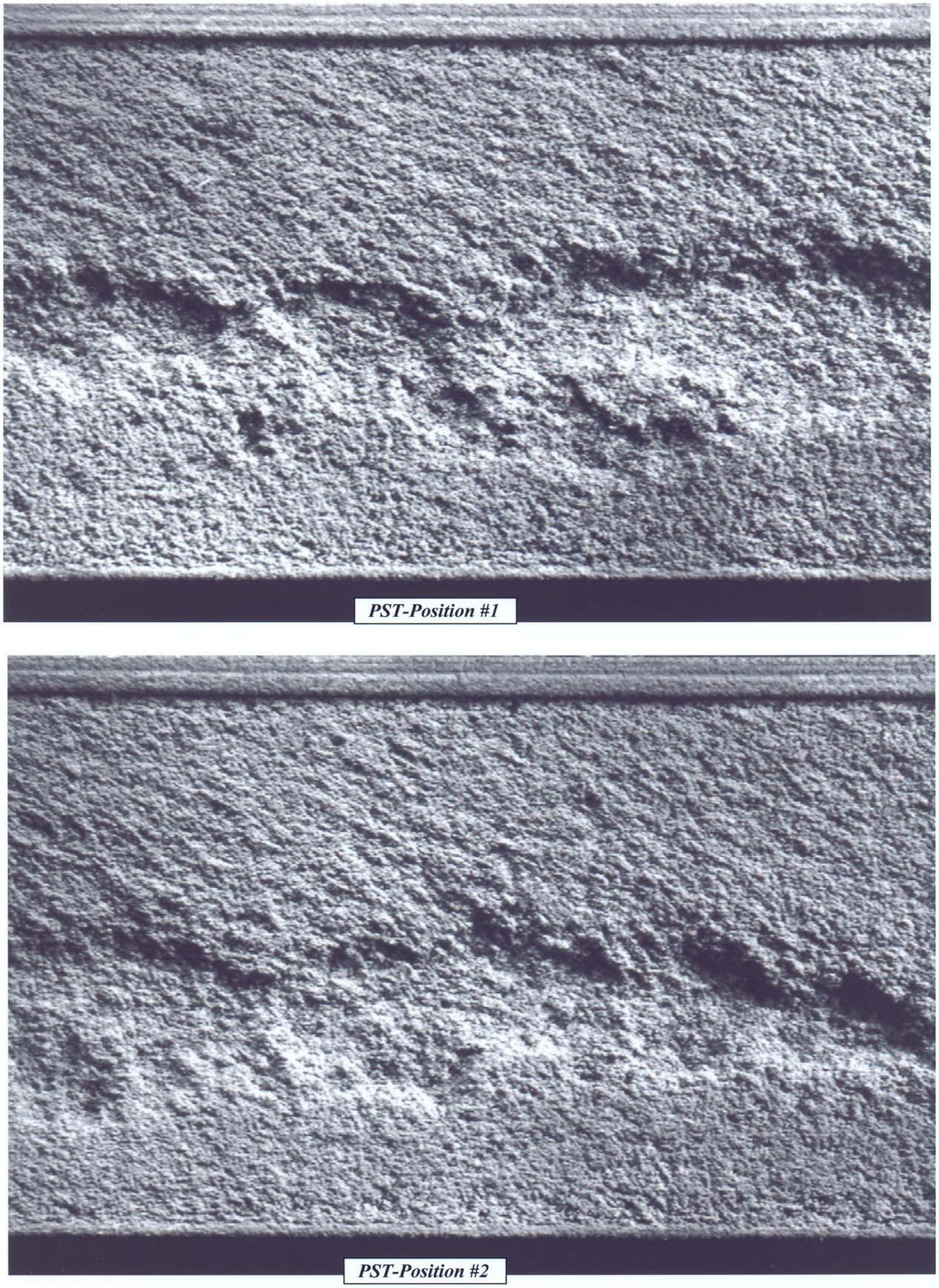
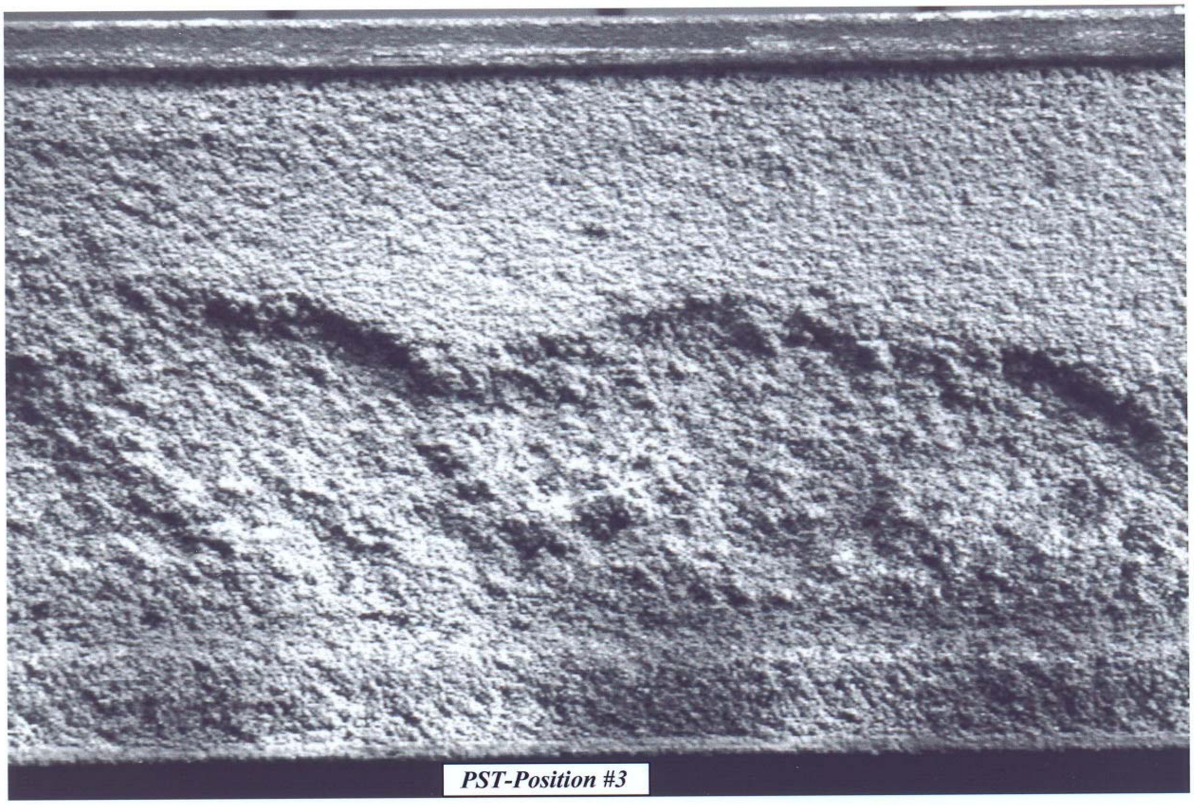


Figure 16. Macroscopic photos of the spall patches of LCA-314 coating on #51363 stage 6 ring. PST location numbers shown. Original size of top-to-bottom coated track is 1.1 inches.



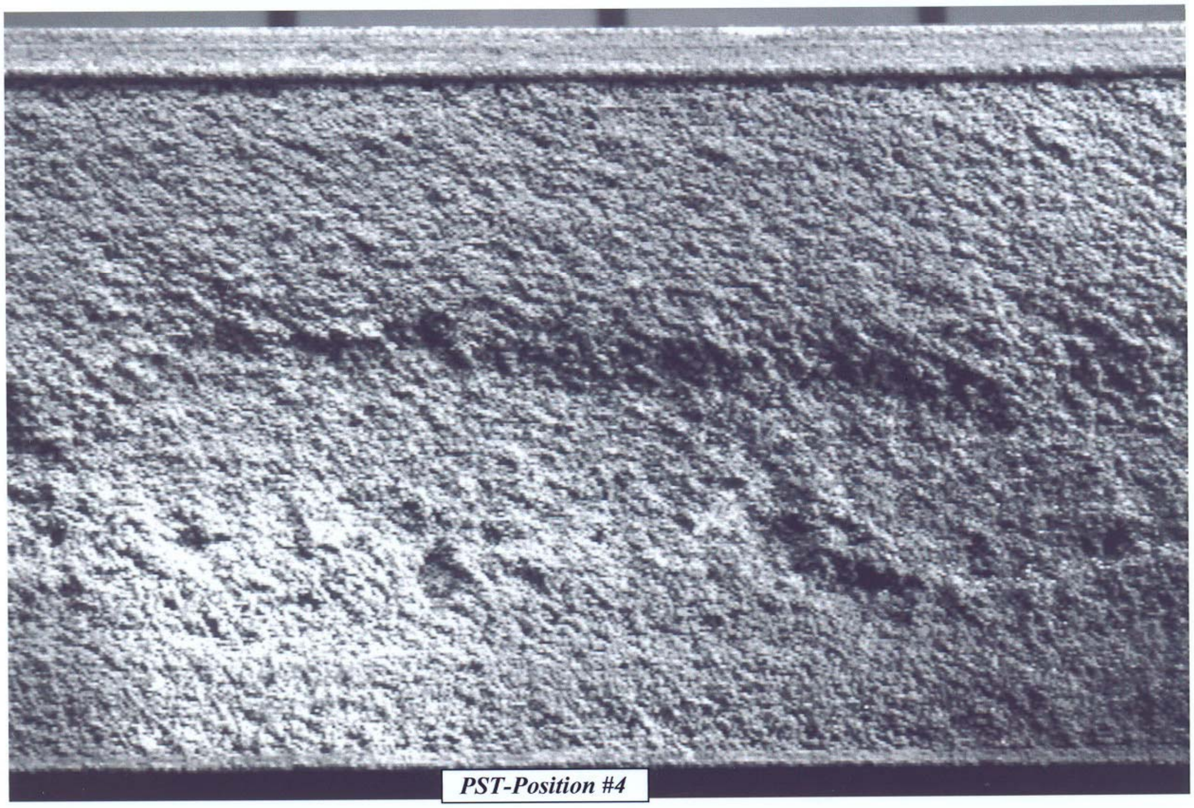
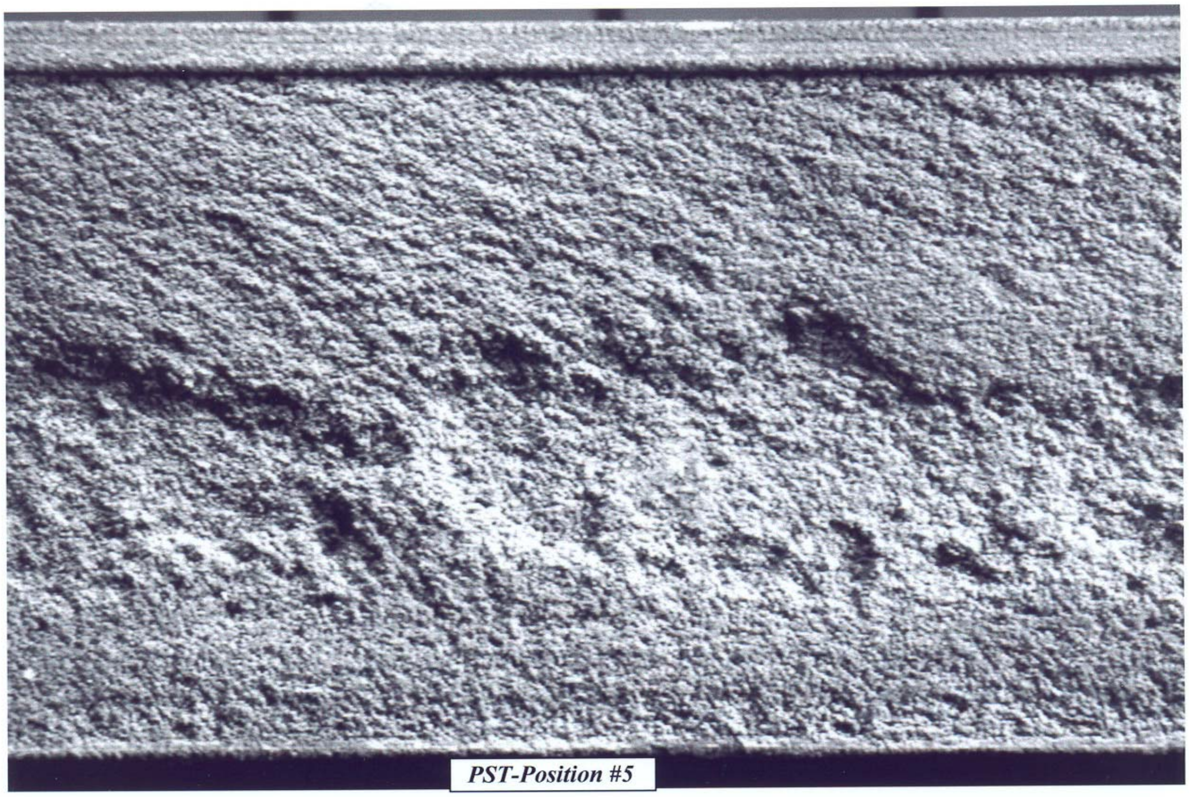


Figure 16 (cont.). Macroscopic photos of the spall patches of LCA-314 coating on #51363 stage 6 ring. PST location numbers shown. Original size of top-to-bottom coated track is 1.1 inches.



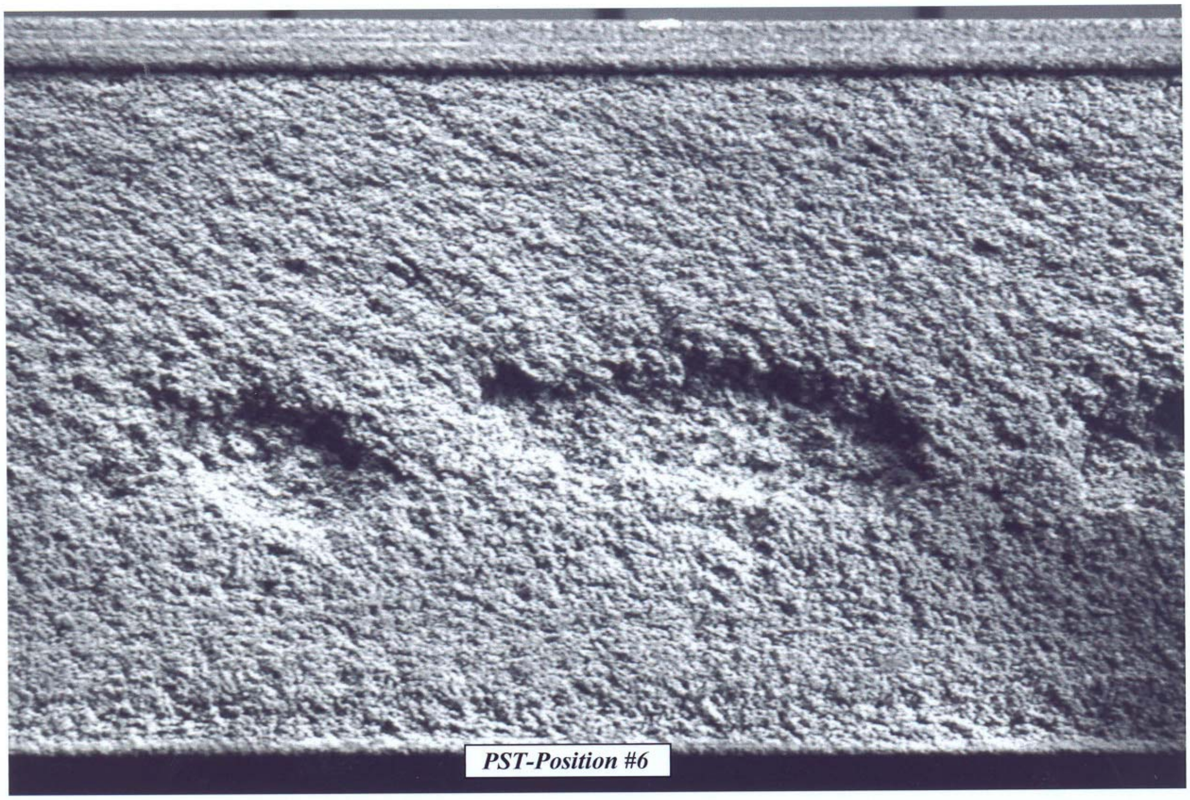
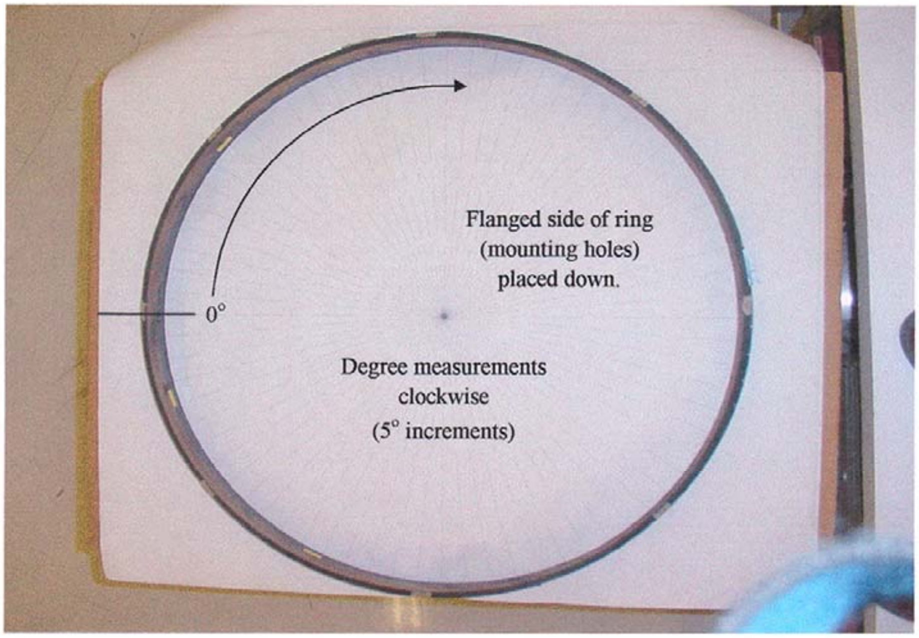


Figure 16 (cont.). Macroscopic photos of the spall patches of LCA-314 coating on #51363 stage 6 ring. PST location numbers shown. Original size of top-to-bottom coated track is 1.1 inches.

Trent #51363 Stage 6 Compressor Ring Coating Investigation



General Dimensions:

Nominal I.D. = 71.6 cm (28.18898")
Nominal Height = 8.4 cm (3.307087")
Nominal Coating area width = 2.9 cm (1.141732")

AST
Number Locations

Location (degrees)	**Location Number**
0	1
40	2
88	3
131	4
178	5
223	6
273	7
321	8

PST
Number Locations

Location (degrees)	**Location Number**	**Spall Depth from Surface of Coating*** (mils)	**Spall Depth from Groove to Surface of Spall**** (mils)	**Spall Width @ Location Number** (mils)	**Coating Recess Edge Opposite Flange*** (mils)
40	1	52	145.7	0.438	7.1
110	2	45	144.3	0.250	9.6
211	3	50.3	143.5	0.469	17.5
253	4	49.5	142.9	0.375	6.4
297	5	52.3	144.9	0.438	9.6
342	6	46.5	147.8	0.219	7.2

* Readings taken with 0-1" depth mic spanning substrate on both sides of coating area.
** Readings taken with 0-1" point mic from bottom of spalled area to bottom of groove in on the back side of the coating area.

Figure 17. Photo of #51363 stage 6 ring. AST and PST location number correlation and to angular position. Measurements of spall patch dimensions of typical examples of Fig. 16.

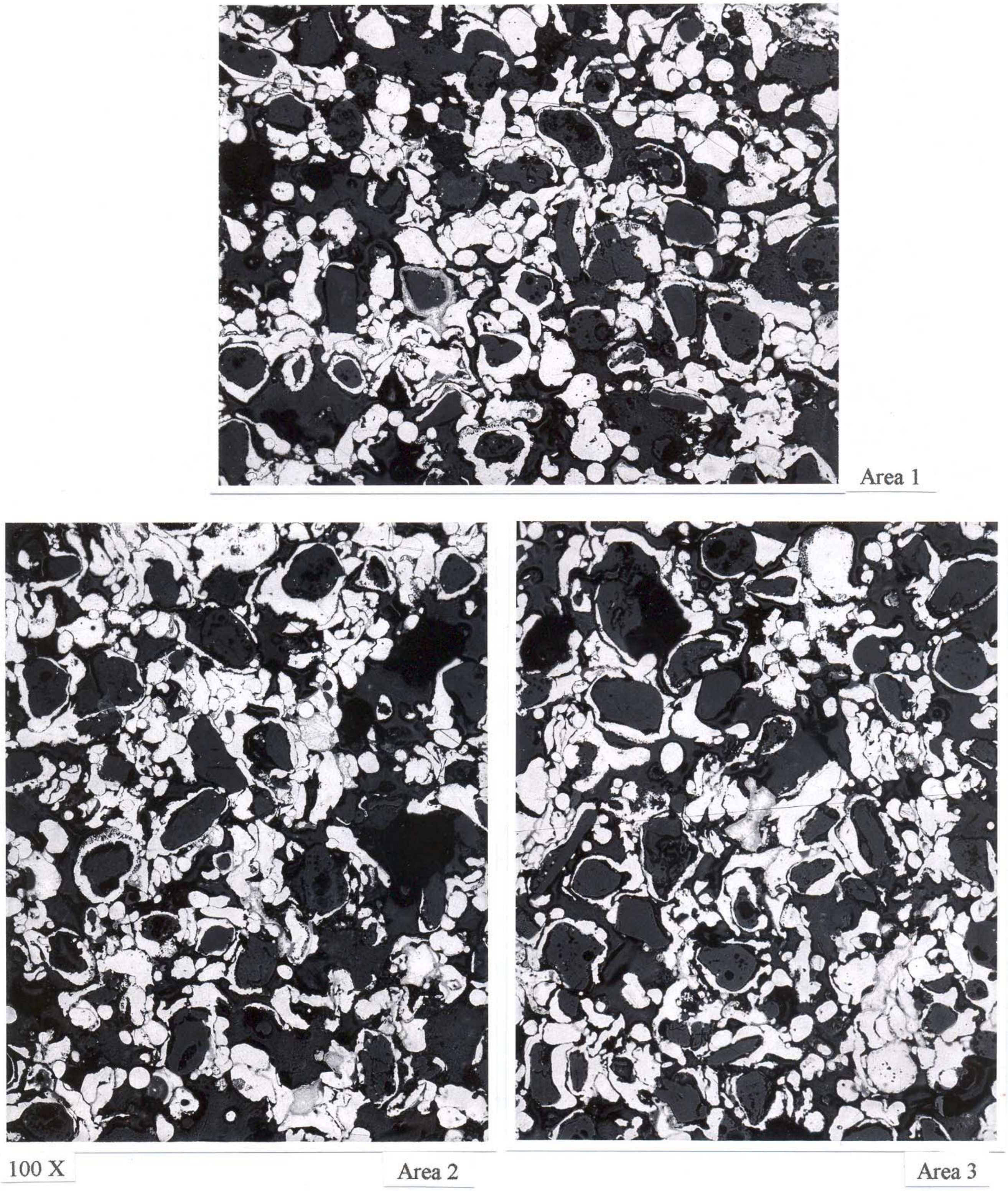


Figure 18a. Optical micrographs of LCA-314 coating chip taken from #51363 stage 6 ring. Three random areas for subsequent analysis for percent metal phase. EV 40177. 93 X magnification.

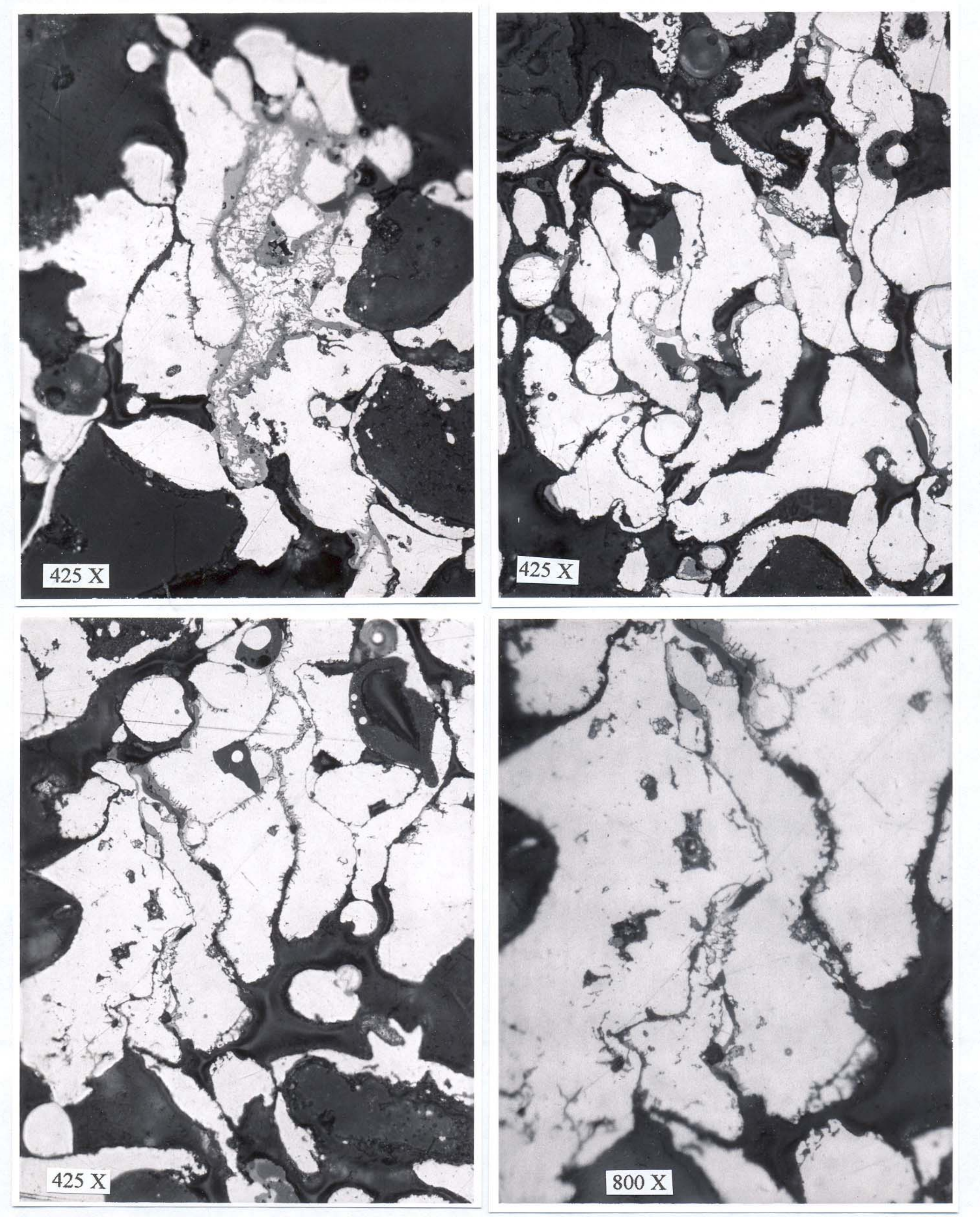
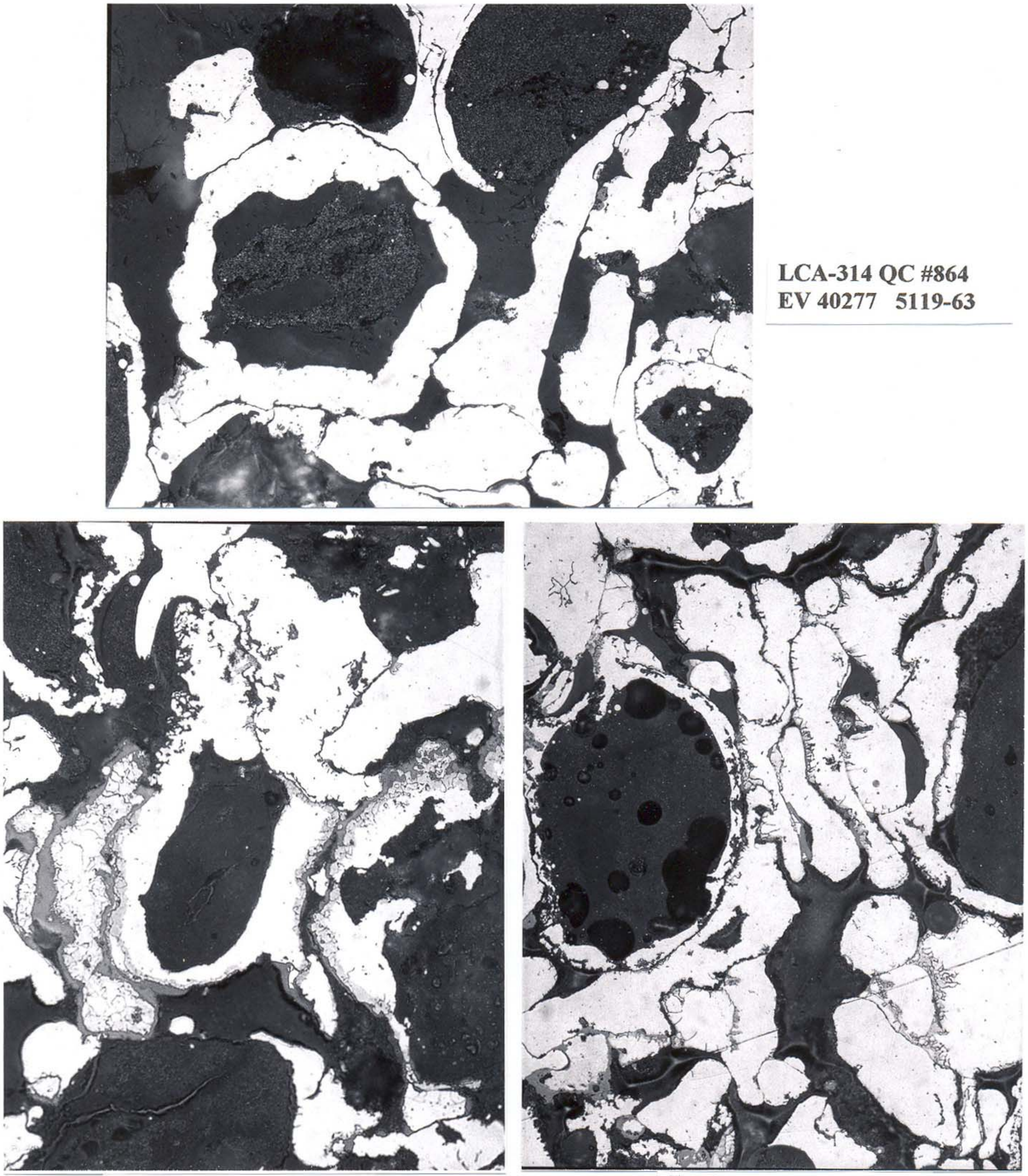


Figure 18b. Optical micrographs of LCA-314 coating chip taken from #51363 stage 6 ring. Detail of NiCrAl phase and severe oxidation formed at splat boundaries during engine operation. Magnification as noted X 0.91.



LCA-314 QC #864
EV 40277 5119-63

Engine run LCA-314
#51067 stage 6
EV 40155 5126-207-10B

Engine run LCA-314
#51363 stage 6 (chips)
EV 40177 5119-50-27

Figure 18c. Optical micrographs of LCA-314 showing degrees of oxidation present after coating (QC #864) as compared to after engine exposure. 390 X magnification.

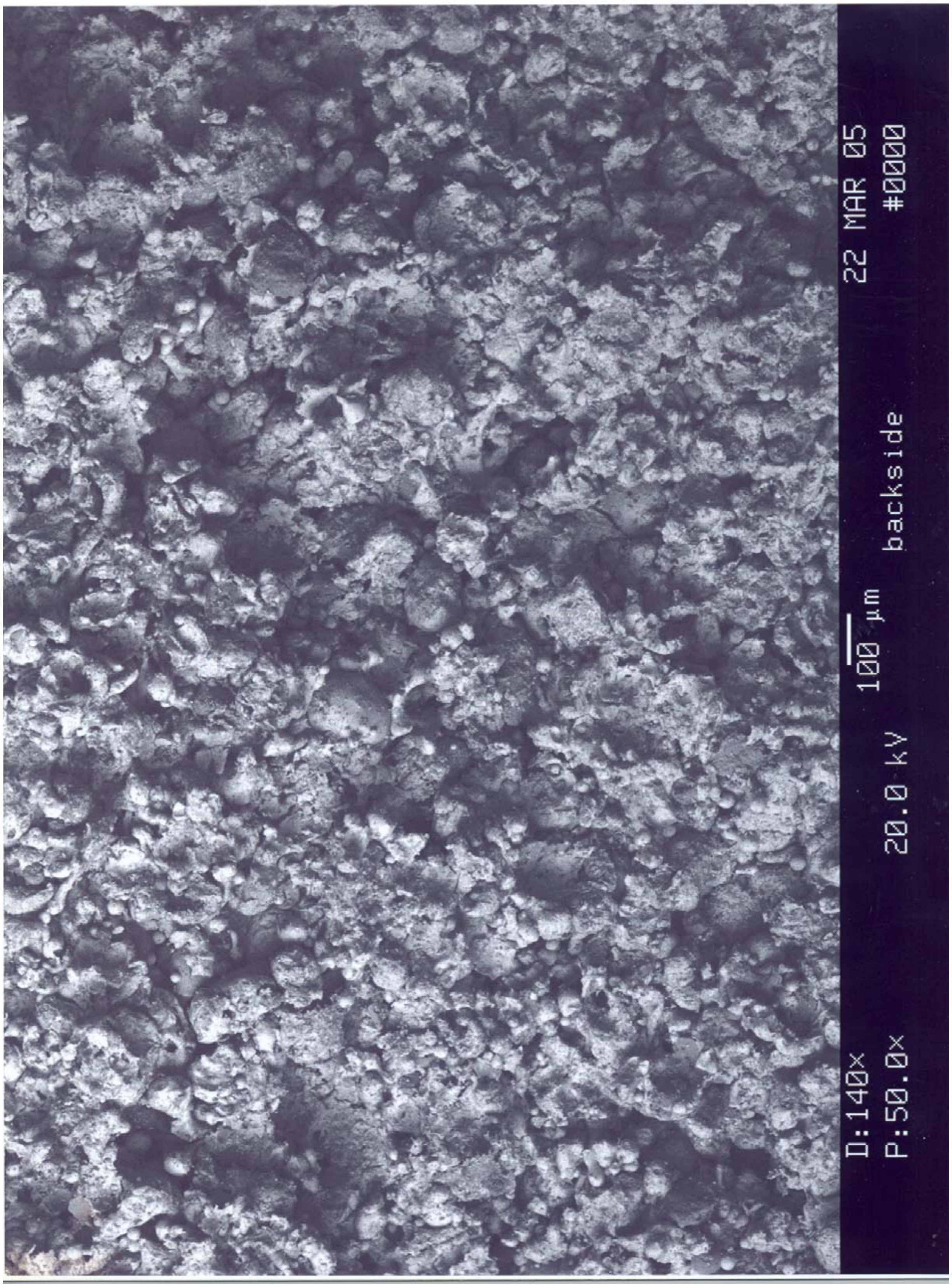


Figure 19a. SEM micrograph of backside of LCA-314 coating chip taken from #51363 stage 6 ring. 90 X magnification.

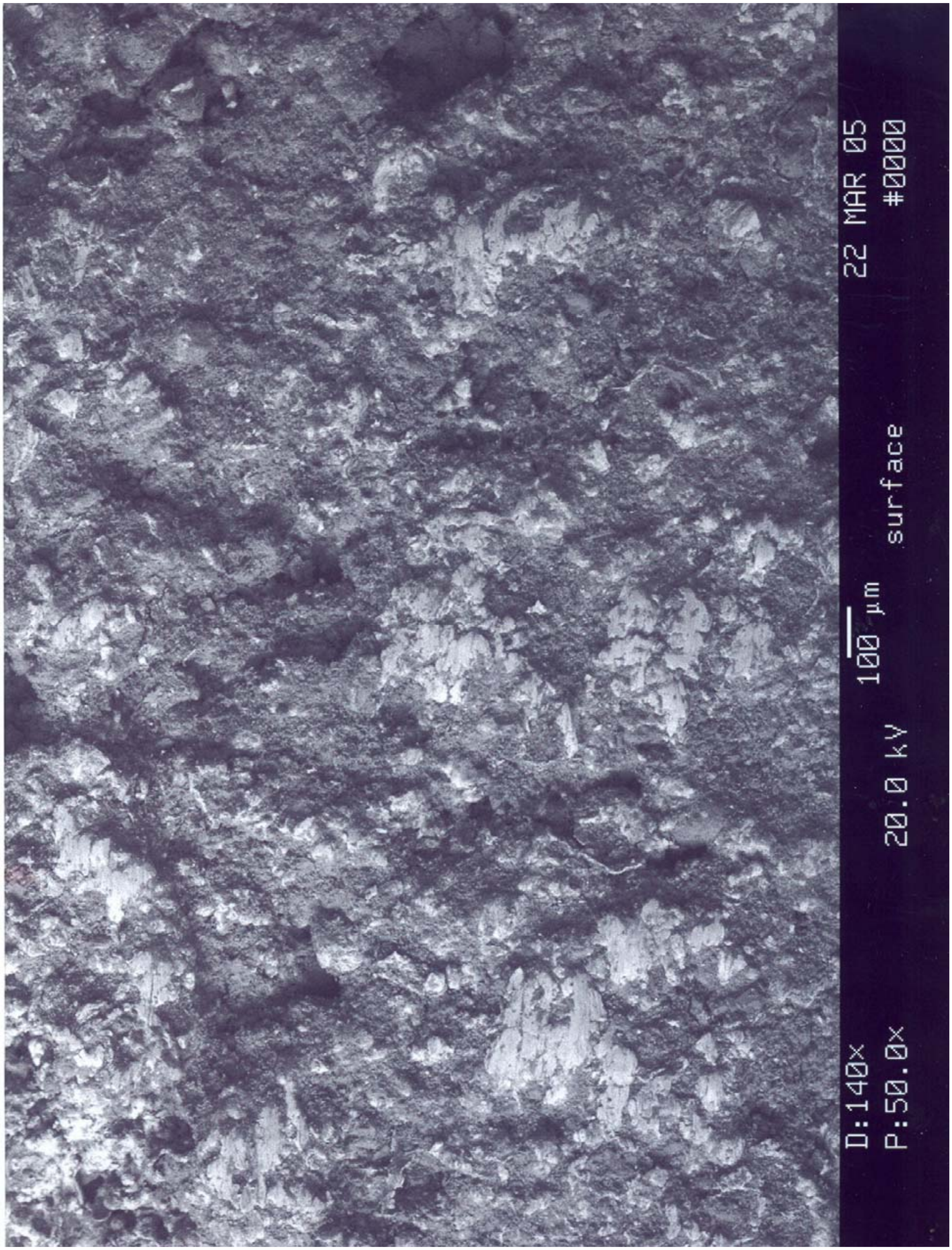
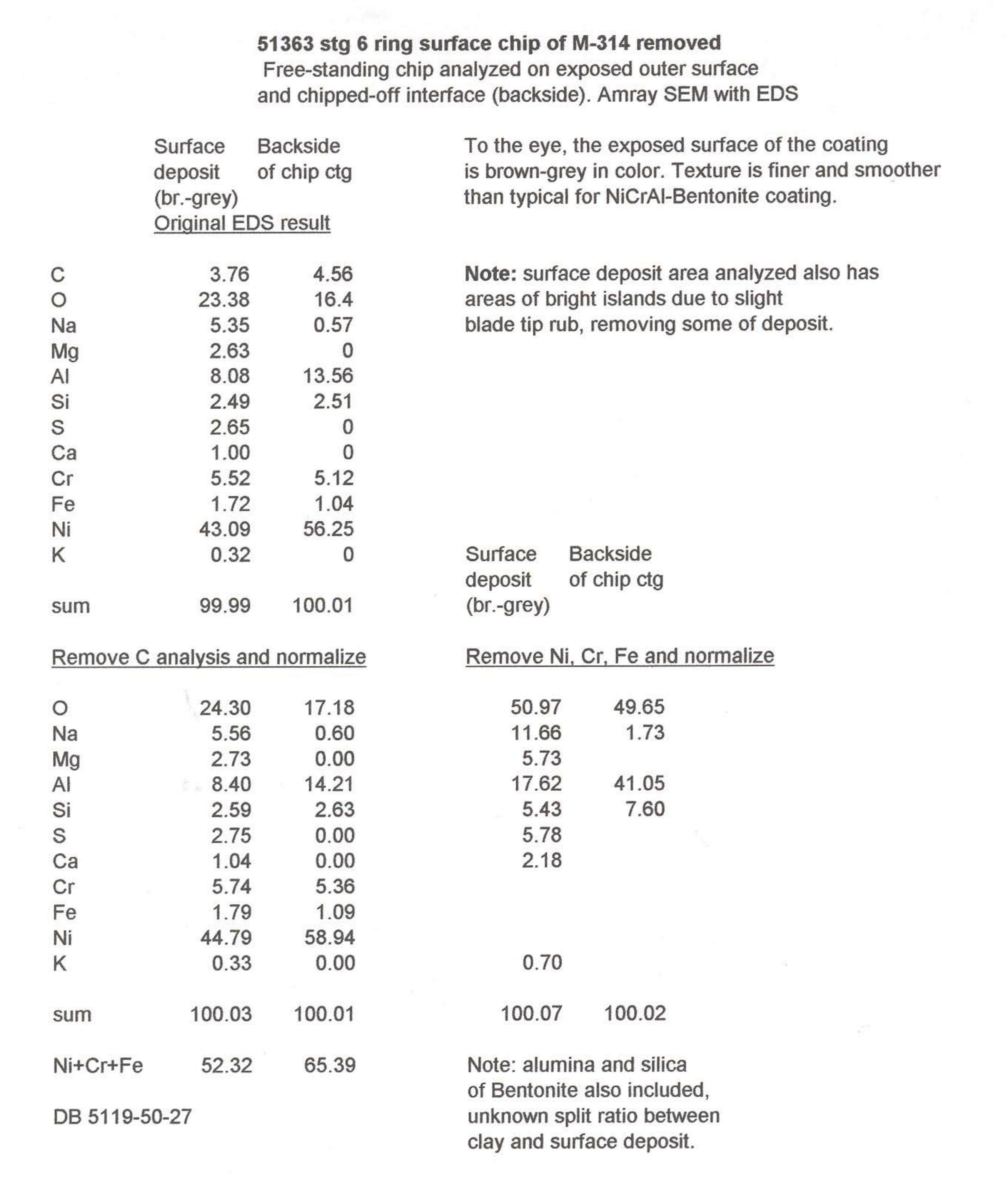


Figure 19b. SEM micrograph of front side of LCA-314 coating chip taken from #51363 stage 6 ring, showing fine-grained surface deposit on top of the 314 and small areas of light rub contact. Bright metallic smear of the rub areas suggest minimal oxidation after rub. 90 X magnification.



51363 stg 6 ring surface chip of M-314 removed

Free-standing chip analyzed on exposed outer surface
and chipped-off interface (backside). Amray SEM with EDS

To the eye, the exposed surface of the coating is brown-grey in color. Texture is finer and smoother than typical for NiCrAl-Bentonite coating.

	Surface deposit (br.-grey) Original EDS result	Backside of chip ctg
C	3.76	4.56
O	23.38	16.4
Na	5.35	0.57
Mg	2.63	0
Al	8.08	13.56
Si	2.49	2.51
S	2.65	0
Ca	1.00	0
Cr	5.52	5.12
Fe	1.72	1.04
Ni	43.09	56.25
K	0.32	0
sum	99.99	100.01

Note: surface deposit area analyzed also has areas of bright islands due to slight blade tip rub, removing some of deposit.

	Remove C analysis and normalize		Remove Ni, Cr, Fe and normalize	
			Surface deposit (br.-grey)	Backside of chip ctg
O	24.30	17.18	50.97	49.65
Na	5.56	0.60	11.66	1.73
Mg	2.73	0.00	5.73	
Al	8.40	14.21	17.62	41.05
Si	2.59	2.63	5.43	7.60
S	2.75	0.00	5.78	
Ca	1.04	0.00	2.18	
Cr	5.74	5.36		
Fe	1.79	1.09		
Ni	44.79	58.94		
K	0.33	0.00	0.70	
sum	100.03	100.01	100.07	100.02
Ni+Cr+Fe	52.32	65.39		

DB 5119-50-27

Note: alumina and silica of Bentonite also included, unknown split ratio between clay and surface deposit.

Figure 20. EDS analyses of the front and backside of the LCA-314 coating chip areas shown in Figs 19a and 19b.

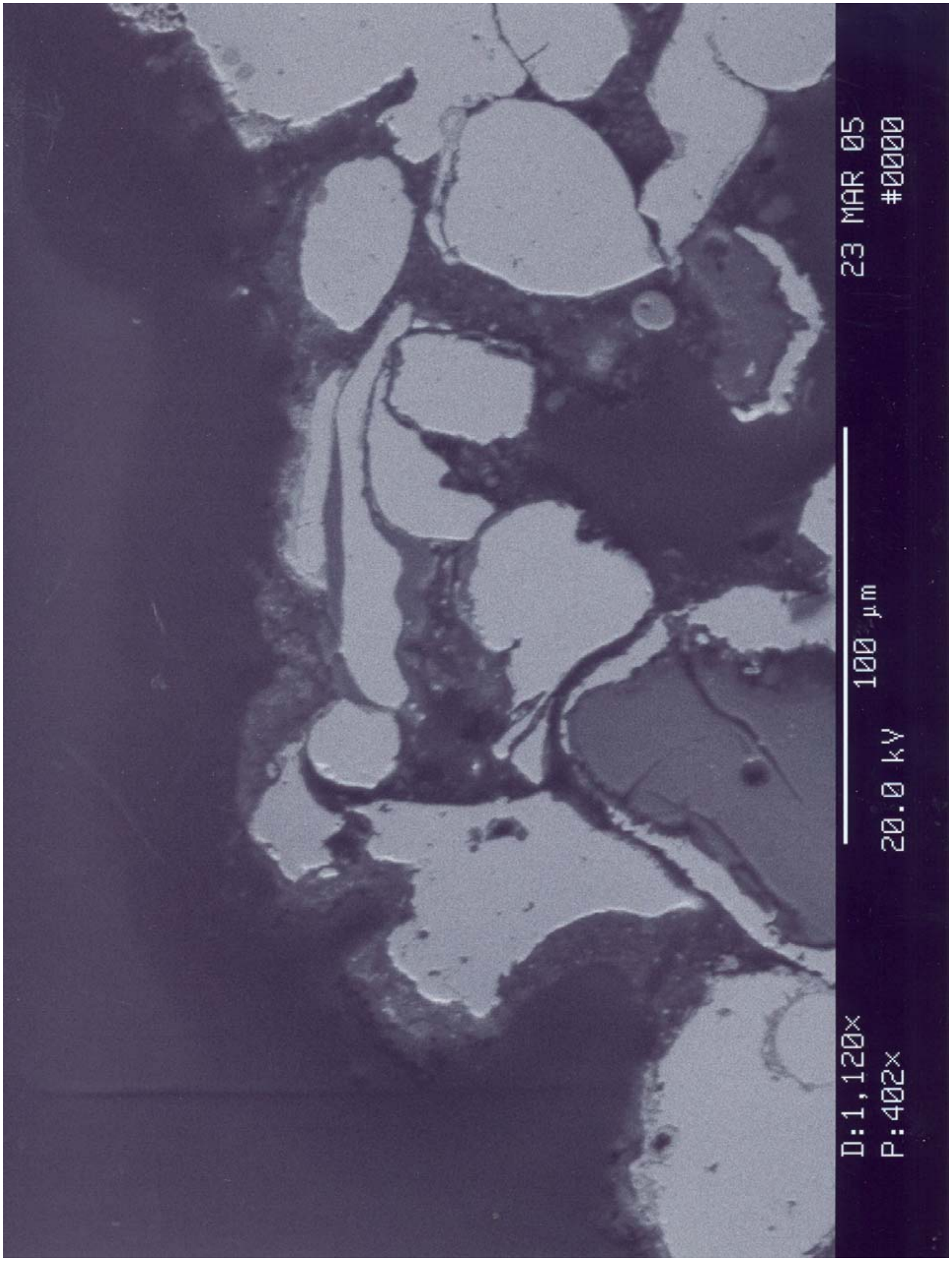
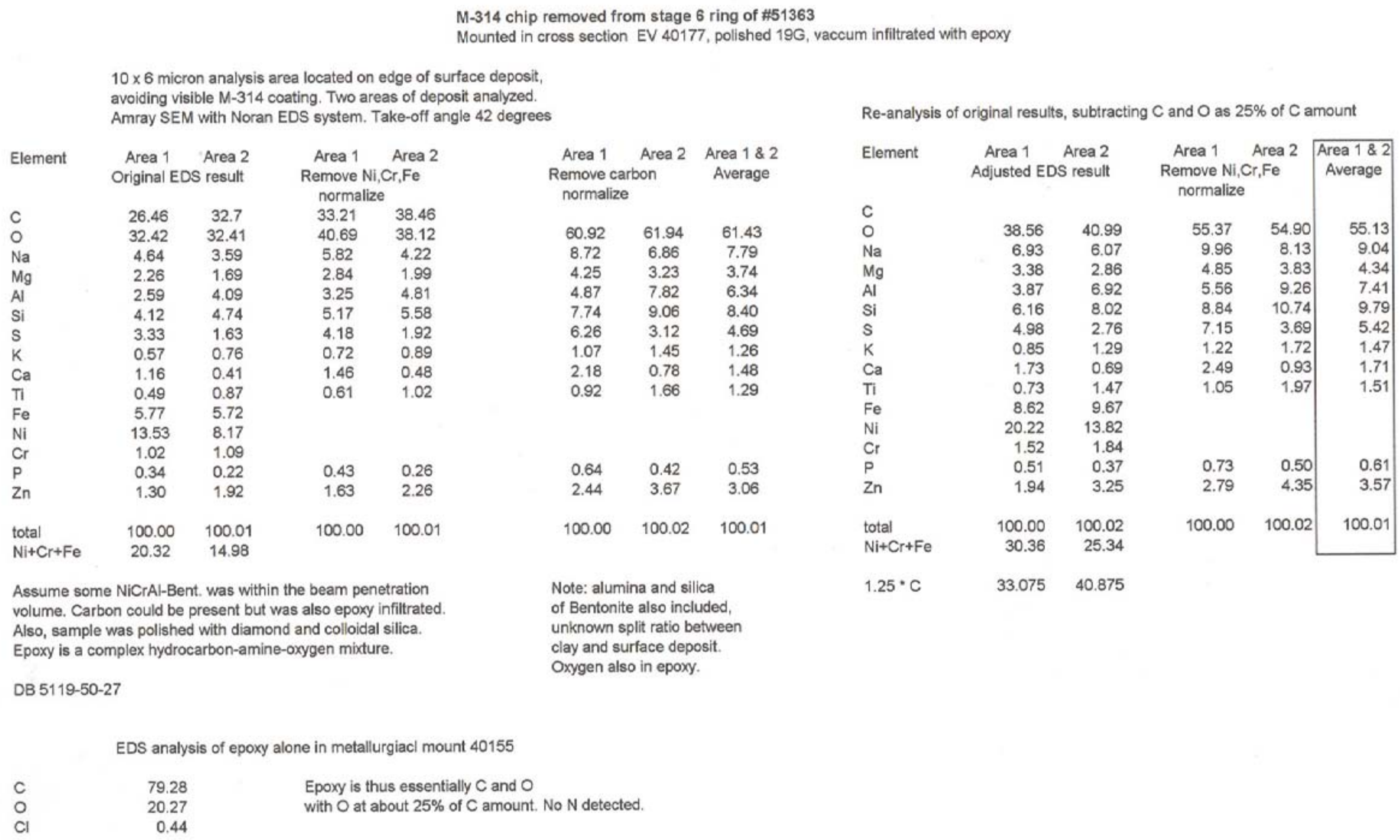


Figure 21a. SEM micrograph of polished cross section of LCA-314 coating chip taken from #51363 stage 6 ring, showing the normal 314 coating plus a fine-grained surface deposit that is also seen to penetrate into the 314 porosity. 715 X magnification.

Figure 21b. SEM micrograph of LCA-314 coating for Fig 21a, at higher magnification showing area of EDS analysis within surface deposit layer in order to identify its composition. 1080 X magnification.



M-314 chip removed from stage 6 ring of #51363
Mounted in cross section EV 40177, polished 19G, vaccum infiltrated with epoxy

10 x 6 micron analysis area located on edge of surface deposit,
avoiding visible M-314 coating. Two areas of deposit analyzed.
Amray SEM with Noran EDS system. Take-off angle 42 degrees

Element	Area 1	Area 2	Area 1	Area 2	Area 1	Area 2	Area 1 & 2
	Original EDS result		Remove Ni,Cr,Fe normalize		Remove carbon normalize		Average
C	26.46	32.7	33.21	38.46			
O	32.42	32.41	40.69	38.12	60.92	61.94	61.43
Na	4.64	3.59	5.82	4.22	8.72	6.86	7.79
Mg	2.26	1.69	2.84	1.99	4.25	3.23	3.74
Al	2.59	4.09	3.25	4.81	4.87	7.82	6.34
Si	4.12	4.74	5.17	5.58	7.74	9.06	8.40
S	3.33	1.63	4.18	1.92	6.26	3.12	4.69
K	0.57	0.76	0.72	0.89	1.07	1.45	1.26
Ca	1.16	0.41	1.46	0.48	2.18	0.78	1.48
Ti	0.49	0.87	0.61	1.02	0.92	1.66	1.29
Fe	5.77	5.72					
Ni	13.53	8.17					
Cr	1.02	1.09					
P	0.34	0.22	0.43	0.26	0.64	0.42	0.53
Zn	1.30	1.92	1.63	2.26	2.44	3.67	3.06
total	100.00	100.01	100.00	100.01	100.00	100.02	100.01
Ni+Cr+Fe	20.32	14.98					

Assume some NiCrAl-Bent. was within the beam penetration volume. Carbon could be present but was also epoxy infiltrated. Also, sample was polished with diamond and colloidal silica. Epoxy is a complex hydrocarbon-amine-oxygen mixture.

Note: alumina and silica of Bentonite also included, unknown split ratio between clay and surface deposit. Oxygen also in epoxy.

DB 5119-50-27

Re-analysis of original results, subtracting C and O as 25% of C amount

Element	Area 1	Area 2	Area 1	Area 2	Area 1 & 2
	Adjusted EDS result		Remove Ni,Cr,Fe normalize		Average
C					
O	38.56	40.99	55.37	54.90	55.13
Na	6.93	6.07	9.96	8.13	9.04
Mg	3.38	2.86	4.85	3.83	4.34
Al	3.87	6.92	5.56	9.26	7.41
Si	6.16	8.02	8.84	10.74	9.79
S	4.98	2.76	7.15	3.69	5.42
K	0.85	1.29	1.22	1.72	1.47
Ca	1.73	0.69	2.49	0.93	1.71
Ti	0.73	1.47	1.05	1.97	1.51
Fe	8.62	9.67			
Ni	20.22	13.82			
Cr	1.52	1.84			
P	0.51	0.37	0.73	0.50	0.61
Zn	1.94	3.25	2.79	4.35	3.57
total	100.00	100.02	100.00	100.02	100.01
Ni+Cr+Fe	30.36	25.34			
1.25 * C	33.075	40.875			

EDS analysis of epoxy alone in metallurgiacl mount 40155

C	79.28
O	20.27
Cl	0.44

Epoxy is thus essentially C and O with O at about 25% of C amount. No N detected.

Figure 22.EDS analyses of polished cross section of coating chip taken from #51363 stage 6 ring. Analysis area is small box indicated in Fig. 21b, located on the thin surface layer of material on top of the LCA-314 coating. Second area is also in this layer, different location. Final average estimate of composition is outlined in box.

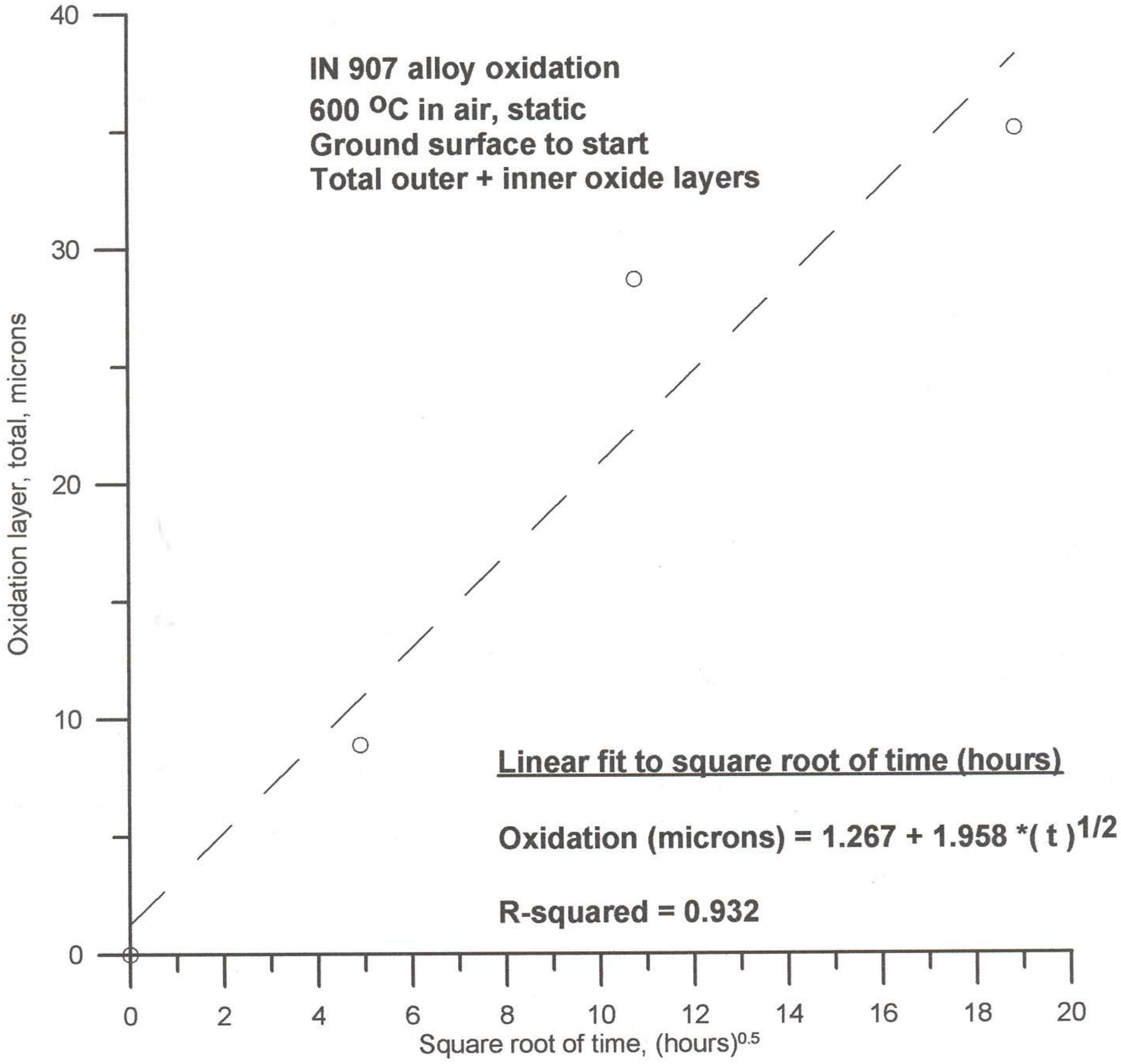


Figure 23. Plot of oxidation data at 600 °C in air for sample of IN 907 taken from #51067 stage 6 ring, ground, and then furnace exposed at PST. Linear fit indicated to square root of exposure time for total outer + inner oxide layers.

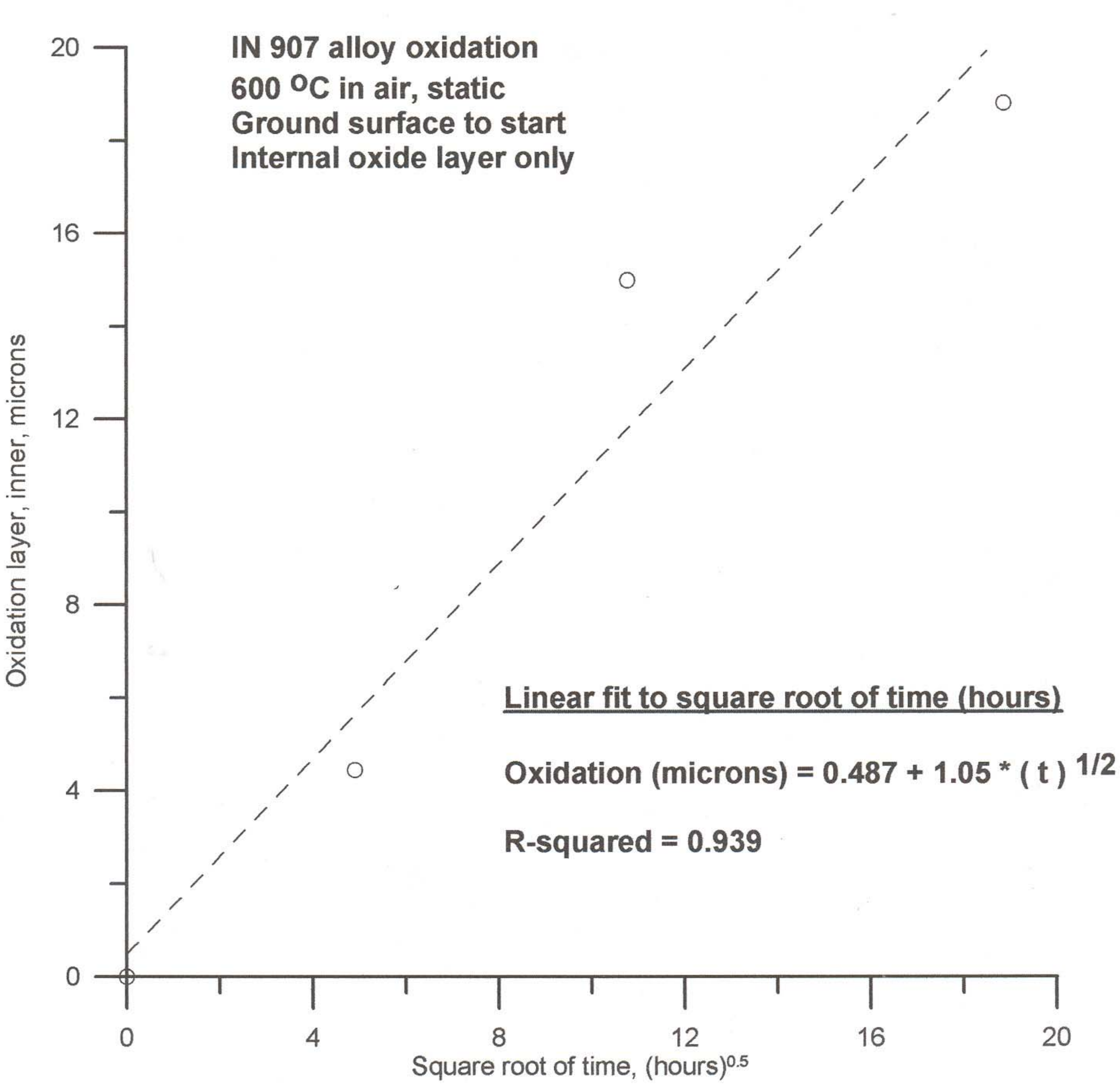


Figure 24. Plot of oxidation data at 600 ^{o}C in air for sample of IN 907 taken from #51067 stage 6 ring, ground, and then furnace exposed at PST. Linear fit indicated to square root of exposure time for just inner oxide layer.

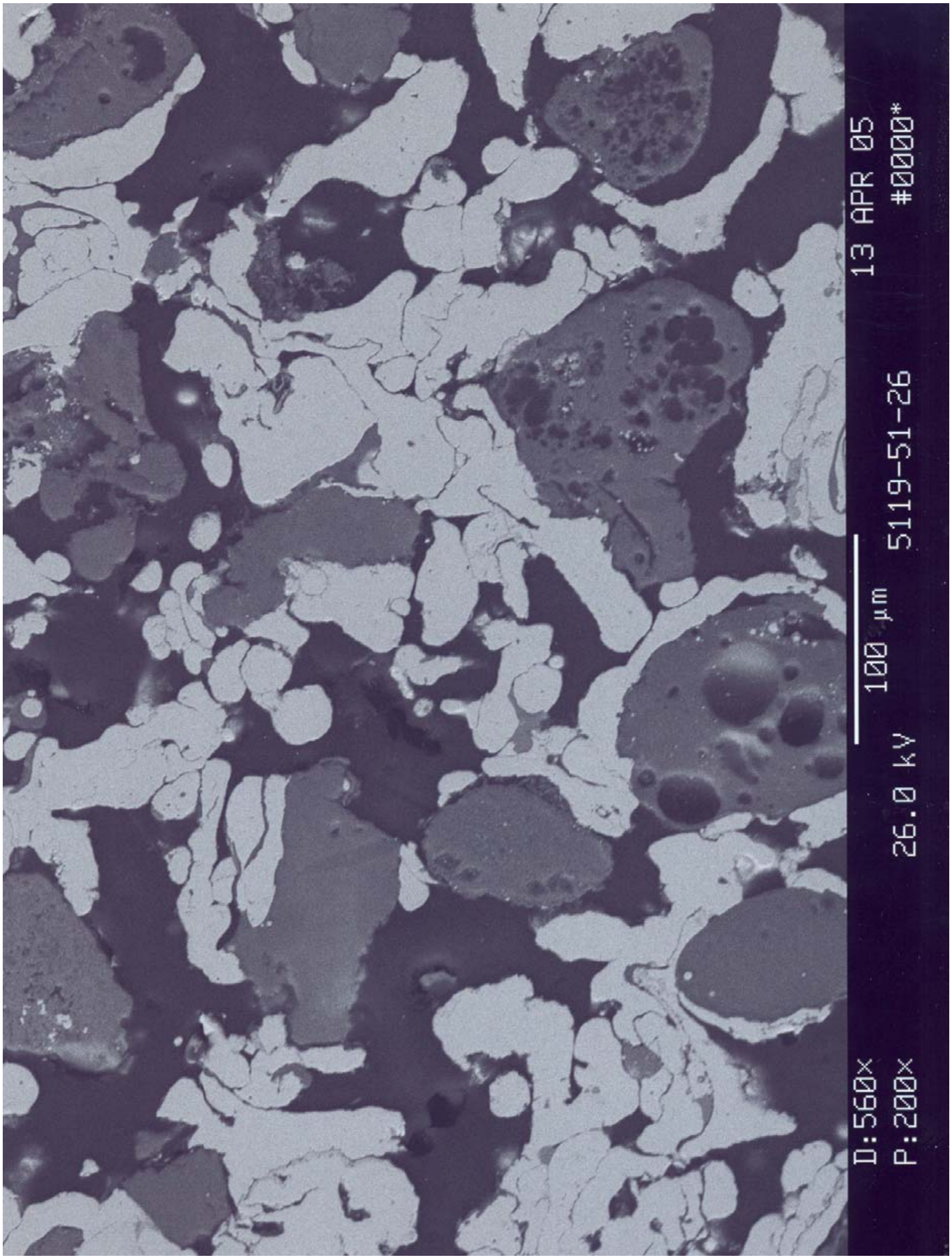


Figure 25. SEM micrograph of PST furnace oxidation sample of NiCrAl-Bentonite coating, exposed for 453 hours at 600 ^{o}C in air. 350 X magnification.

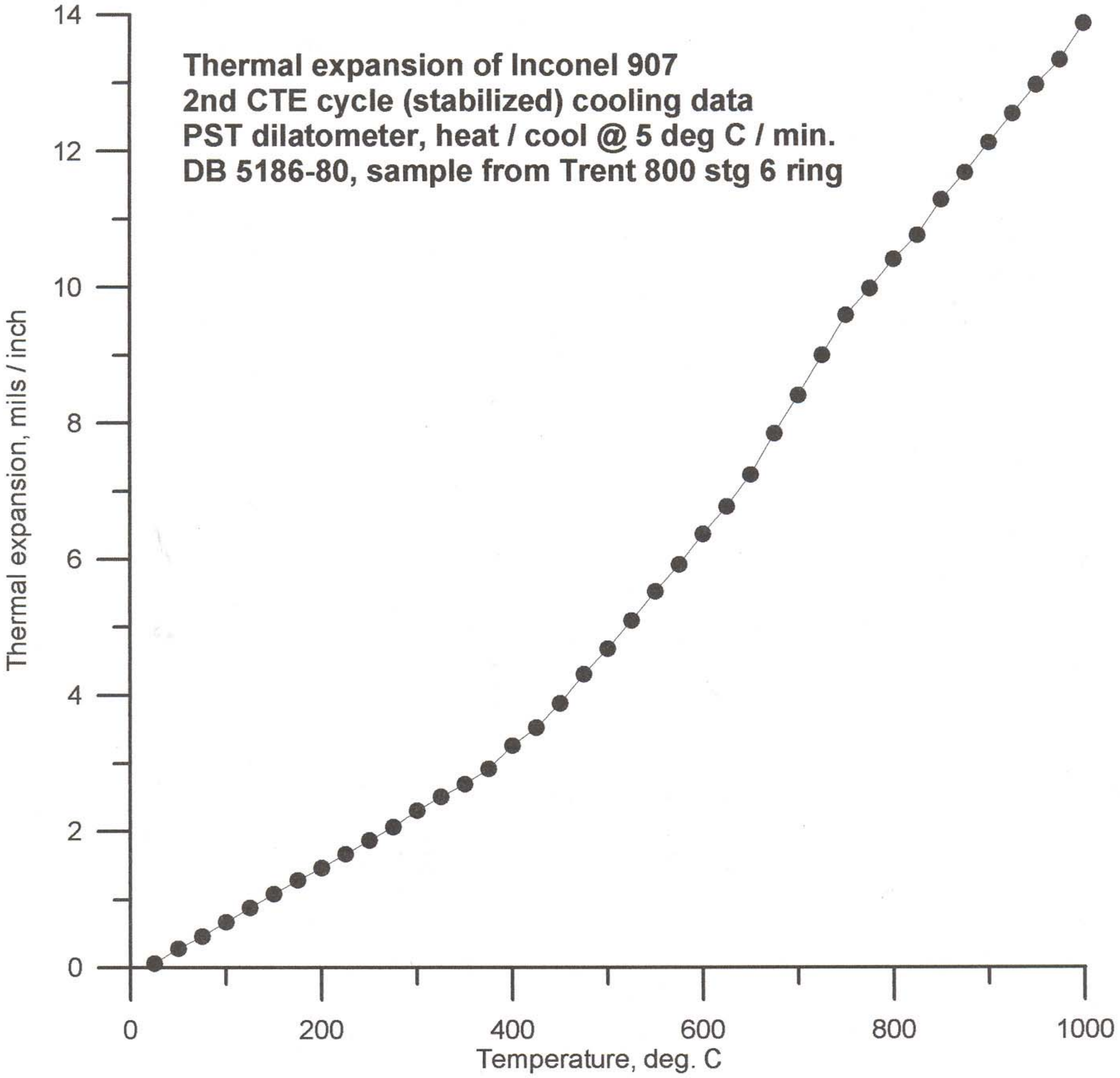


Figure 26. Stabilized thermal expansion of IN 907 alloy, sample from #51067 stage 6 ring.

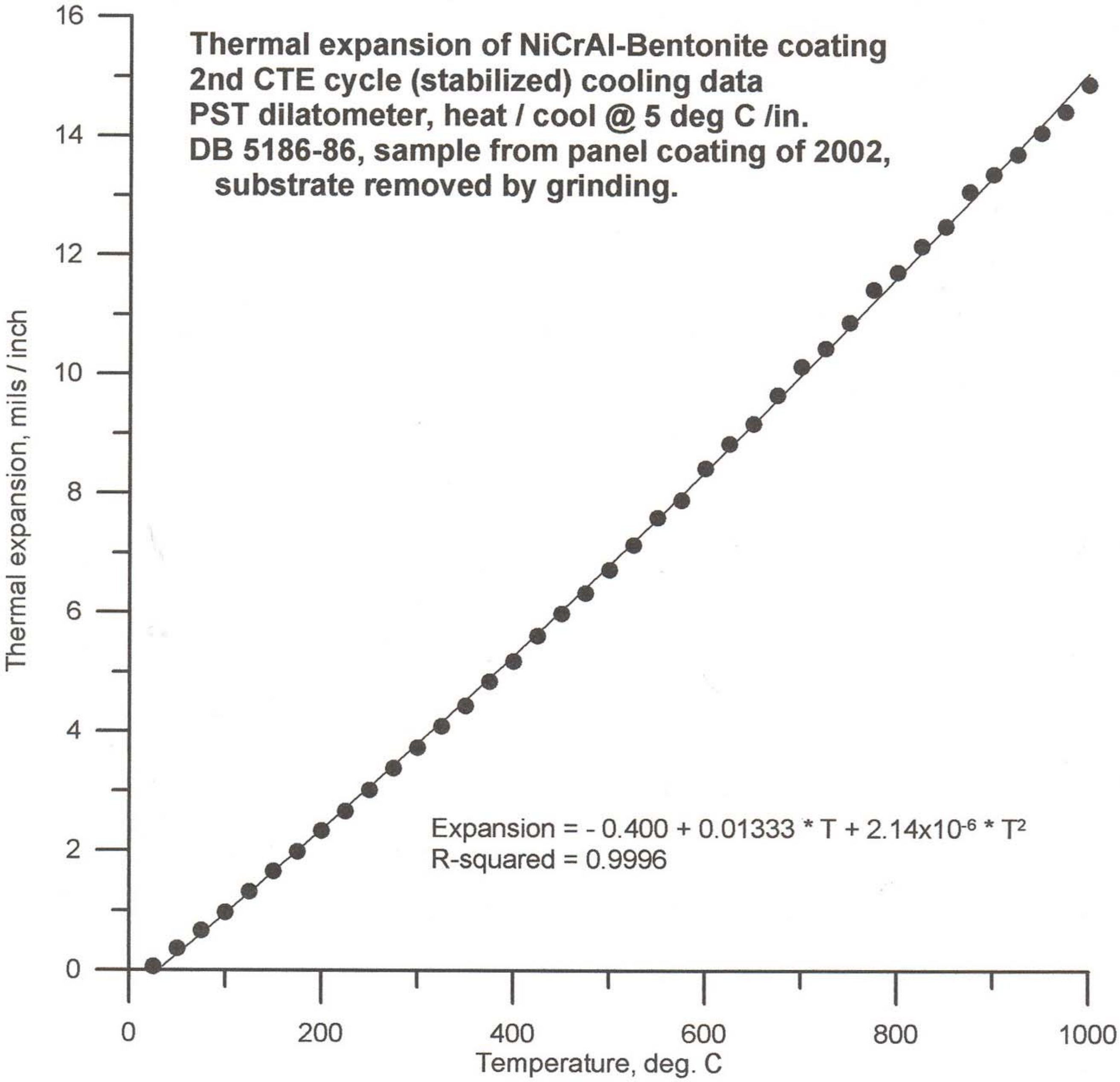


Figure 27. Stabilized thermal expansion of NiCrAl-Bentonite coating, sample from PST archives.

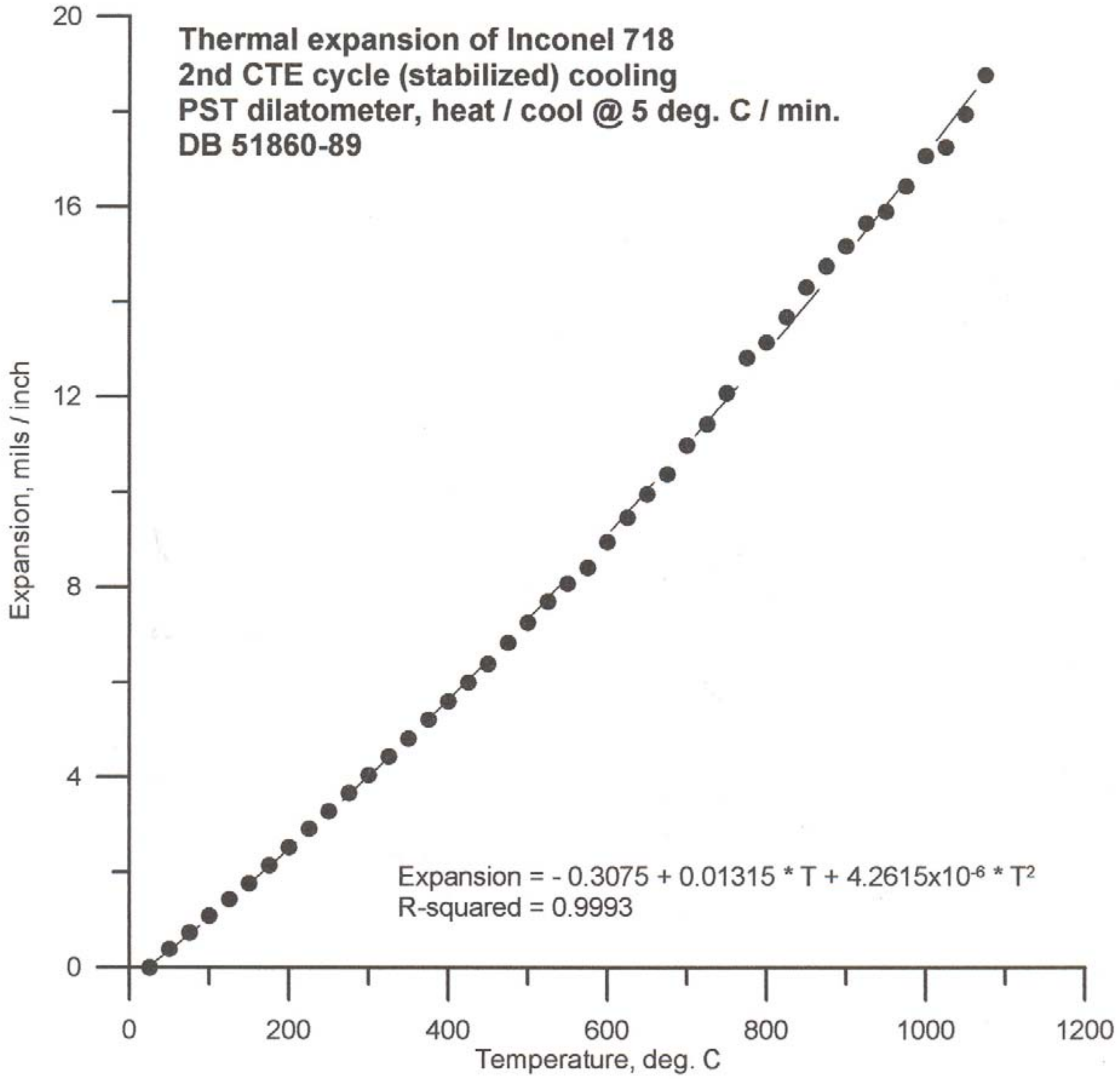


Figure 28. Stabilized thermal expansion of IN 718 alloy, sample from PST archives.

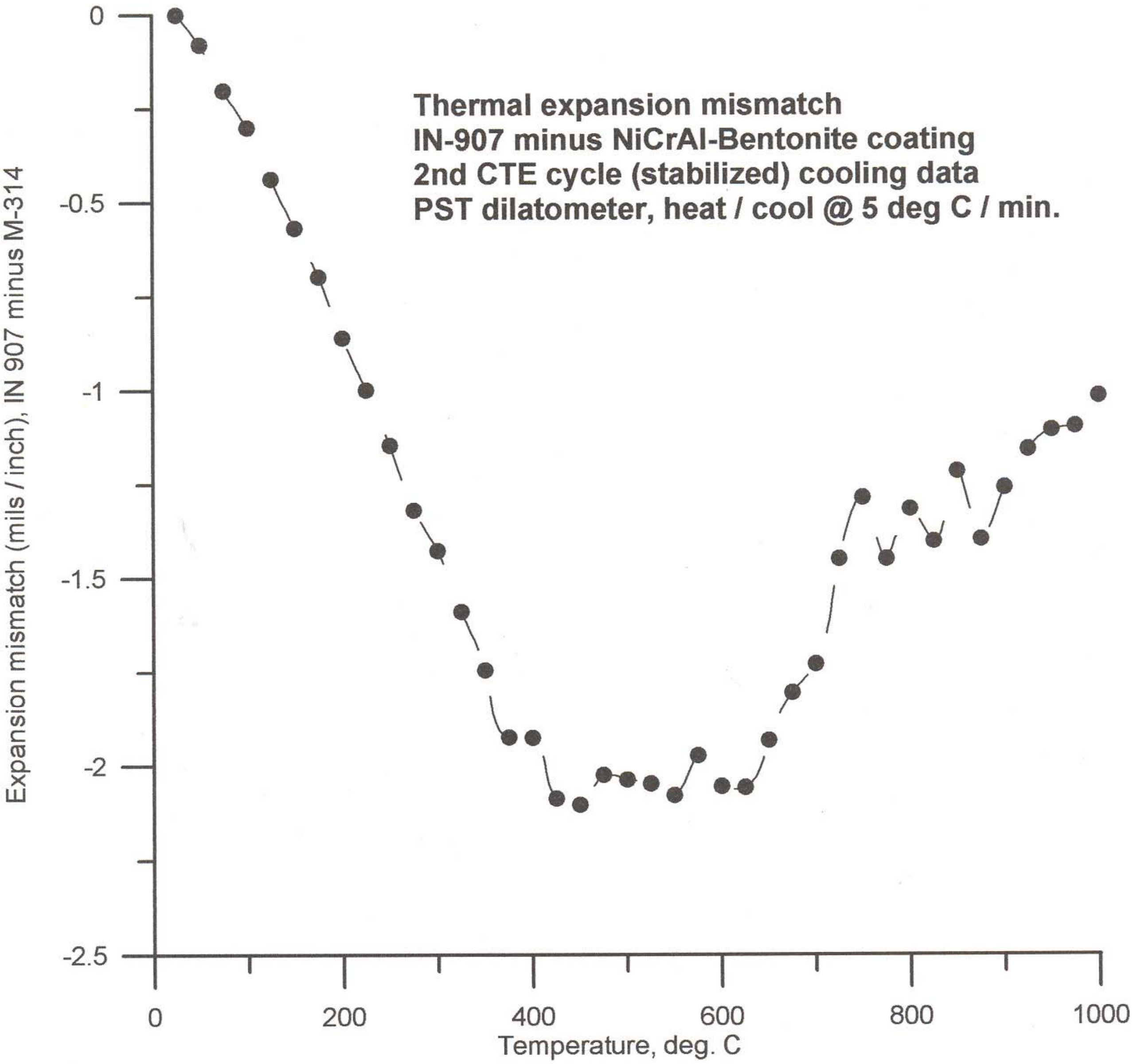


Figure 29. Difference in stabilized thermal expansion between IN 907 alloy and NiCrAl-Bentonite coating.

Figure 30. Low angle erosion test rig at PST, with segment of wear track of #51067 stage 6 ring with remnant LCA-314 still adhered after flight exposure. Pure air erosion at 500 ft./sec., 340 cfh flow, 20 degree impingement. In this test, aft edge of coated ring was upstream, erosion spot centered on piece is oval.

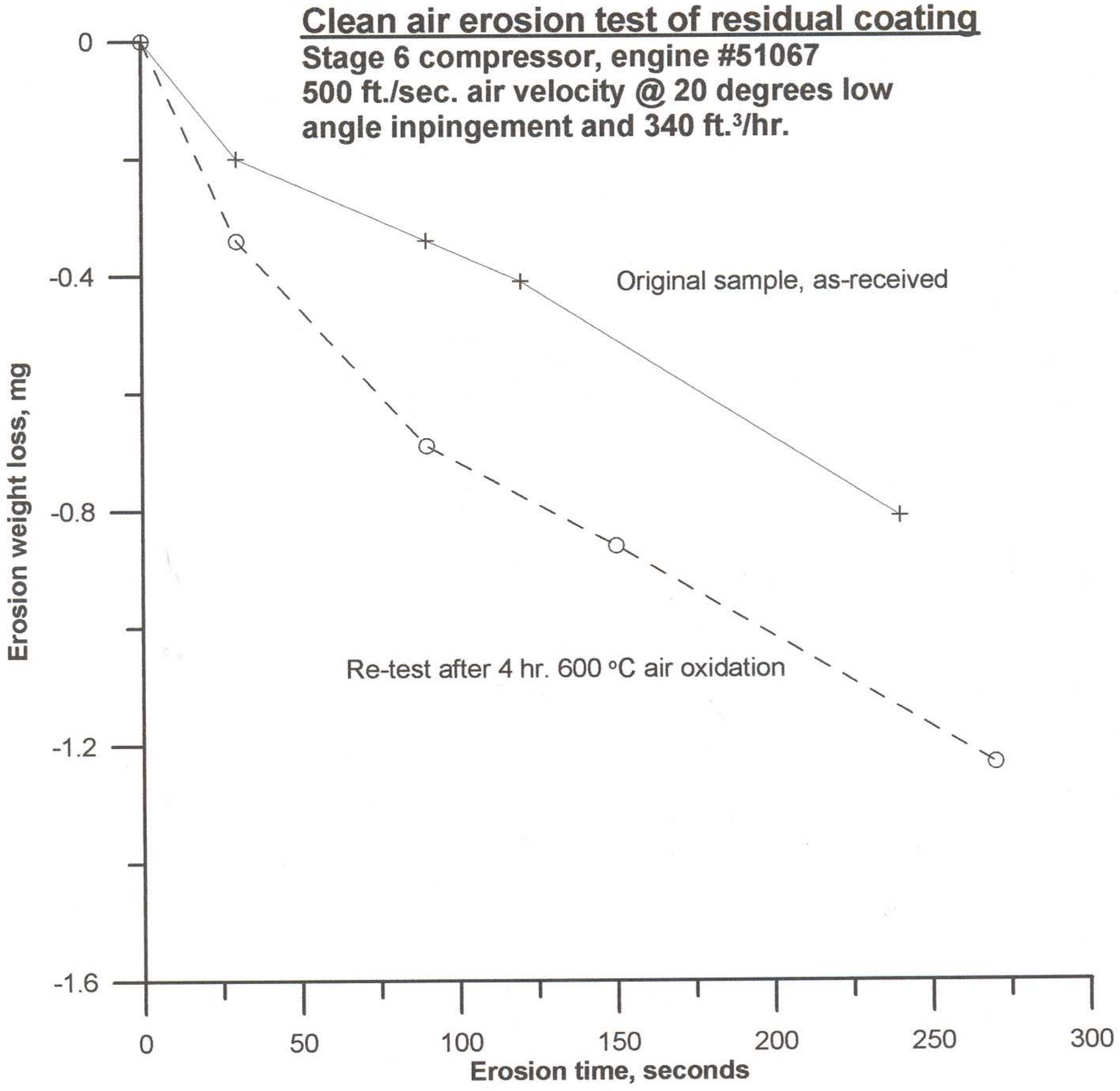
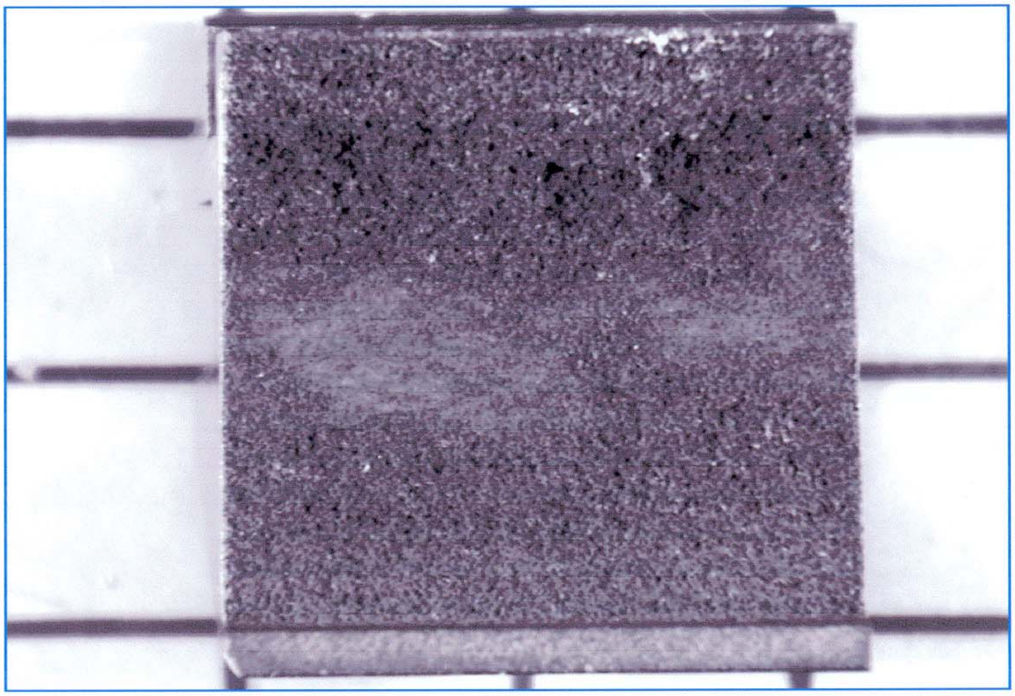
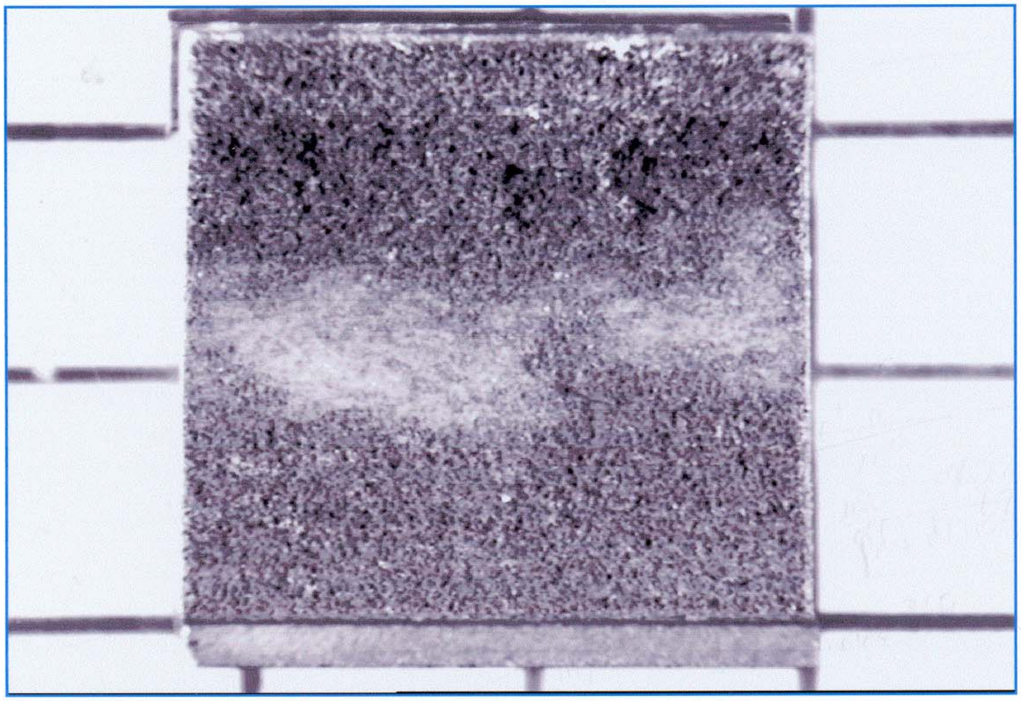


Figure 31. Clean air erosion weight loss vs. time data of remnant LCA-314 coating on stage 6 substrate, sample of Fig. 30 taken from flight-exposed #51067 engine. Upper curve is as-received sample, lower is after first test and subsequent 4 hour oxidation at 600 ^{o}C.



Pre-Erosion Testing



Post-Erosion Testing

Figure 32. Macrophotos of erosion sample of Figs. 30 and 31, before test and after first as-received erosion exposure.

PRAXAIR SURFACE TECHNOLOGIES

Where is CMAS Found?

Volcanic Ash

Redoubt Volcano, Alaska (1990)

Major air traffic routes over the North Pacific, in close proximity to active volcanoes

Figure 33

Figure 33. Map of active volcanoes in the North Pacific region.

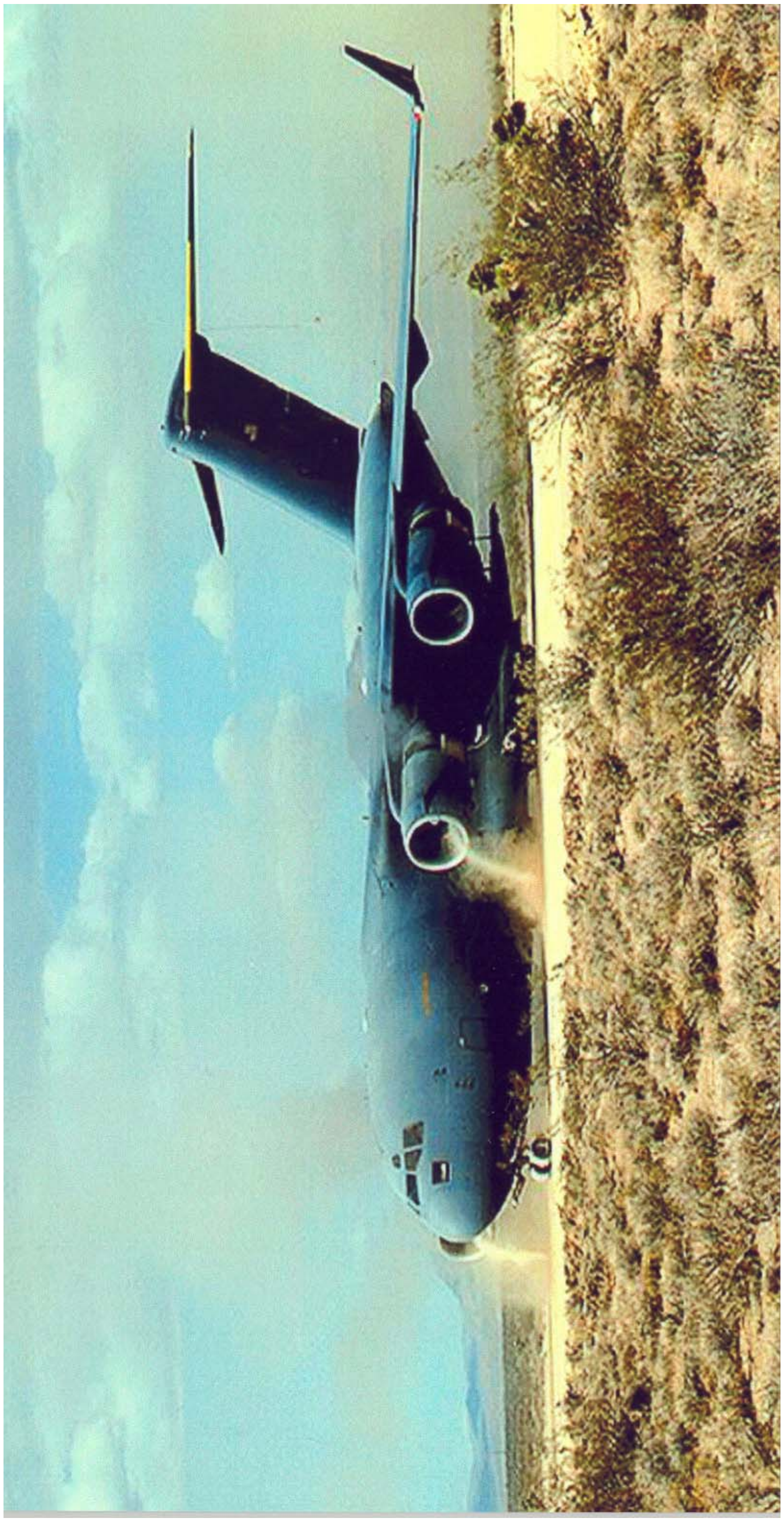


Figure 34. Military aircraft pulling dust into engines while on the runway in unknown desert area.

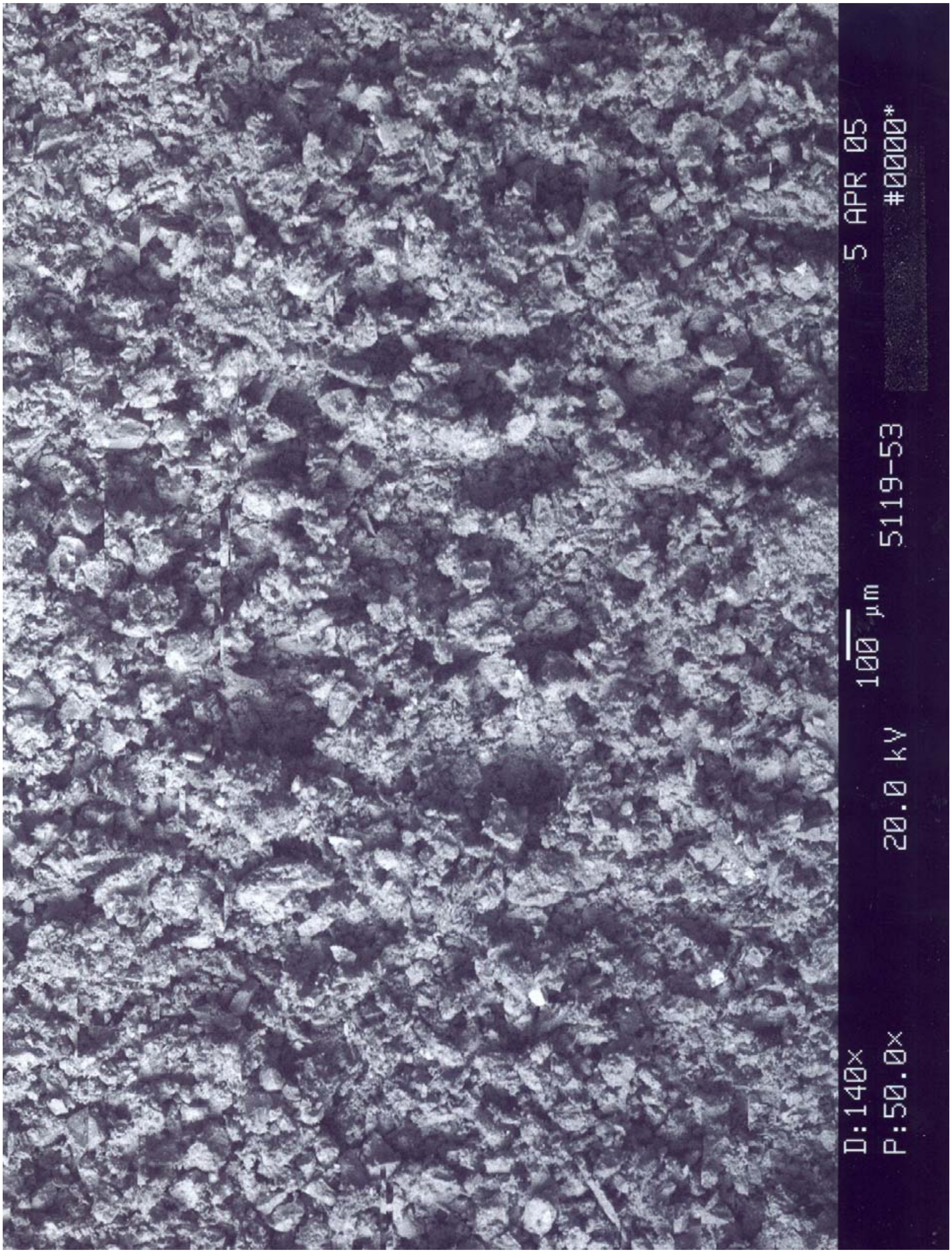
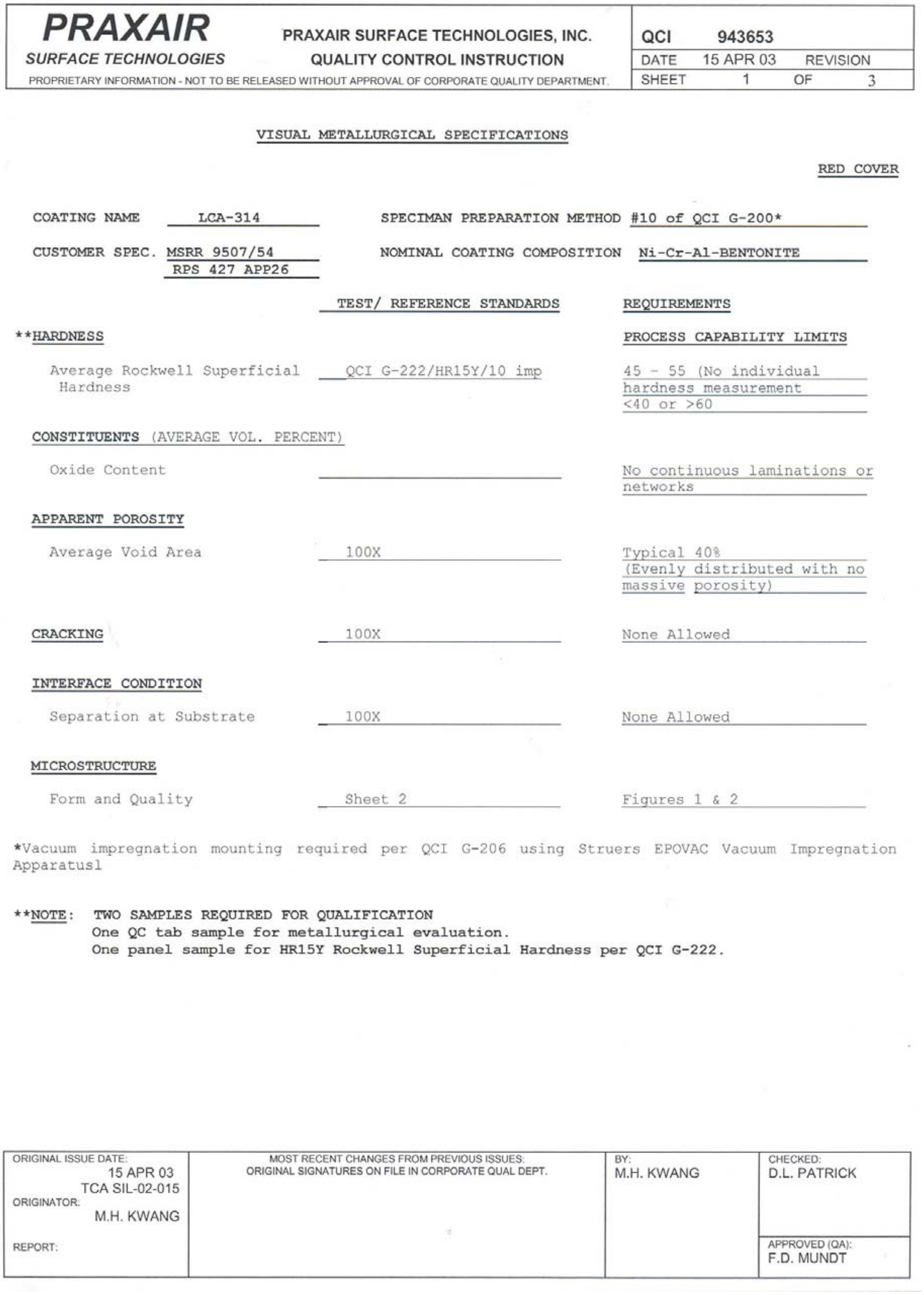


Figure 35. SEM micrograph of surface of powder from Mt. Saint Helens volcanic eruption of May 1980. Particle size appears to be roughly 5 to 30 microns. 90 X magnification.



PRAXAIR *SURFACE TECHNOLOGIES*	PRAXAIR SURFACE TECHNOLOGIES, INC. QUALITY CONTROL INSTRUCTION	QCI 943653
		DATE 15 APR 03 REVISION
PROPRIETARY INFORMATION - NOT TO BE RELEASED WITHOUT APPROVAL OF CORPORATE QUALITY DEPARTMENT.		SHEET 1 OF 3

VISUAL METALLURGICAL SPECIFICATIONS

RED COVER

COATING NAME LCA-314

SPECIMAN PREPARATION METHOD #10 of QCI G-200*

CUSTOMER SPEC. MSRR 9507/54
RPS 427 APP26

NOMINAL COATING COMPOSITION Ni-Cr-Al-BENTONITE

	TEST/ REFERENCE STANDARDS	REQUIREMENTS
****HARDNESS**		PROCESS CAPABILITY LIMITS
Average Rockwell Superficial Hardness	QCI G-222/HR15Y/10 imp	45 - 55 (No individual hardness measurement <40 or >60
CONSTITUENTS (AVERAGE VOL. PERCENT)		
Oxide Content		No continuous laminations or networks
APPARENT POROSITY		
Average Void Area	100X	Typical 40% (Evenly distributed with no massive porosity)
CRACKING	100X	None Allowed
INTERFACE CONDITION		
Separation at Substrate	100X	None Allowed
MICROSTRUCTURE		
Form and Quality	Sheet 2	Figures 1 & 2

*Vacuum impregnation mounting required per QCI G-206 using Struers EPOVAC Vacuum Impregnation Apparatusl

**NOTE: TWO SAMPLES REQUIRED FOR QUALIFICATION
One QC tab sample for metallurgical evaluation.
One panel sample for HR15Y Rockwell Superficial Hardness per QCI G-222.

ORIGINAL ISSUE DATE: 15 APR 03 TCA SIL-02-015 ORIGINATOR: M.H. KWANG REPORT:	MOST RECENT CHANGES FROM PREVIOUS ISSUES: ORIGINAL SIGNATURES ON FILE IN CORPORATE QUAL DEPT.	BY: M.H. KWANG	CHECKED: D.L. PATRICK APPROVED (QA): F.D. MUNDT

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		DATE 15 APR 03	REVISION
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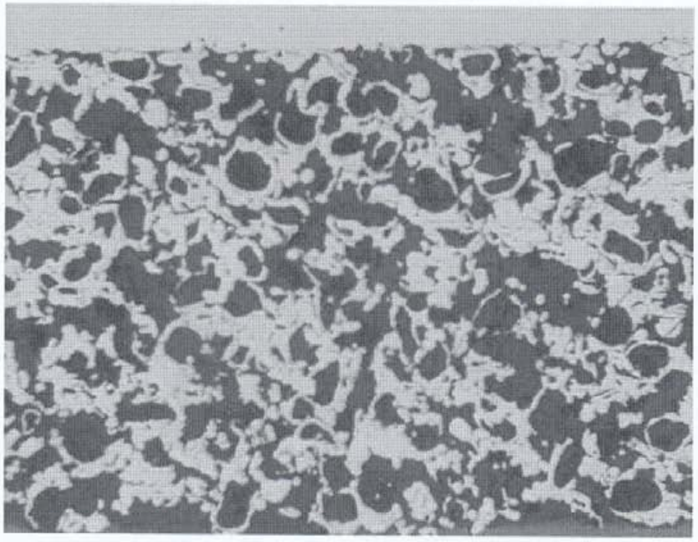

FIGURE 1 - Typical microstructure LCA 314, 50X, Brightfield
AST Singapore Sample# 314NS#2

ORIGINAL ISSUE DATE: 15 APR 03 TCA SIL-02-015 ORIGINATOR: M.H. KWANG REPORT:	MOST RECENT CHANGES FROM PREVIOUS ISSUES: ORIGINAL SIGNATURES ON FILE IN CORPORATE QUAL DEPT.	BY: M.H. KWANG	CHECKED: D.L. PATRICK APPROVED (QA): F.D. MUNDT

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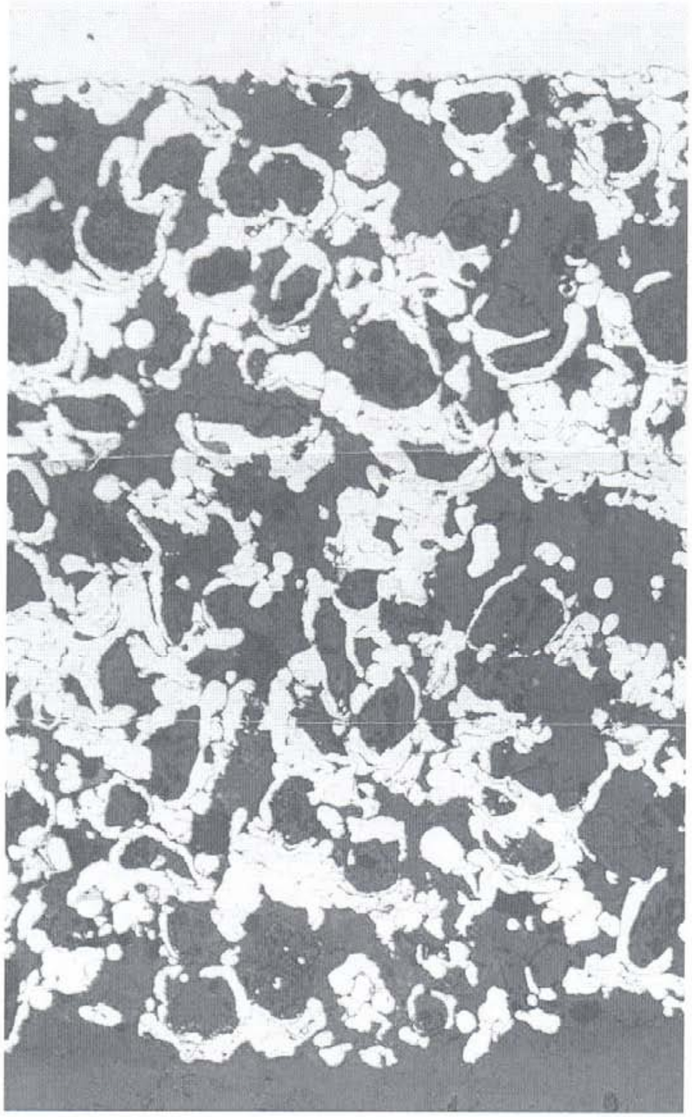
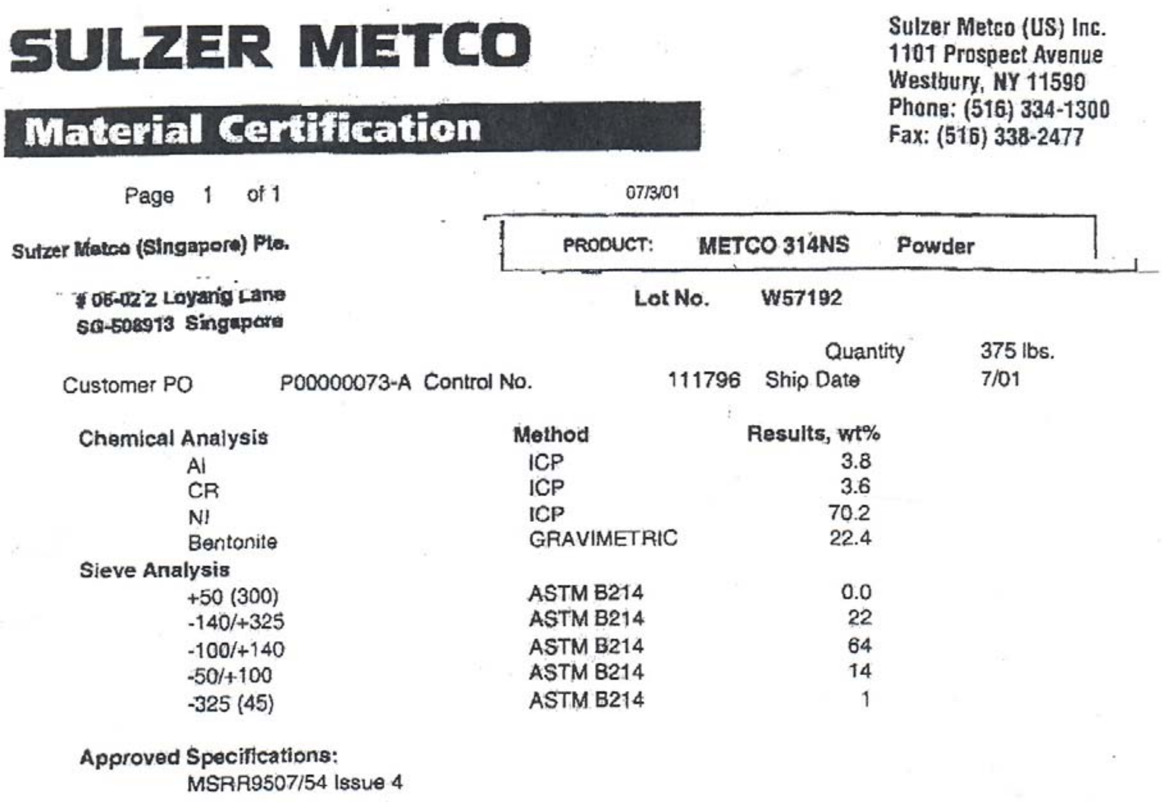


FIGURE 2 - Typical microstructure LCA 314, 100X, Brightfield
AST Singapore Sample 314NS#2

ORIGINAL ISSUE DATE: 15 APR 03 TCA SIL-02-015 ORIGINATOR: M.H. KWANG	MOST RECENT CHANGES FROM PREVIOUS ISSUES: ORIGINAL SIGNATURES ON FILE IN CORPORATE QUAL DEPT.	BY: M.H. KWANG	CHECKED: D.L. PATRICK
REPORT:			APPROVED (QA): F.D. MUNDT



SULZER METCO

Material Certification

Sulzer Metco (US) Inc.
1101 Prospect Avenue
Westbury, NY 11590
Phone: (516) 334-1300
Fax: (516) 338-2477

Page 1 of 1

07/3/01

Sulzer Metco (Singapore) Pte.
06-02 2 Loyang Lane
SG-508913 Singapore

PRODUCT: METCO 314NS Powder

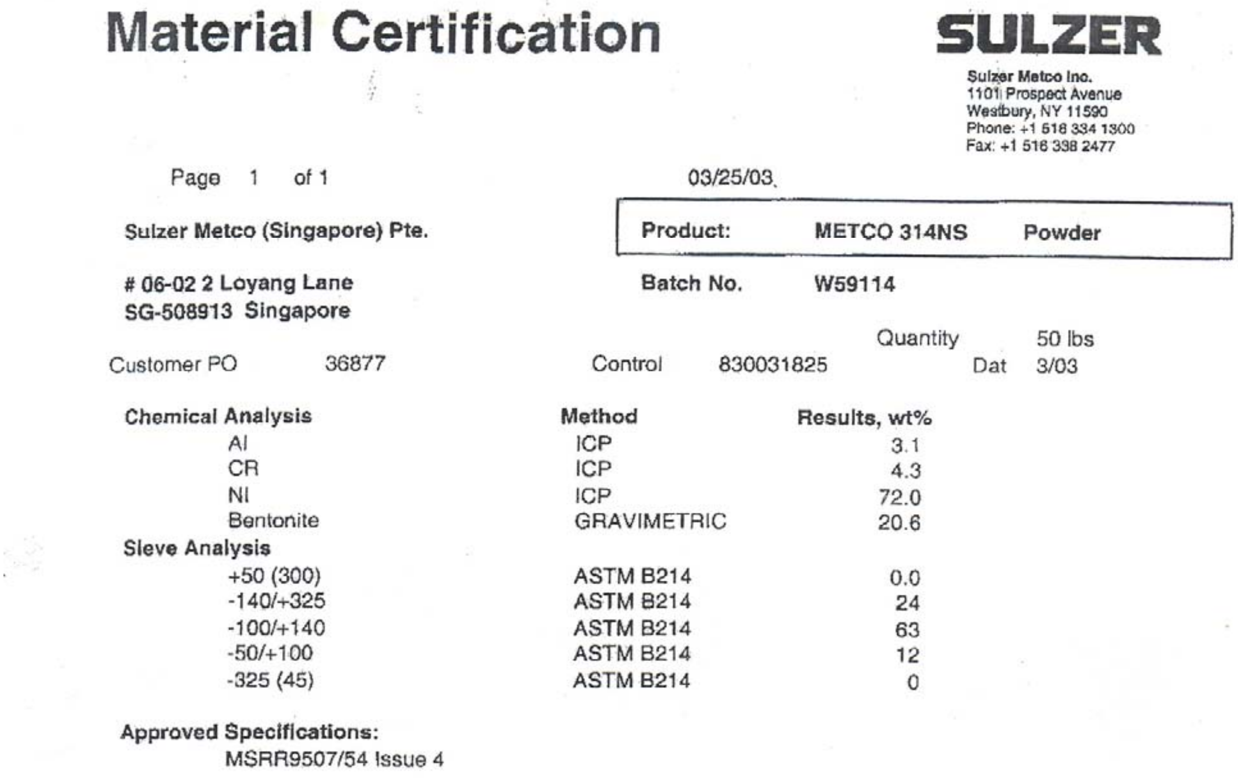
Lot No. W57192

Quantity 375 lbs.

Customer PO P00000073-A Control No. 111796 Ship Date 7/01

Chemical Analysis	Method	Results, wt%
Al	ICP	3.8
CR	ICP	3.6
NI	ICP	70.2
Bentonite	GRAVIMETRIC	22.4
Sieve Analysis		
+50 (300)	ASTM B214	0.0
-140/+325	ASTM B214	22
-100/+140	ASTM B214	64
-50/+100	ASTM B214	14
-325 (45)	ASTM B214	1

Approved Specifications:
MSRR9507/54 Issue 4



Material Certification

SULZER

Sulzer Metco Inc.
1101 Prospect Avenue
Westbury, NY 11590
Phone: +1 516 334 1300
Fax: +1 516 338 2477

Page 1 of 1

03/25/03

Sulzer Metco (Singapore) Pte.

06-02 2 Loyang Lane
SG-508913 Singapore

Product: METCO 314NS Powder

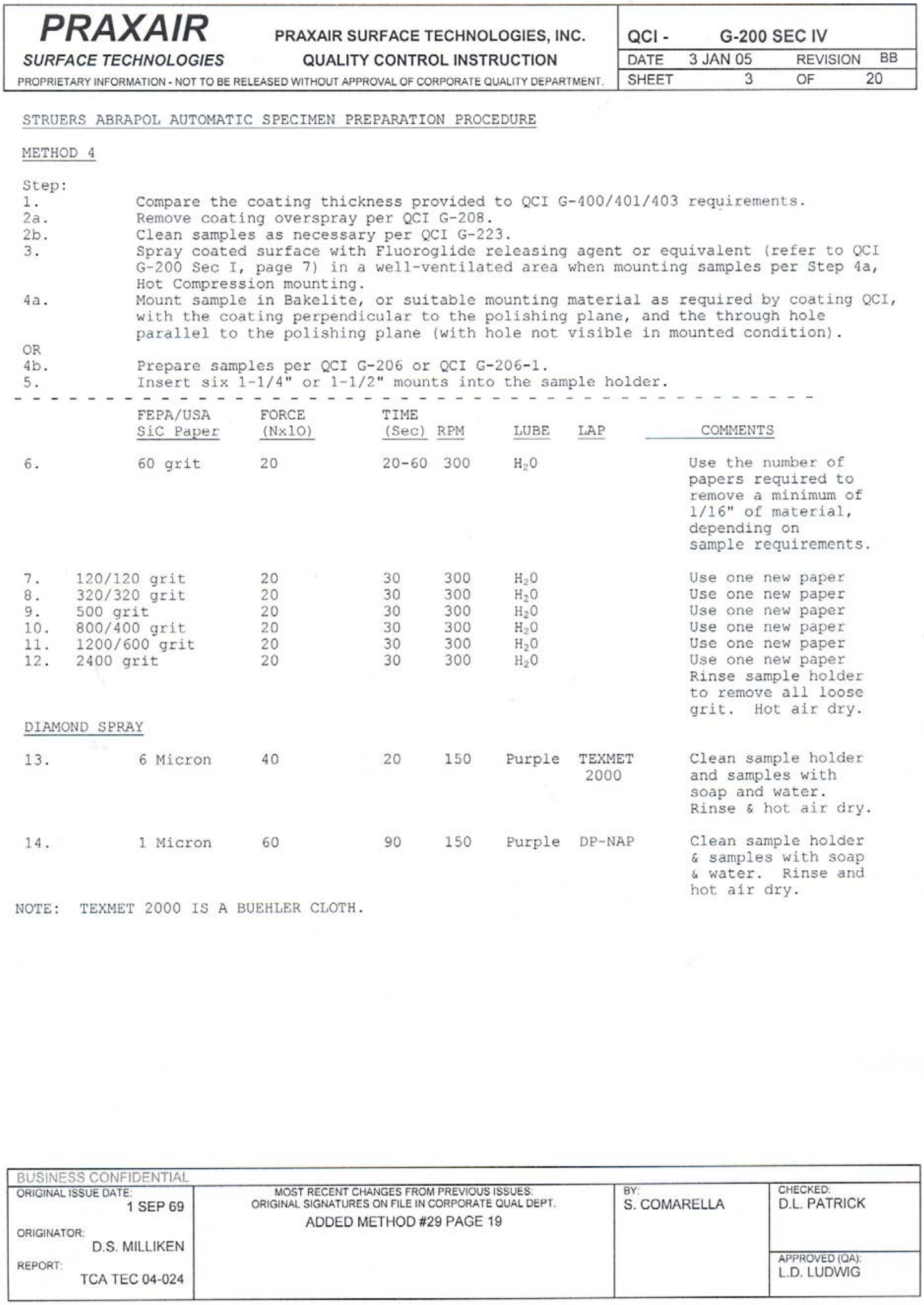
Batch No. W59114

Quantity 50 lbs

Customer PO 36877 Control 830031825 Dat 3/03

Chemical Analysis	Method	Results, wt%
Al	ICP	3.1
CR	ICP	4.3
NI	ICP	72.0
Bentonite	GRAVIMETRIC	20.6
Sieve Analysis		
+50 (300)	ASTM B214	0.0
-140/+325	ASTM B214	24
-100/+140	ASTM B214	63
-50/+100	ASTM B214	12
-325 (45)	ASTM B214	0

Approved Specifications:
MSRR9507/54 Issue 4



PRAXAIR SURFACE TECHNOLOGIES	PRAXAIR SURFACE TECHNOLOGIES, INC. QUALITY CONTROL INSTRUCTION	QCI - G-200 SEC IV
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STRUERS ABRAPOL AUTOMATIC SPECIMEN PREPARATION PROCEDURE

METHOD 4

Step:

1. Compare the coating thickness provided to QCI G-400/401/403 requirements.
2a. Remove coating overspray per QCI G-208.
2b. Clean samples as necessary per QCI G-223.
3. Spray coated surface with Fluoroglide releasing agent or equivalent (refer to QCI G-200 Sec I, page 7) in a well-ventilated area when mounting samples per Step 4a, Hot Compression mounting.
4a. Mount sample in Bakelite, or suitable mounting material as required by coating QCI, with the coating perpendicular to the polishing plane, and the through hole parallel to the polishing plane (with hole not visible in mounted condition).

OR

4b. Prepare samples per QCI G-206 or QCI G-206-1.
5. Insert six 1-1/4" or 1-1/2" mounts into the sample holder.

	FEPA/USA SiC Paper	FORCE (Nx10)	TIME (Sec)	RPM	LUBE	LAP	COMMENTS
6.	60 grit	20	20-60	300	H_2O		Use the number of papers required to remove a minimum of 1/16" of material, depending on sample requirements.
7.	120/120 grit	20	30	300	H_2O		Use one new paper
8.	320/320 grit	20	30	300	H_2O		Use one new paper
9.	500 grit	20	30	300	H_2O		Use one new paper
10.	800/400 grit	20	30	300	H_2O		Use one new paper
11.	1200/600 grit	20	30	300	H_2O		Use one new paper
12.	2400 grit	20	30	300	H_2O		Use one new paper Rinse sample holder to remove all loose grit. Hot air dry.
DIAMOND SPRAY							
13.	6 Micron	40	20	150	Purple	TEXMET 2000	Clean sample holder and samples with soap and water. Rinse & hot air dry.
14.	1 Micron	60	90	150	Purple	DP-NAP	Clean sample holder & samples with soap & water. Rinse and hot air dry.

NOTE: TEXMET 2000 IS A BUEHLER CLOTH.

BUSINESS CONFIDENTIAL

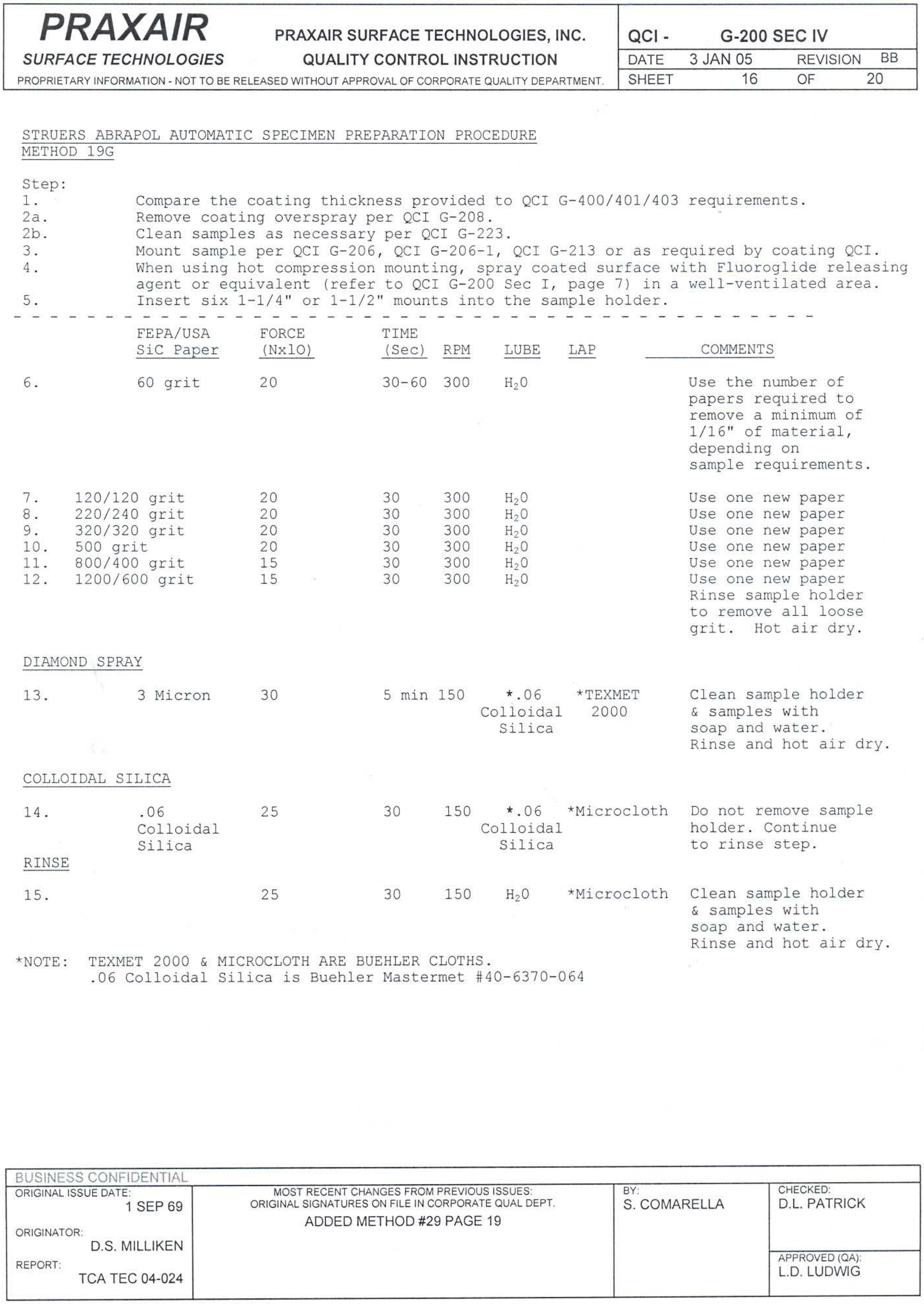
ORIGINAL ISSUE DATE: 1 SEP 69 ORIGINATOR: D.S. MILLIKEN REPORT: TCA TEC 04-024	MOST RECENT CHANGES FROM PREVIOUS ISSUES: ORIGINAL SIGNATURES ON FILE IN CORPORATE QUAL DEPT. ADDED METHOD #29 PAGE 19	BY: S. COMARELLA	CHECKED: D.L. PATRICK APPROVED (QA): L.D. LUDWIG

STRUERS ABRAPOL AUTOMATIC SPECIMEN PREPARATION PROCEDURE

METHOD 10

Step:
1. Compare the coating thickness provided to QCI G-400/401/403 requirements.
2a. Remove coating overspray per QCI G-208.
2b. Clean samples as necessary per QCI G-223.
3a. Spray coated surface with Fluoroglide releasing agent or equivalent (refer to QCI G-200 Sec I, page 7) in a well-ventilated area.
3b. Wrap sample in aluminum foil per QCI G-205 if required by coating QCI when using Hot Compression mounting technique. *NOTE: DO NOT WRAP SPECIMEN IN ALUMINUM FOIL (PER QCI G-205) WHEN MOUNTING IN EPOXY COLD MOUNT.*
4. Mount sample in Bakelite, or suitable mounting material as required by application, with the coating perpendicular to the polishing plane, and the through hole parallel to the polishing plane (with hole not visible in mounted condition).
5. Insert six 1-1/4" or 1-1/2" mounts into the sample holder.

	FEPA/USA SiC Paper	FORCE (Nx10)	TIME (Sec)	RPM	LUBE	LAP	COMMENTS
6.	60 grit	20	20-60	300	H_2O		Use the number of papers required to remove a minimum of 1/16" of material, depending on sample requirements.
7.	120/120 grit	30	30	300	H_2O		Use one new paper
8.	220/240 grit	30	30	300	H_2O		Use one new paper
9.	320/320 grit	30	30	300	H_2O		Use one new paper
10.	500 grit	30	30	300	H_2O		Use one new paper
11.	800/400 grit	30	30	300	H_2O		Use one new paper
12.	1200/600 grit	30	60	300	H_2O		Use one new paper
13.	2400 grit	30	30	300	H_2O		Use one new paper Rinse sample holder to remove all loose grit. Hot air dry.
DIAMOND SPRAY							
14.	1 Micron	20	40	150	Purple	DP-NAP	Clean sample holder and samples with soap and water. Rinse and hot air dry.



PRAXAIR *SURFACE TECHNOLOGIES*	PRAXAIR SURFACE TECHNOLOGIES, INC. QUALITY CONTROL INSTRUCTION	QCI - G-200 SEC IV
		DATE 3 JAN 05 REVISION BB
PROPRIETARY INFORMATION - NOT TO BE RELEASED WITHOUT APPROVAL OF CORPORATE QUALITY DEPARTMENT.		SHEET 16 OF 20

STRUERS ABRAPOL AUTOMATIC SPECIMEN PREPARATION PROCEDURE
METHOD 19G

Step:
1. Compare the coating thickness provided to QCI G-400/401/403 requirements.
2a. Remove coating overspray per QCI G-208.
2b. Clean samples as necessary per QCI G-223.
3. Mount sample per QCI G-206, QCI G-206-1, QCI G-213 or as required by coating QCI.
4. When using hot compression mounting, spray coated surface with Fluoroglide releasing agent or equivalent (refer to QCI G-200 Sec I, page 7) in a well-ventilated area.
5. Insert six 1-1/4" or 1-1/2" mounts into the sample holder.

	FEPA/USA SiC Paper	FORCE (Nx10)	TIME (Sec)	RPM	LUBE	LAP	COMMENTS
6.	60 grit	20	30-60	300	H_2O		Use the number of papers required to remove a minimum of 1/16" of material, depending on sample requirements.
7.	120/120 grit	20	30	300	H_2O		Use one new paper
8.	220/240 grit	20	30	300	H_2O		Use one new paper
9.	320/320 grit	20	30	300	H_2O		Use one new paper
10.	500 grit	20	30	300	H_2O		Use one new paper
11.	800/400 grit	15	30	300	H_2O		Use one new paper
12.	1200/600 grit	15	30	300	H_2O		Use one new paper Rinse sample holder to remove all loose grit. Hot air dry.
DIAMOND SPRAY							
13.	3 Micron	30	5 min	150	*.06 Colloidal Silica	*TEXMET 2000	Clean sample holder & samples with soap and water. Rinse and hot air dry.
COLLOIDAL SILICA							
14.	.06 Colloidal Silica	25	30	150	*.06 Colloidal Silica	*Microcloth	Do not remove sample holder. Continue to rinse step.
RINSE							
15.		25	30	150	H_2O	*Microcloth	Clean sample holder & samples with soap and water. Rinse and hot air dry.

*NOTE: TEXMET 2000 & MICROCLOTH ARE BUEHLER CLOTHS.
.06 Colloidal Silica is Buehler Mastermet #40-6370-064

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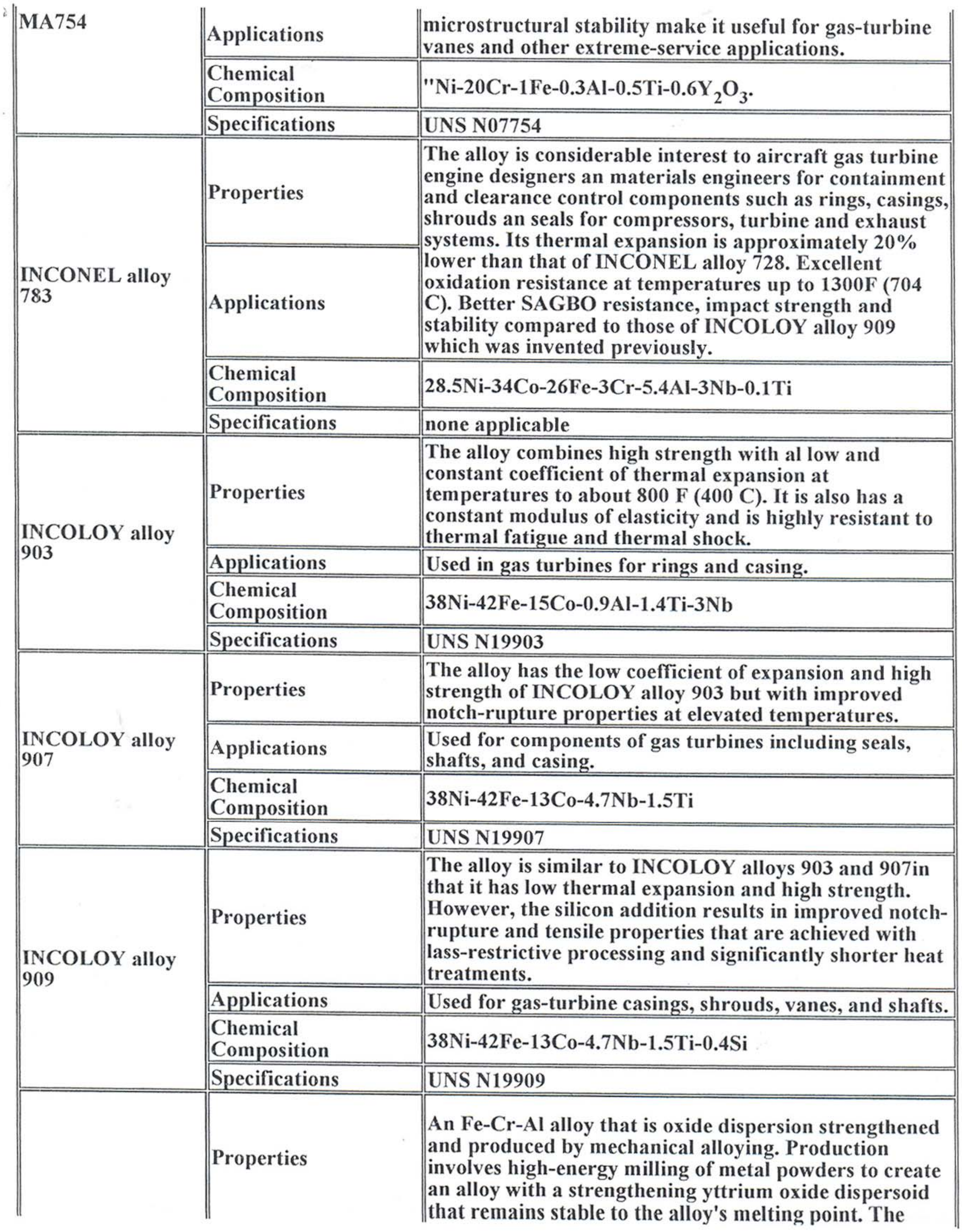

MA754	Applications	microstructural stability make it useful for gas-turbine vanes and other extreme-service applications.
	Chemical Composition	"Ni-20Cr-1Fe-0.3Al-0.5Ti-0.6Y_2O_3.
	Specifications	UNS N07754
INCONEL alloy 783	Properties	The alloy is considerable interest to aircraft gas turbine engine designers an materials engineers for containment and clearance control components such as rings, casings, shrouds an seals for compressors, turbine and exhaust systems. Its thermal expansion is approximately 20% lower than that of INCONEL alloy 728. Excellent oxidation resistance at temperatures up to 1300F (704 C). Better SAGBO resistance, impact strength and stability compared to those of INCOLOY alloy 909 which was invented previously.
	Applications	
	Chemical Composition	28.5Ni-34Co-26Fe-3Cr-5.4Al-3Nb-0.1Ti
	Specifications	none applicable
INCOLOY alloy 903	Properties	The alloy combines high strength with al low and constant coefficient of thermal expansion at temperatures to about 800 F (400 C). It is also has a constant modulus of elasticity and is highly resistant to thermal fatigue and thermal shock.
	Applications	Used in gas turbines for rings and casing.
	Chemical Composition	38Ni-42Fe-15Co-0.9Al-1.4Ti-3Nb
	Specifications	UNS N19903
INCOLOY alloy 907	Properties	The alloy has the low coefficient of expansion and high strength of INCOLOY alloy 903 but with improved notch-rupture properties at elevated temperatures.
	Applications	Used for components of gas turbines including seals, shafts, and casing.
	Chemical Composition	38Ni-42Fe-13Co-4.7Nb-1.5Ti
	Specifications	UNS N19907
INCOLOY alloy 909	Properties	The alloy is similar to INCOLOY alloys 903 and 907in that it has low thermal expansion and high strength. However, the silicon addition results in improved notch-rupture and tensile properties that are achieved with lass-restrictive processing and significantly shorter heat treatments.
	Applications	Used for gas-turbine casings, shrouds, vanes, and shafts.
	Chemical Composition	38Ni-42Fe-13Co-4.7Nb-1.5Ti-0.4Si
	Specifications	UNS N19909
	Properties	An Fe-Cr-Al alloy that is oxide dispersion strengthened and produced by mechanical alloying. Production involves high-energy milling of metal powders to create an alloy with a strengthening yttrium oxide dispersoid that remains stable to the alloy's melting point. The

Addendum to PST Technical Note TN 05-14

21 Sept. 2005

The following comments are a brief summary of PST findings and conclusions from TN 05-14 after a telephone conference on 20 Sept. 2005 with PST, RR and SAESL personnel. Both RR and PST reviewed their own report findings and these were discussed at length. PST findings are outlined below. At the conclusion of the teleconference, both RR and PST maintained their original conclusions.

PST pointed out, as shown in TN 05-14, that the AST quality control panels for coating LCA- 314 met the RR specification of 40 % metal (by comparison to the standard photo, or by detailed evaluation of specific samples using SEM images and linear intercept metal phase counting), and that they also met the RR specification of 45 to 55 R15Y superficial hardness. In one case when PST was given the opportunity to evaluate a coated ring (stage 6 #51363), it was found to have met the same hardness and % metal content as its companion quality panel coating, done just subsequent to the ring under the same exact coating conditions. This shows that the AST quality panels do in fact represent the coating on the companion rings. All AST quality panels to date have met RR specification for hardness and metal content.

It was shown in TN 05-14 that particle erosion was one mechanism of NiCrAl metal jacket loss in the coating of ring #51067. Fig. 3b shows surface loss of metal layer and its peel-back; Figs 6-7 show cross sections of metal jacket loss on the leading edge of the coating. In addition to metal layer particle erosion, PST showed the #51067 ring coating was highly oxidized in service, weakening the bond between particles by an interposed oxide film (Fig 18c). Thus, whole LCA-314 coating particles could be liberated by severe particle erosion. Only one in four particles of the NiCrAl-Bentonite coating lost by erosion / cavitation from within the coating could give the observed 29 % metal analysis in the engine-run #51067 (compared to its 40% metal in its companion Quality panel). PST was further able to show that the SIA run #51363 stage 6 ring had surface deposits on top of the LCA-314 coating which also penetrated into the coating porosity (Figs. 14, 19b and 21a). This deposit is consistent with

“CMAS”, calcia-magnesia-alumina-silica, a known airborne contaminate in some regions.

Despite the evidence for erosion in service, the specification for the acceptable quality of the coating contains no evaluation for erosion. PST advanced the concept that the current RR specification for the LCA-314 coatings, is not adequate to insure the desired erosion resistance that the coating may experience in some service exposures. The LCA-314 coating on Trent compressor ring #51363 met the RR specification for that coating but still experienced erosion in service. It may be that two coatings, both meeting the specified hardness and metal content could have different erosion resistance. This could be due to the degree of microscopic adhesion between the metallic jackets on adjacent particles. Hardness and metallic content would not reveal this degree of adhesion. PST suggested a particle erosion test or a tensile bond test be considered. The bond test would give the average adhesive strength between particles within the coating, which would need to meet some minimum value as determined by RR. This three-way analysis of the quality panels would thus verify acceptable hardness and metal content (suggesting the abradability standard had been achieved) and the particle adhesion strength of the coating (which would address erosion resistance).

It remains the PST position that the all AST LCA-314 coatings to date have fully met the present RR specification for Metco 314. It is always our purpose to provide quality coatings that meet or exceed the rigors of the intended service. However, now we have evidence of the engine experience of particle erosion that may occur, and suggest additional quality tests to improve this important coating.

LCA-314 Coatings on Trent 800 Compressor Rings

What RR and PST Agree on

- **Engine-run #51067 stage 6 has 27-29% NiCrAl after exposure.**
- **QC panel for #51067 has % metal and hardness per RR spec.**

- **Engine-run #51363 stage 6 ring has 43% metal and hardness within RR spec.**
- **QC panel for #51363 has % metal and hardness per RR spec.**

- **Engine-run #51067 stage 6 ring itself (IN 907) is highly oxidized on free surfaces and under M-450 bondcoat. Oxide penetrates IN 907 grain boundaries, with cracks penetrating oxide layer.**
- **Oxidation of #51067 cases & coatings occurred in service.**

Observations by PST

- **53 Trent 800 compressor rings coated by AST with LCA-314. Five of these reported coating loss by erosion, all from Singapore Airlines. No other operators have reported problems [but 90% of rings were for SIA].**
- **Trent stage 6 ring from #51363 removed for erosion loss, had heavy surface deposit of CMAS on LCA-314.**
- **Trent stage 6 ring from #51373, not coated by AST, removed for heavy rub loss, Singapore Airlines.**

What RR and PST Do Not Agree on

- **Origin of loss of particles observed in engine-run #51067 stage 6 LCA-314 coating :**
  - **RR believes inadequate particle adhesion, due to AST spray process.**
  - **PST believes loss is due to service conditions encountered – oxidation-weakened particle-to-particle bond and high velocity air erosion (cavitation) and particle erosion (by CMAS). This is based upon findings that QC for #51067 is correct, and that both QC and actual ring coating for #51363 are correct.**

APPENDIX C: TECHNICAL ANALYSIS REPORT

ATSB TECHNICAL ANALYSIS REPORT
BE200400022

Review and commentary on analyses of high-pressure compressor casing lining damage

Rolls-Royce Trent 800, ESN 51067

NR Blyth
Senior Transport Safety Investigator – Technical Analysis
B.App.Sc(Metallurgy), MIEAust

Released in accordance with section 25 of the *Transport Safety Investigation Act 2003*

INTRODUCTION

On 25 August 2004, the left engine of a Boeing Co. 777-312 aircraft, registered 9V-SYB, sustained a series of surges/compressor stalls during the take-off run from Melbourne aerodrome. Witnesses reported hearing several loud bangs and observing the engine emitting orange flames. Following the takeoff, the flight crew shut the engine down and returned the aircraft to the aerodrome, where a one-engine-inoperative landing was made.

Following removal from the aircraft, the failed engine (a Rolls-Royce Trent 800, serial number 51067) was freighted to Singapore Aero-Engine Services Limited (SAESL), where it was progressively disassembled and examined, under observation by the ATSB investigator in charge. On the basis of the examination and an analysis of the FDR/QAR[1] data, Rolls Royce concluded that the surge events were directly attributable to an aerodynamic stall condition developing within the engine high-pressure compressor assembly. Directly contributing to that condition was a reduction in stall margin associated with the erosion and loss of rotor casing lining material at the rear stages of the high-pressure compressor.

The Trent 800 compressor casing linings (stages 2-6) were last refurbished in October 2003 by Asian Surface Technologies (AST), using a high-temperature metal spraying process to apply an abradable coating of 'Metco 314' – a composite material comprising bentonite (clay) particles encapsulated in nickel-chromium-aluminium alloy jackets. At the time of the surge event, the engine had been operating for 2,256h/614cyc TSO/CSO[2] respectively.

The Technical Analysis section of the ATSB undertook a review of the available information relating to the loss of lining material within the compressor casing including consideration of and comment on the findings of analyses conducted by Rolls Royce and Praxair Surface Technologies (PST, a joint venture partner in AST).

[1] Rolls-Royce Service Component Investigation Report, No. SCIR 64628, Issue 3

[2] Praxair Surface Technologies Inc, Technical Note 05-14, including addendum dated 21 September 2005.

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[1] FDR/QAR: Flight Data Recorder/Quick Access Recorder

[2] TSO/CSO: Time Since Overhaul/Cycles Since Overhaul

REVIEW AND COMMENTARY

Characteristics of metal-sprayed coatings

Thermally sprayed coatings such as the Metco 314 applied to stages 2 – 6 of ESN 51067 have physical properties that are derived from the nature of the feed material/s and the conditions under which the coatings are applied. The physical integrity of a sprayed coating depends to a significant extent on the density and fusion/bonding of the individual particles that make up the coating mass. Resistance to erosive material loss such as sustained within the compressor rotor path linings from ESN 51067 is derived from the effectiveness of inter-particle fusion and the total fused particle area. Both those features are directly influenced by the spraying process parameters. Quantitative metallographic assessment and hardness testing provides a comparative measurement of coating quality after application and allows the establishment of control limits for factors that affect particle density, fusion and distribution.

Examination findings – Rolls Royce and PST

An investigative metallurgical assessment of the compressor abradable lining condition was carried out by Rolls Royce and involved visual examination, profile measurement and metallographic study, supplemented by scanning electron microscopy. Included in the examination was the study of several quality control samples prepared at the same time as the application of the original lining to the compressor casings.

Following completion of the manufacturer’s examination, Praxair Surface Technologies (PST) requested and was supplied by the manufacturer with a section of the stage-6 compressor casing from ESN 51067 on which to base their investigation. PST also examined quality control sample number 466, which was the sample prepared at the time the abradable lining was applied to the stage-6 casing of ESN 51067.

Both PST and Rolls Royce independently determined that the stage-6 compressor casing lining had a total metal content of approximately 27-29% by volume. The manufacturer’s guidelines for sprayed coatings specified a target level of 40% metal by volume. Both organisations also confirmed that the quality control sample (#466) for the ESN 51067 stage-6 casing had a metal content around 40% and a hardness of 49 – 51 R15Y, which was within the manufacturer’s guidelines. The coating remaining on the casings from ESN 51067 was insufficient for hardness measurement.

On the basis of their examination of the quality control sample (#466), PST held that the coating applied to the stage-6 compressor ring installed in ESN 51067 was compliant with the metal volume and hardness guidelines at the time it was released into service. The low metal-volume content of the coating as-measured was attributed by PST to severe oxidation of the coating, leading to the weakening of the cohesive bond between particles and the extraction and loss of particles from deep within the coating during engine operation. PST also theorised that the deposition of a suspected CMAS[3] material on the surfaces of the coating may have had a detrimental effect on the cohesive strength of the coating, leading to the premature breakdown.

Rolls Royce, in its analysis, made the link between the premature loss of the compressor casing coatings and the observed low metallic content/high porosity of the applied coating material. With a lower proportion of metal available for fusion, the bulk cohesive strength of the coating would be reduced, thus rendering it more susceptible to erosion. The manufacturer also cited the presence of a high number of incompletely melted/fused particles as a further influence in the increased 'friability' of the coating.

ATSB review and commentary on examination findings

An assessment of the established factual material associated with the damage sustained by ESN 51067 was conducted and a logic tree (figure 1) was prepared to highlight the possible factors contributing to the coating damage and hence the engine surge events. From that assessment, four possible contributors were identified.

1. Coating application process deficiency

Suboptimal spraying process parameters can result in coatings failing to meet quality control guidelines in respect of density (metal volume) and inter-particle fusion, with a consequent susceptibility to accelerated in-service erosion and failure. While PST held that the low coating density was a result of the degradation of an otherwise satisfactory coating during engine operation and cited the satisfactory condition of the quality control sample as evidence, the manufacturer's reports of a high number of incompletely melted particles would suggest that the as-applied coating was inadequate.

2. Ingestion of CMAS materials

PST's detection of a CMAS type deposit over the surfaces of a degraded compressor casing ring (ESN 51363) prompted the claim that the deposit may have affected the cohesive strength of the coating and thus led to premature erosion. PST acknowledged that it was not known whether the presence of CMAS materials on the surfaces of Metco 314 and related coatings could have a detrimental effect. CMAS materials are known to be problematic to some high-temperature coatings found within engine turbine sections, where the materials are deposited when molten and promote coating spalling upon cooling. The temperatures associated with compressor operation are well below the melting temperatures of CMAS materials.

3. Abnormally elevated compressor temperatures

Elevated inter-particle, bond coat and substrate oxidation levels were cited by PST as a possible factor promoting coating degradation and an indication of abnormally

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[3] 'Calcia-Magnesia-Alumina-Silica' – terminology used to describe the family of compounds making up airborne dusts that may be ingested by gas turbine aero engines.

high temperatures within the compressor section of ESN 51067. Oxidised coating microstructures were confirmed by both PST and Rolls Royce, however the implications of the oxidation in terms of its effect on coating cohesive strength was not established. Elevated temperature oxidation tests on samples of the substrate and coating materials by PST reportedly produced much less oxidation that that presented by the engine rings, suggesting that engine temperatures may have been considerably above the nominal 600°C test temperature. Of note however, was that the oxidation tests were carried out in static air at atmospheric pressure and not under the typical high velocity, high-pressure air conditions that exist within the operational compressor assembly. Such variations can significantly affect the oxidation rates of exposed materials. Also of significance was the manufacturer's statement that a review of engine operating and performance parameters for the previous 400 flights found no evidence of abnormal operation.

4. Excessive operational thermal cycling

Measured thermal expansion differences between the compressor ring substrate and the Metco 314 coating were proposed by PST as a possible contributor to through-thickness cracking developing from repeated thermal cycling associated with engine flight cycles. PST acknowledged the absence of any physical evidence of this mechanism having played a part in the erosion sustained by the rings from ESN 51067 and considered the theory as speculative. If a thermal-fatigue type mechanism had developed in some form within the coatings, the resultant failure mechanism would most likely be the 'patchy' spallation of coating sections, not the progressive erosion type behaviour as observed.

FINDINGS

Analyses conducted by Rolls Royce and PST have been unable to conclusively establish the reasons behind the premature erosion of the compressor casing abradable coatings from ESN 51067. Both organisations concurred in respect of the low metal content exhibited by the stage-6 ring coating. Both also agreed that the quality control sample, identified by PST as representing the stage-6 ring, did meet the manufacturer's guidelines for metal content. The organisations differed however in their attribution of a mechanism for the degradation of the compressor ring coatings. In summary, Rolls Royce associated the low density and inadequately fused coating condition to deficiencies within the spraying process, whereas PST held that the condition of the coatings was a result of in-service degradation associated with oxidation from abnormally high operational temperatures and the ingress of CMAS type foreign material.

On the balance of the evidence presented by Rolls Royce and PST from their investigations, the ATSB considers that the coating metal density and particle interfusion issues hold as the most probable factors contributing to the premature degradation of the lining and the engine surge event. While acknowledging the possibility that oxidation may have weakened the coating particle cohesive strength, the significance of this effect had not been quantified in respect of the performance of the coating in service. Other proposed contributors such as CMAS ingestion, extended elevated temperature operation and the effects of thermal cycling were not substantiated by evidence.

Figure 1: Logic tree developed for the examination of the ESN 51067 surge event