APPENDIX D: METALLURGICAL EXAMINATION

LN-OJF EC225 Super Puma Accident
Summary of the Metallurgical Examination of the Epicyclic Gearbox Components at QinetiQ

QINETIQ/18/00263/1.0

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26 January 2018

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LN-OJF EC225 Super Puma Accident

Introduction

Examination of Fractured 2nd Stage Planet Gear S/N 10-1292

- Initial Examination
- Fractography of Through Thickness Fracture
- Examination of Outer Race Surface
- X-Ray Tomography
- Microsections Through Subsurface Cracking
- Microsections Through Micro-Pitting
- Fractography of Subsurface Cracks
- Sequential Polishing Through Spalls 1 - 3
- Materials Conformity

Examination of Second Stage Planet Gear Inner Race S/N 10-1292

Examination of Second Stage Planet Gear Carrier

Discussion & Conclusions

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Fractured Second Stage Planet Gear S/N 10-1292
Initial Examination

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Fractured Second Stage Planet Gear
As received

26 teeth present on fragments, an intact 2nd stage planet has 51 teeth.
Fractured samples account for approximately 51% by weight.

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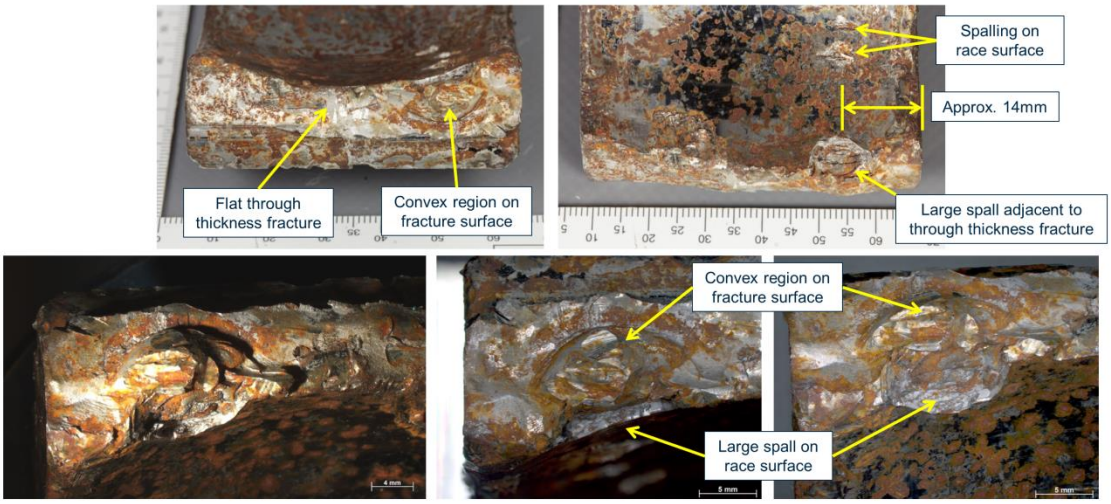
Fractured Second Stage Planet Gear
Sample FE13961 – As Received



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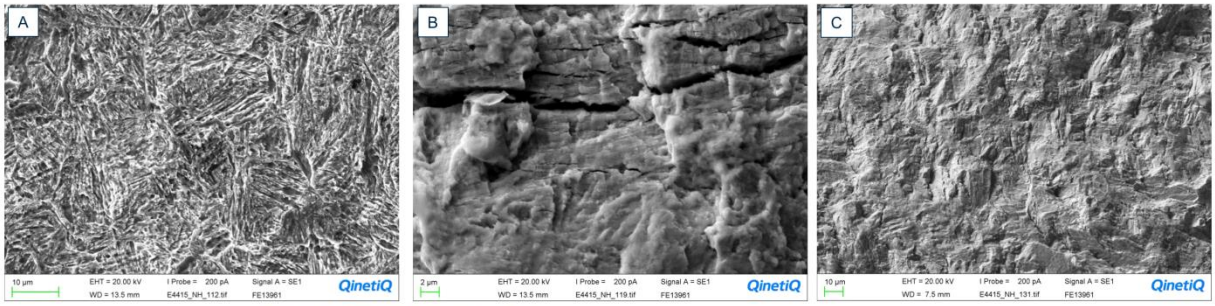
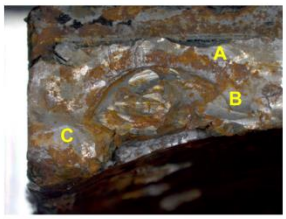
Fractured Second Stage Planet Gear
Sample FE13961 – As Received





SEM examination of the as-received fracture surface shows indications of fatigue (B & C) along with areas of corrosion (A).

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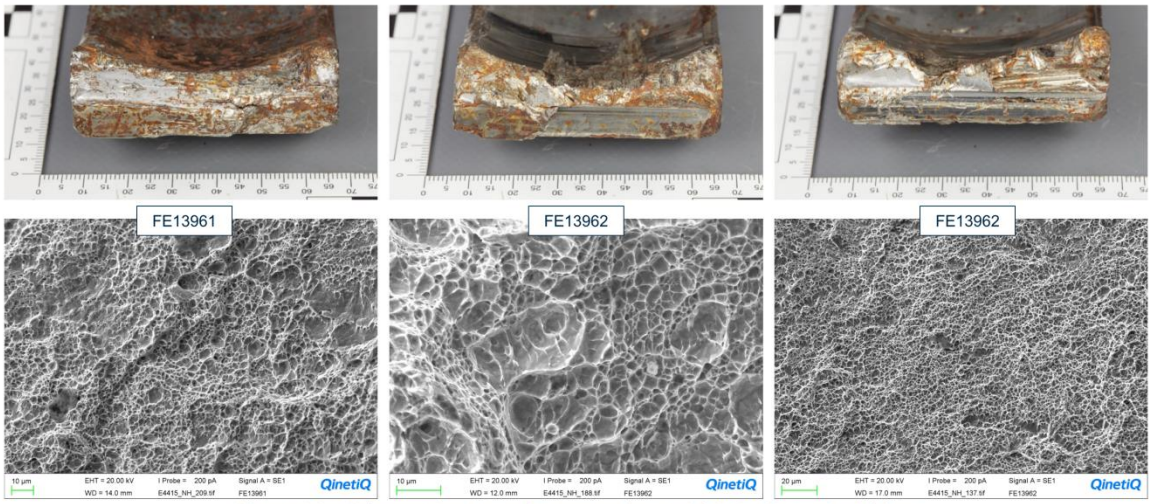
Fractured Second Stage Planet Gear
As received



All remaining 2nd stage planet gear fracture surfaces exhibit ductile overload failure

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Fractured Second Stage Planet Gear S/N 10-1292
Through Thickness Fracture

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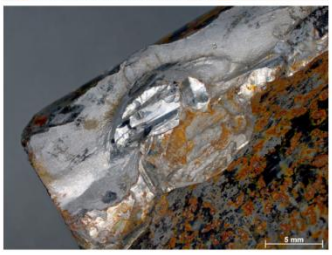
Fractured Second Stage Planet Gear
Sample FE13961 – After Cleaning



Cleaning of fracture surface using a combination of acetate replica stripping and inhibited HCl solution with ultrasonic agitation.
Crack arrest marks visible on fracture surface after cleaning.

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Fractured Second Stage Planet Gear
Sample FE13961 – Summary of Macro Mark Observations

Zone B		
Intensity	QinetiQ	Airbus
Defined	7	8
Less well defined	2	0
Total	9	8

Zone A		
Intensity	QinetiQ	Airbus
Defined	3	3
Less well defined	0	0
Total	3	3

Zone C		
Intensity	QinetiQ	Airbus
Defined	14	27
Less well defined	14	2
Total	28	29

Summary of macro mark observations, solid line – well defined, dashed line – less well defined, see reference [1] for further details.
A number of attempts were made to correlate the macro marks with flight data, including engine stop starts, take-off and landings etc.
No successful correlations were made.

[1] QinetiQ/16/02442/1.0 – QinetiQ / Airbus Helicopters, Macro Mark Counting, 28 June 2016.

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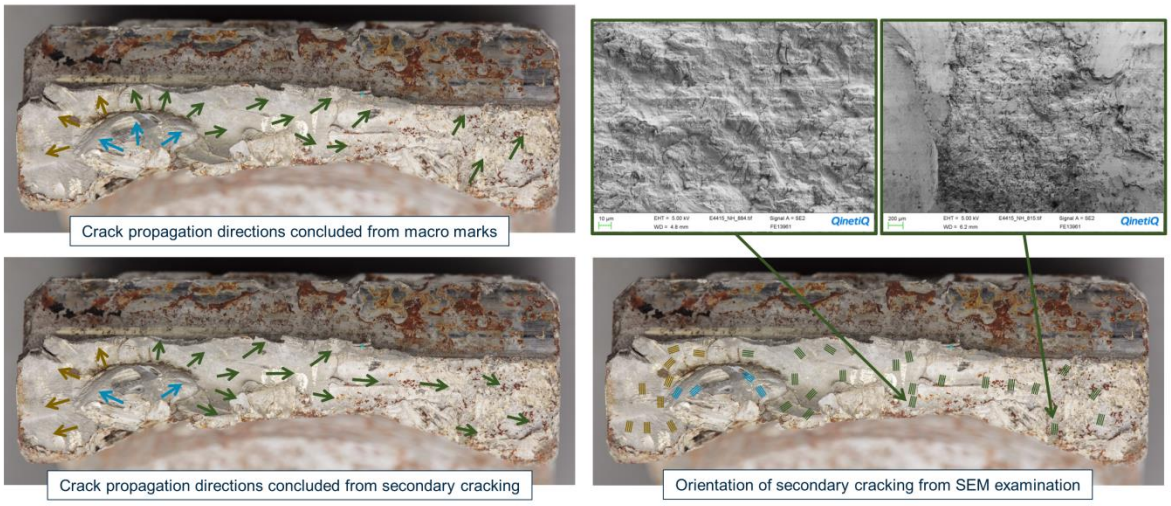
Fractured Second Stage Planet Gear
Sample FE13961 – Through Fracture Crack Propagation Direction



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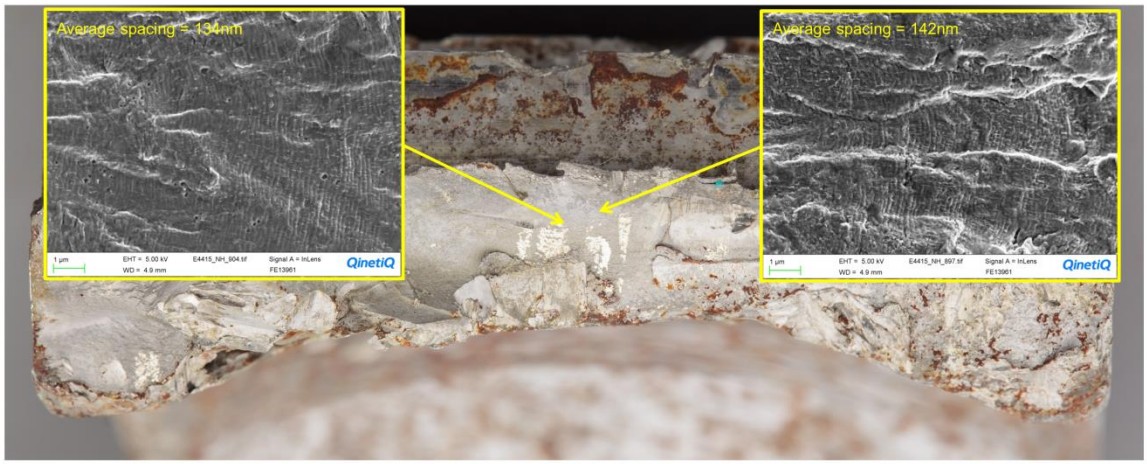
Fractured Second Stage Planet Gear
Sample FE13961 – Fatigue Crack Progression Marks (Striations)



Positive identification of fatigue striations observed on a small region of the through thickness fracture surface, towards the centre of the gear. Insufficient evidence to determine the crack growth rate from striation spacing measurements.

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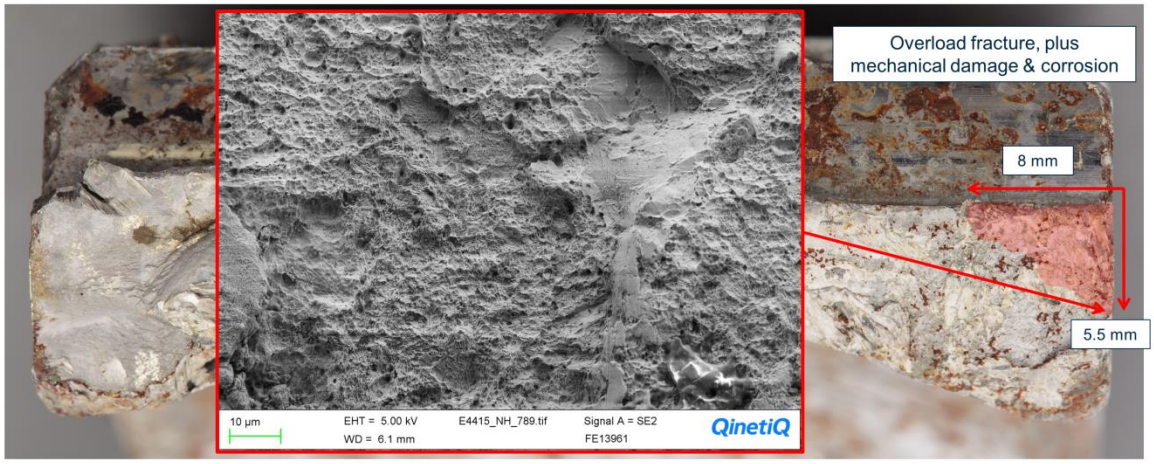
Fractured Second Stage Planet Gear
Sample FE13961 – Final Overload Fracture



Fatigue crack propagation accounts for approximately 95% of the through thickness fracture.

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Fractured Second Stage Planet Gear S/N 10-1292
Examination of Outer Race Surface

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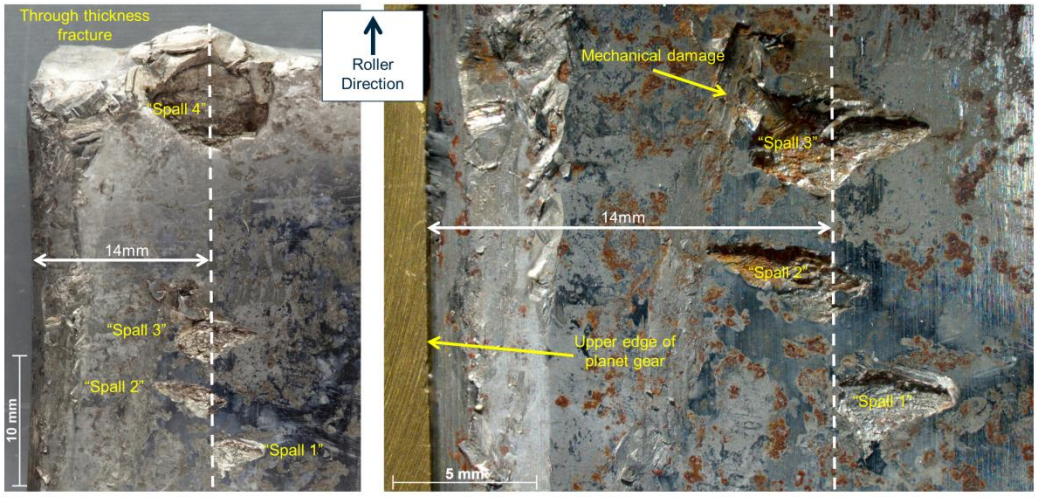
Fractured Second Stage Planet Gear
Sample FE13961 Race Surface – After Cleaning



Note: The line placed at 14mm from the upper edge of the planet gear refers to the approximate location of maximum Hertzian stress for a FAG planet gear, as informed by Airbus Helicopters and previously noted in the AAIB report on the G-REDL accident.

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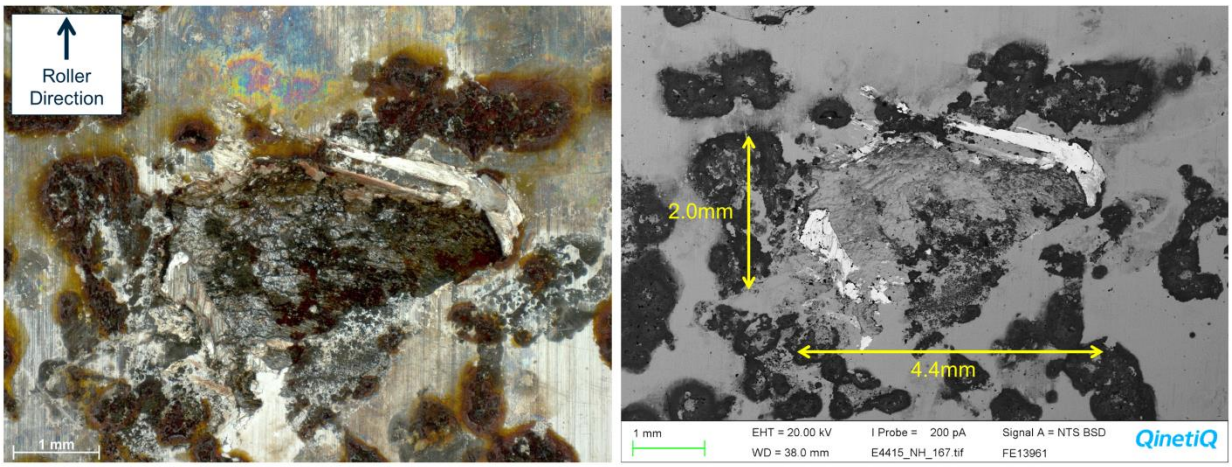
Fractured Second Stage Planet Gear
Sample FE13961 Race Surface – Spall 1 As-Received



Mean depth of spall = 282µm, maximum depth 325µm

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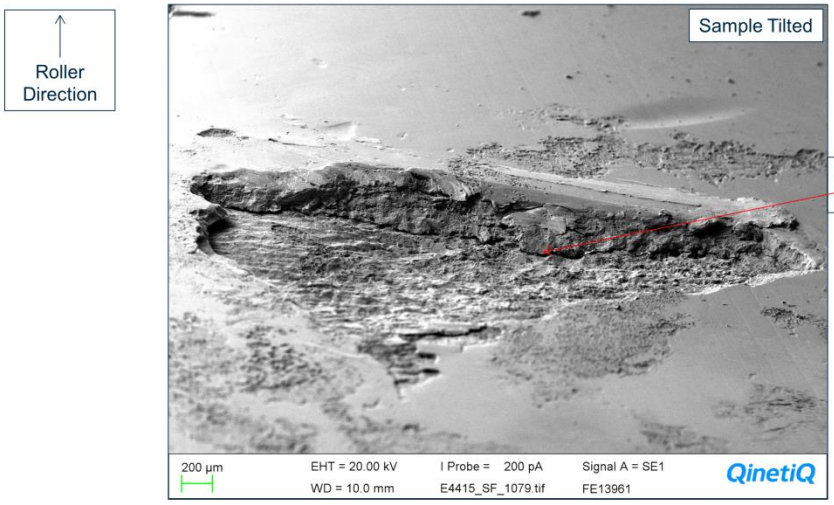
Fractured Second Stage Planet Gear
Sample FE13961 Race Surface – Spall 1 After Cleaning



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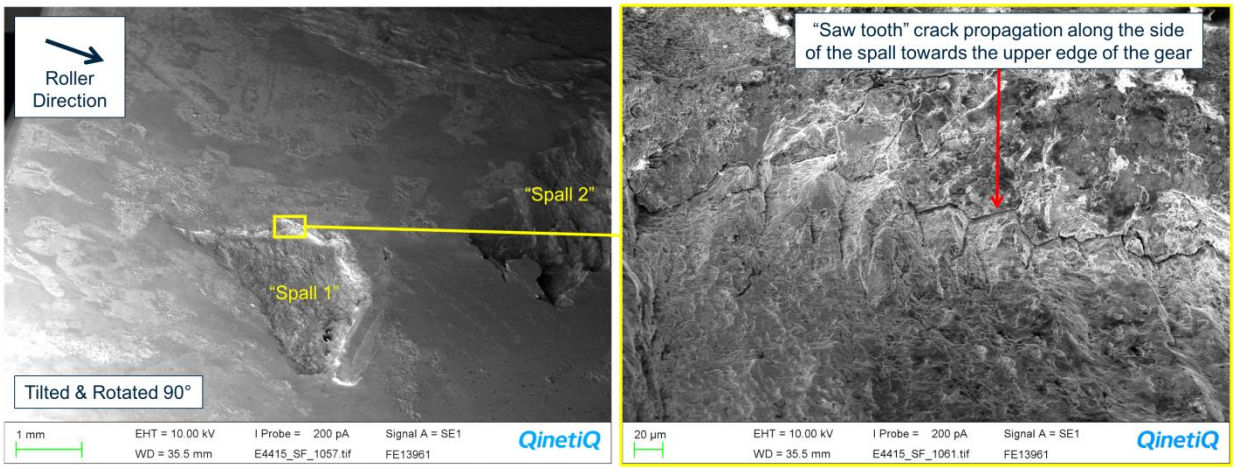
Fractured Second Stage Planet Gear
Sample FE13961 Race Surface – Spall 1 After Cleaning



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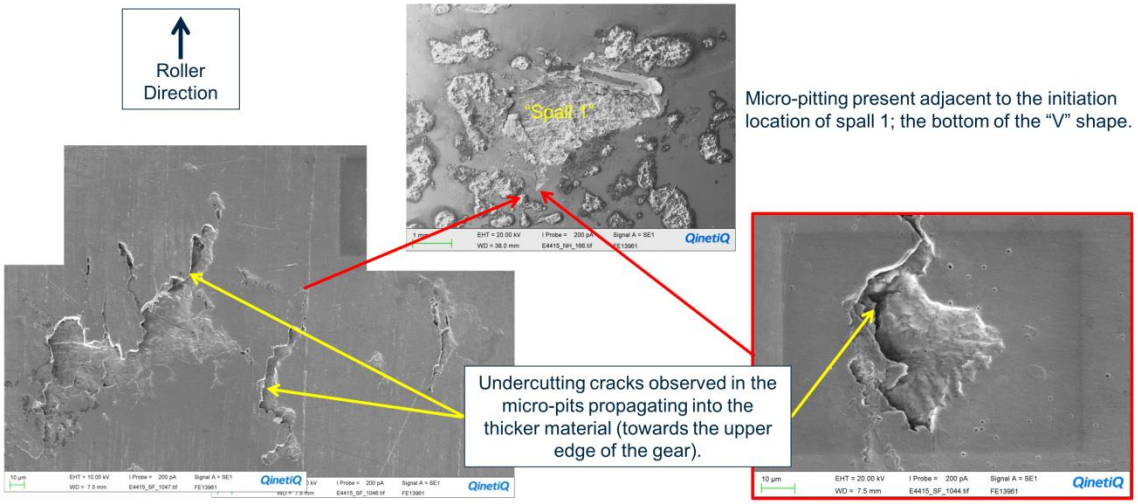
Fractured Second Stage Planet Gear
Sample FE13961 Race Surface – Spall 1 After Cleaning



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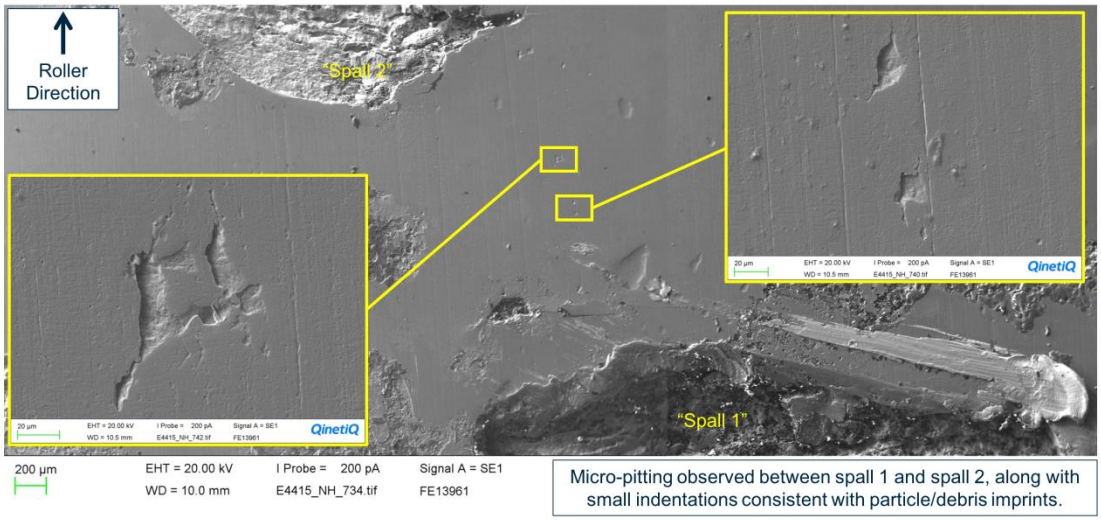
Fractured Second Stage Planet Gear
Sample FE13961 Race Surface – Between Spall 1 and Spall 2



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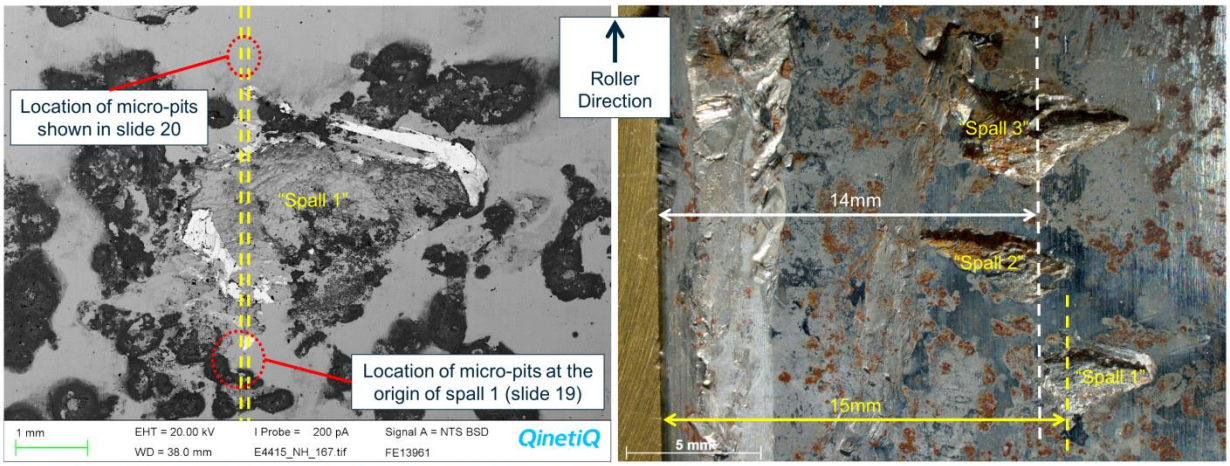
Fractured Second Stage Planet Gear
Sample FE13961 Race Surface – Between Spall 1 and Spall 2



The location of the observed micro-pitting is approximately 15mm from the upper edge of the planet gear – dotted yellow lines.

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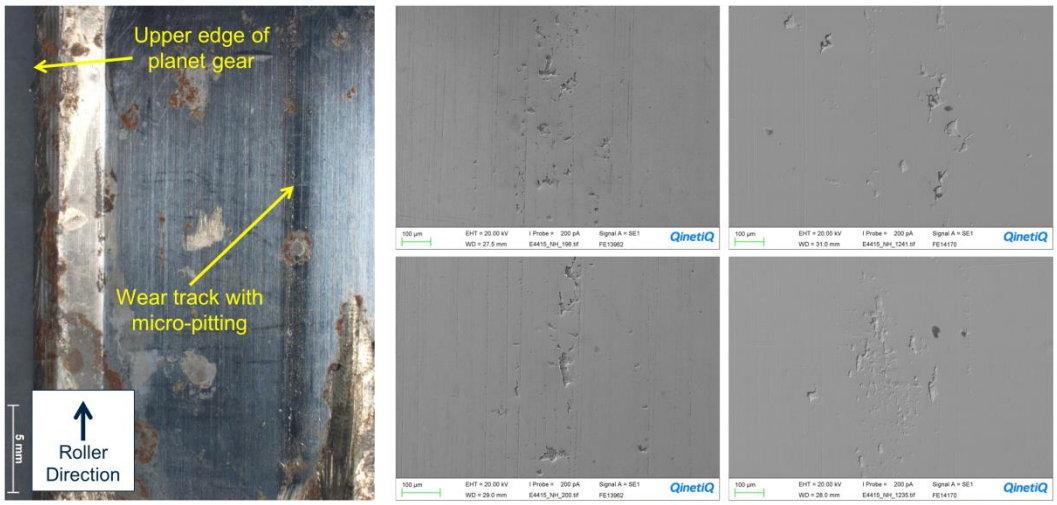
Fractured 2nd Stage Planet Gear
Sample FE13962 Race Surface – Micro-pitting



A wear track containing micro-pitting is also observed on the upper outer-race surface of the second planet gear fragment (sample FE13962).

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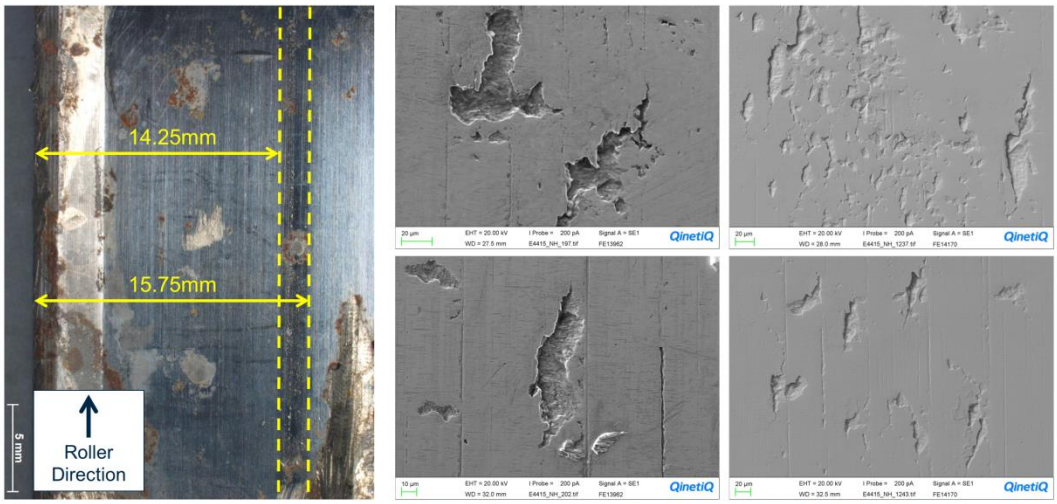
Fractured Second Stage Planet Gear
Sample FE13962 Race Surface – Micro-pitting



These micro-pits are also located approximately 15mm from the upper edge of the gear and again exhibit undercutting cracks.

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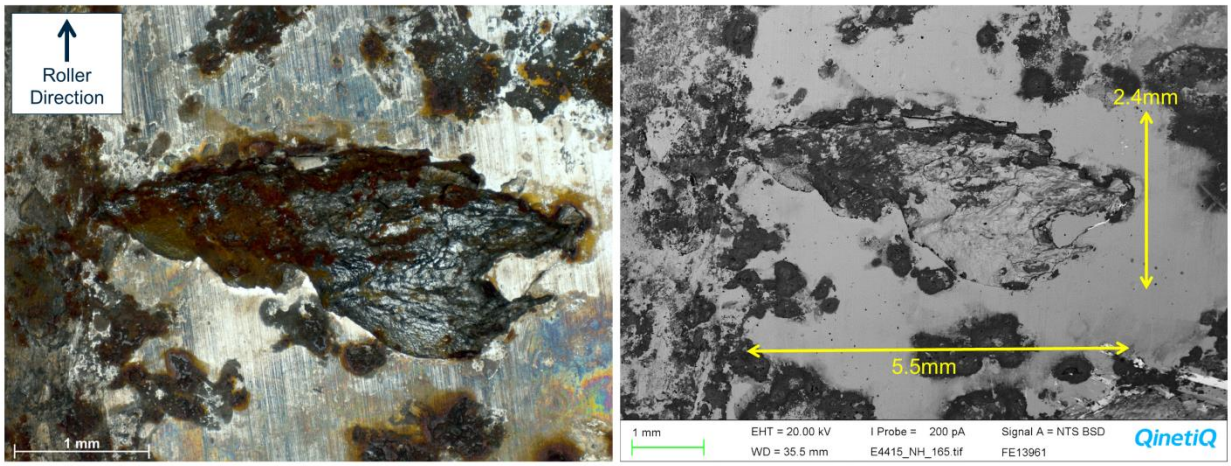
Fractured Second Stage Planet Gear
Sample FE13961 Race Surface – Spall 2 As-Received



Mean depth of spall = 317µm, maximum depth 349µm

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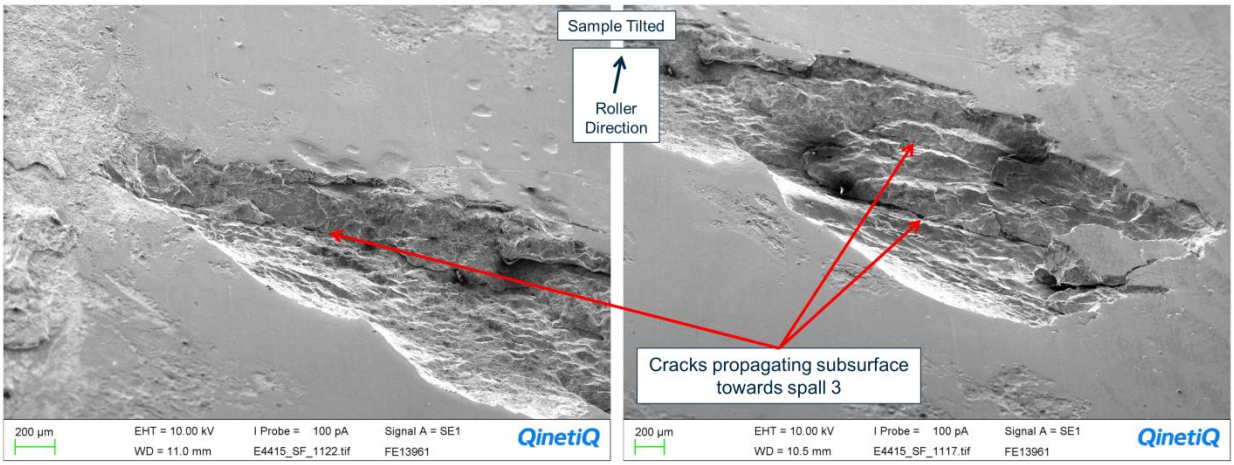
Fractured Second Stage Planet Gear
Sample FE13961 Race Surface – Spall 2 After Cleaning



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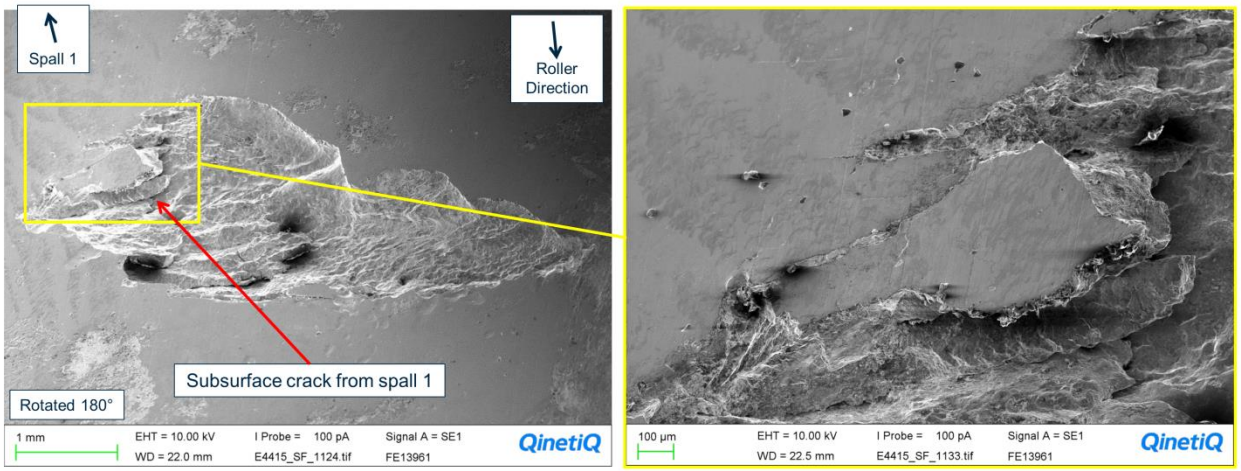
Fractured Second Stage Planet Gear
Sample FE13961 Race Surface – Spall 2 After Cleaning



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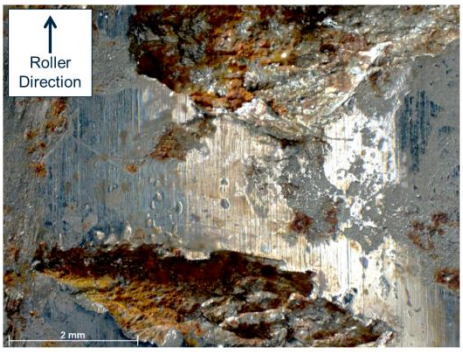
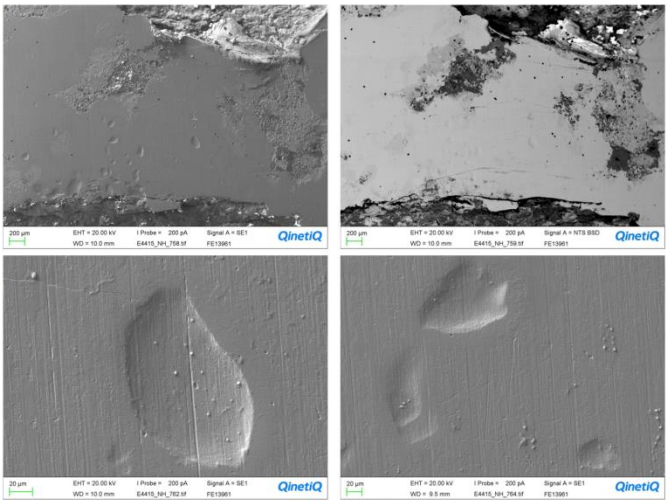
Fractured Second Stage Planet Gear
Sample FE13961 Race Surface – Between Spall 2 and Spall 3





small indentations consistent with particle/debris imprints observed between spall 2 and spall 3.

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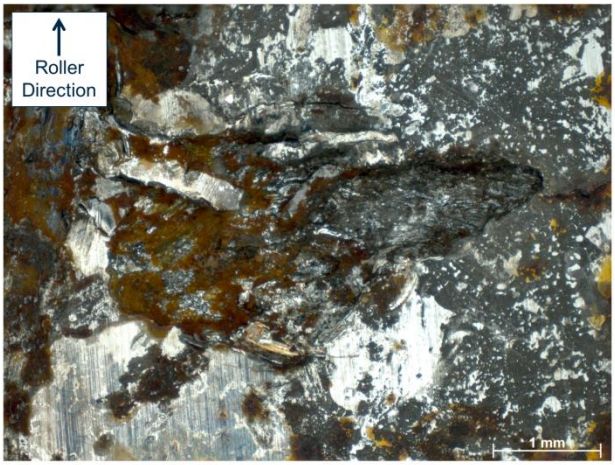
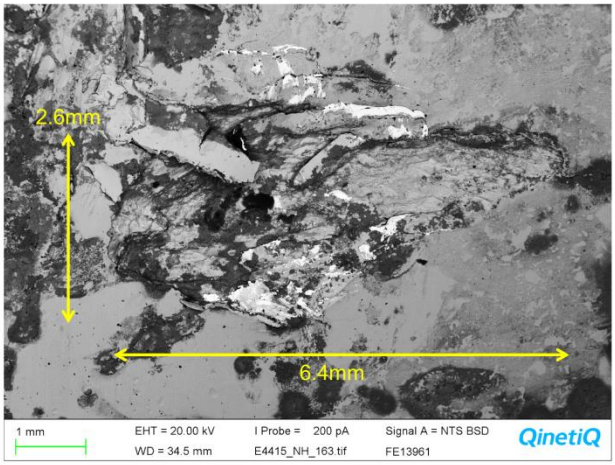
Fractured Second Stage Planet Gear
Sample FE13961 Race Surface – Spall 3 As-Received





Mean depth of spall = 451µm, maximum depth 561µm

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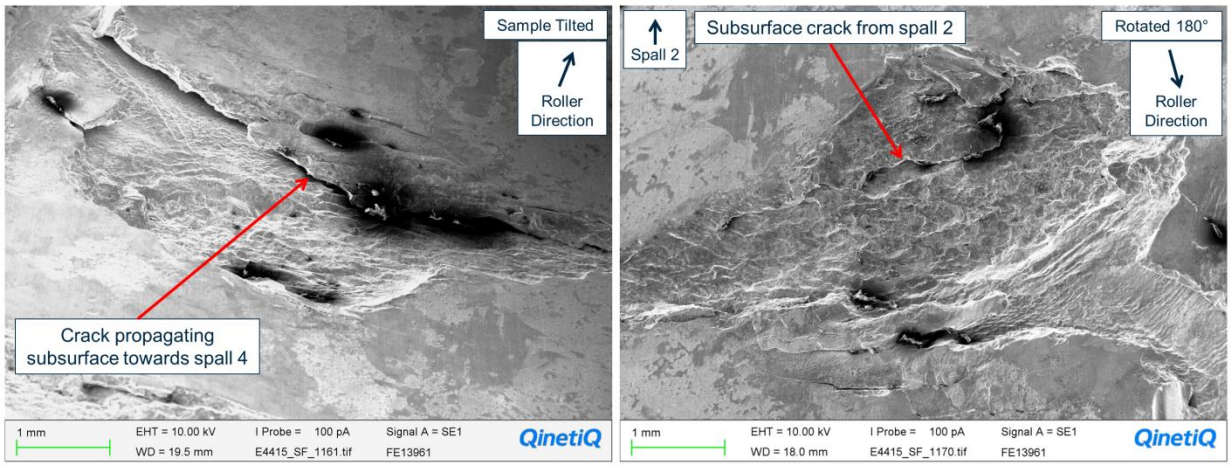
Fractured Second Stage Planet Gear
Sample FE13961 Race Surface – Spall 3 After Cleaning



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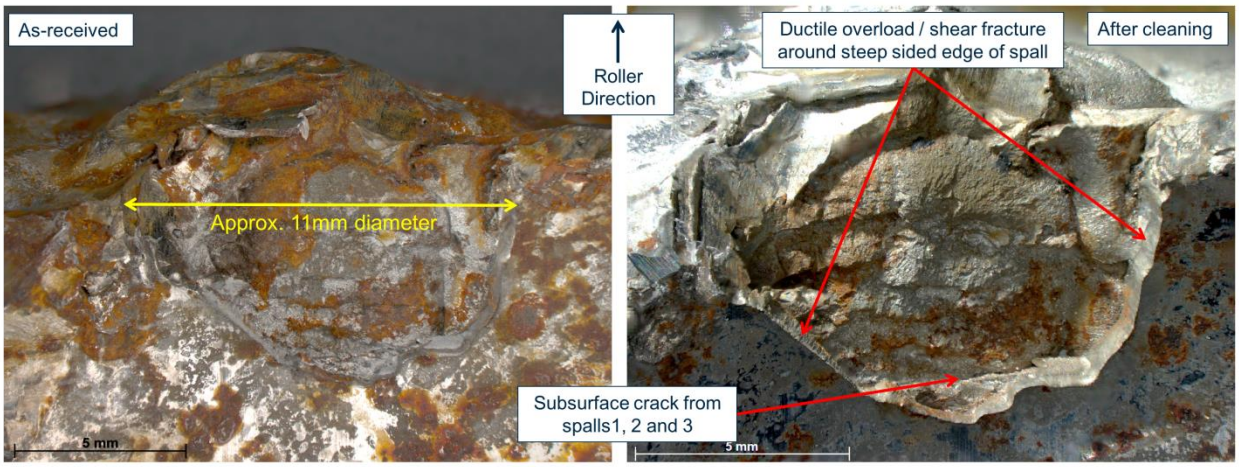
Fractured Second Stage Planet Gear
Sample FE13961 Race Surface – Spall 4



Mean depth of spall = 1.40mm, maximum depth 1.69mm

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Fractured Second Stage Planet Gear S/N 10-1292
X-Ray Tomography

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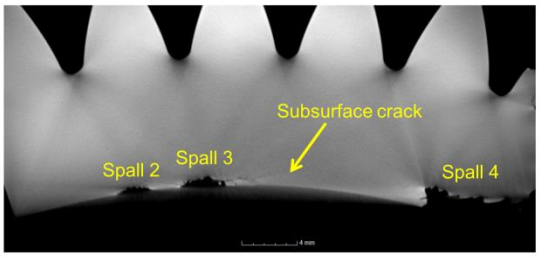
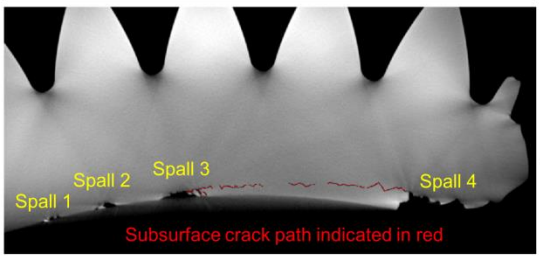
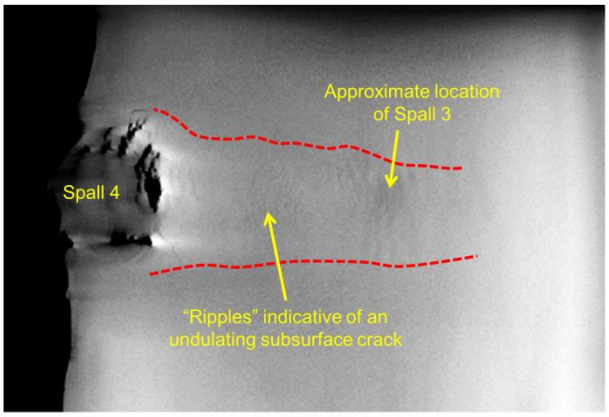
Fractured Second Stage Planet Gear
Sample FE13961 – X-Ray Tomography







Approximate extent of subsurface cracking obtained from X-ray tomography inspection.

The undulating nature of the crack path observed in the initial scans.

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Fractured Second Stage Planet Gear S/N 10-1292
Microsections Through Subsurface Cracking

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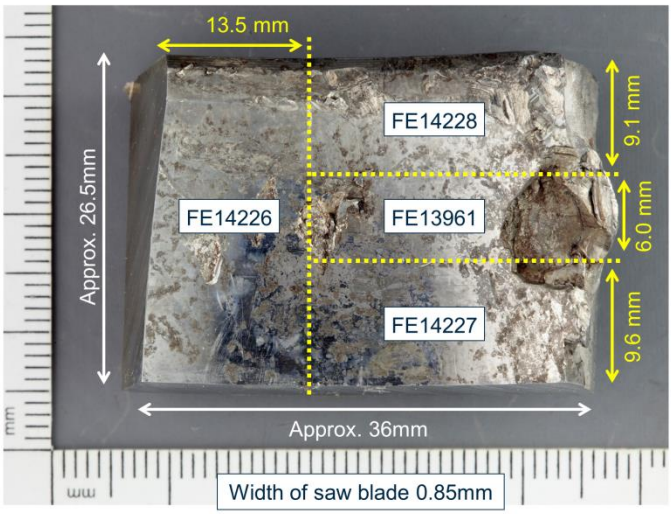
Fractured 2nd Stage Planet Gear
Sample FE13961 – Cutting Plan



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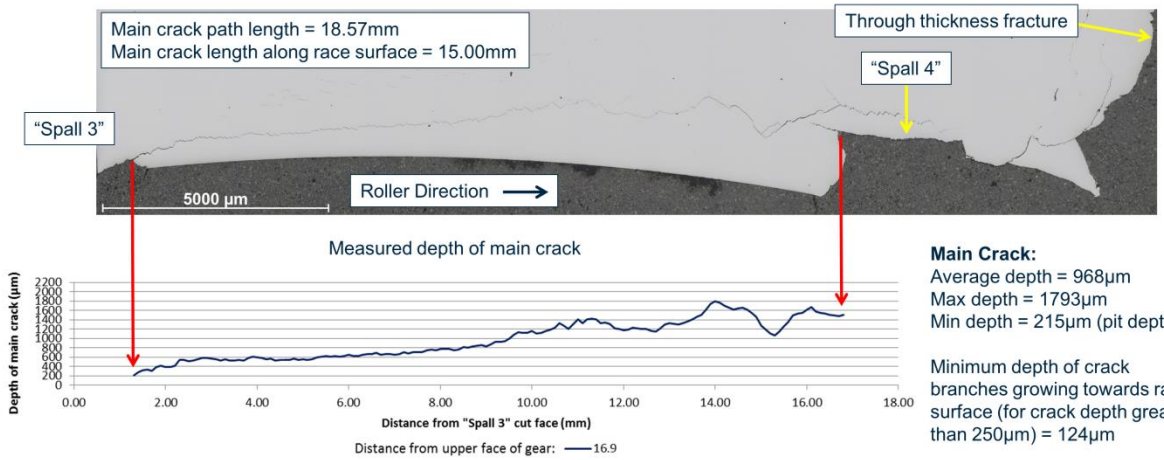
Fractured 2nd Stage Planet Gear
Sample FE14227 – Microsection 16.9mm From Upper Edge



Main Crack:
Average depth = 968µm
Max depth = 1793µm
Min depth = 215µm (pit depth)

Minimum depth of crack branches growing towards race surface (for crack depth greater than 250µm) = 124µm

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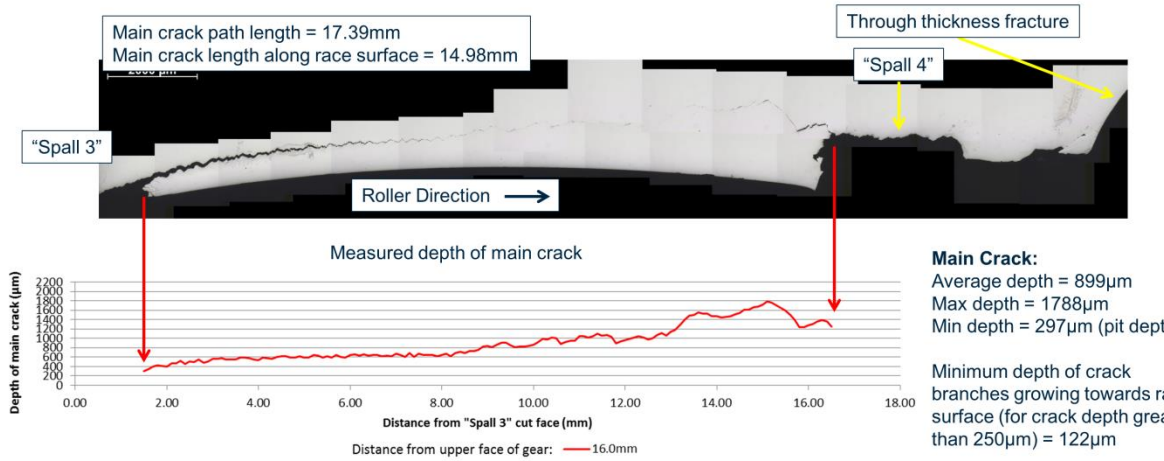
Fractured 2nd Stage Planet Gear
Sample FE13961 – Polished Face 16.0mm From Upper Edge



Main Crack:
Average depth = 899µm
Max depth = 1788µm
Min depth = 297µm (pit depth)

Minimum depth of crack branches growing towards race surface (for crack depth greater than 250µm) = 122µm

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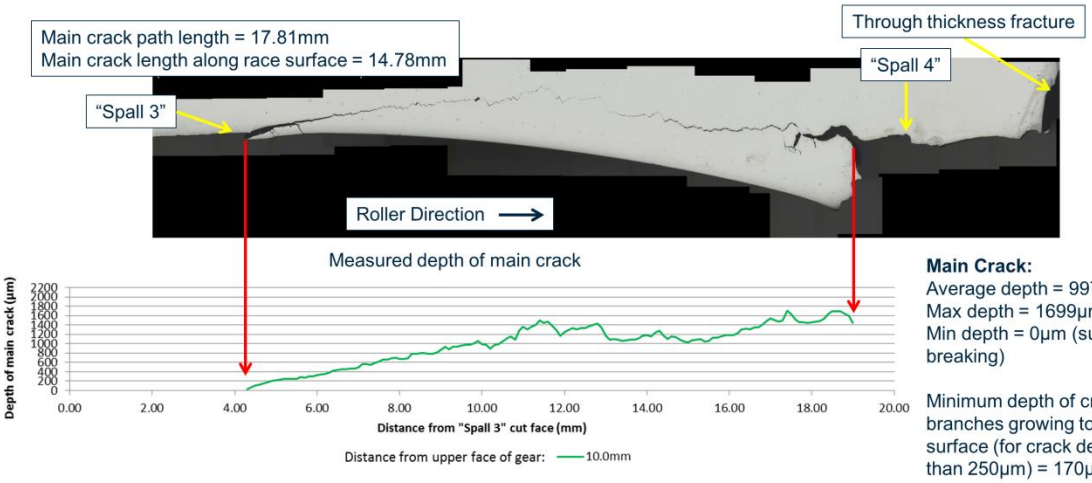
Fractured 2nd Stage Planet Gear
Sample FE13961 – Polished Face 10.0mm From Upper Edge



Main Crack:
Average depth = 997µm
Max depth = 1699µm
Min depth = 0µm (surface breaking)

Minimum depth of crack branches growing towards race surface (for crack depth greater than 250µm) = 170µm

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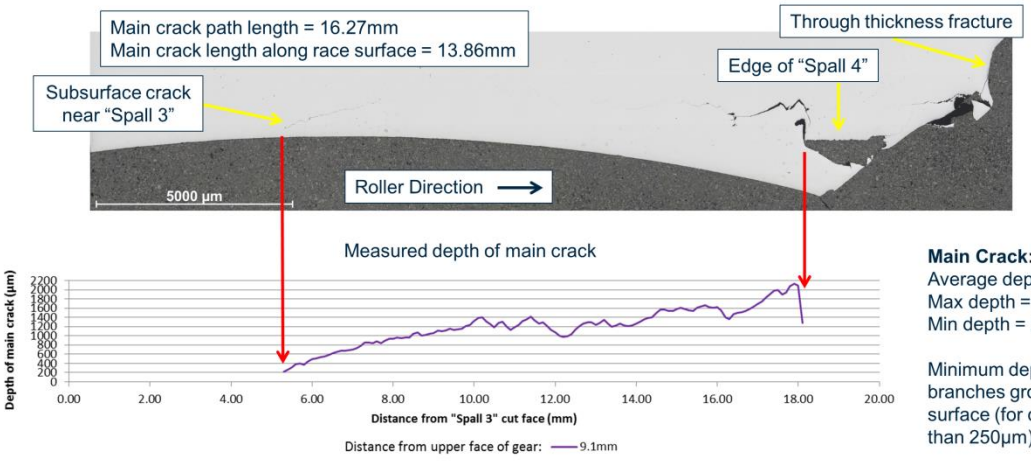
Fractured 2nd Stage Planet Gear
Sample FE14228 – Microsection 9.1mm From Upper Edge



Main Crack:
Average depth = 1206µm
Max depth = 2137µm
Min depth = 217µm

Minimum depth of crack branches growing towards race surface (for crack depth greater than 250µm) = 306µm

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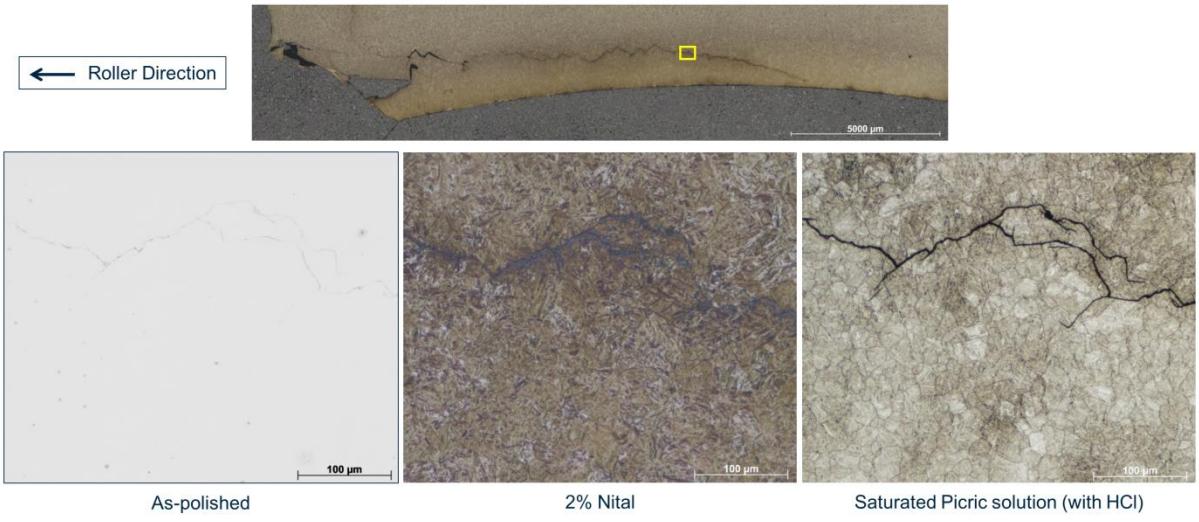
Fractured 2nd Stage Planet Gear
Typical Example of Subsurface Crack Propagation – FE14228 (9.1mm)



As-polished | 2% Nital | Saturated Picric solution (with HCl)

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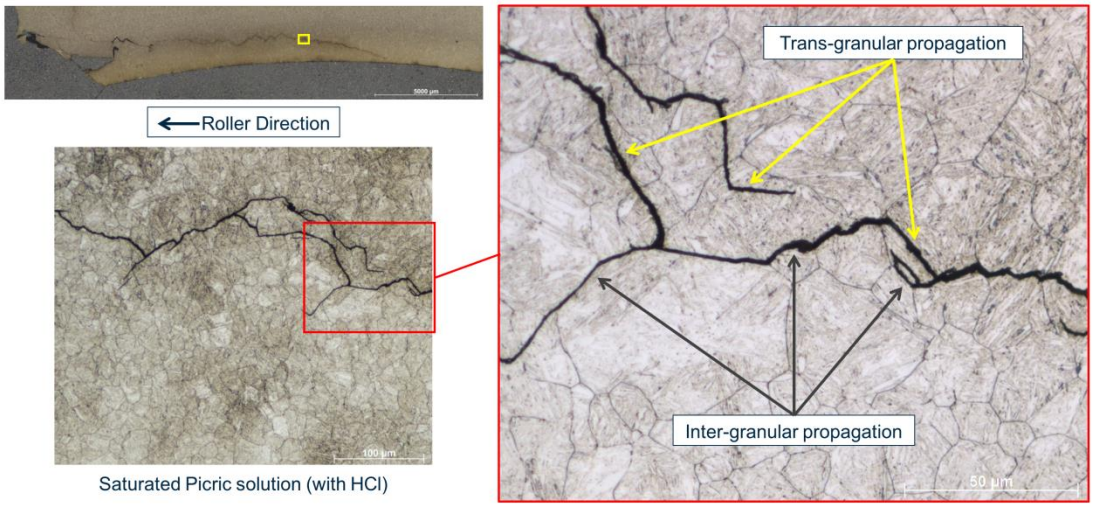
Fractured 2nd Stage Planet Gear
Typical Example of Subsurface Crack Propagation – FE14228 (9.1mm)



Saturated Picric solution (with HCl)

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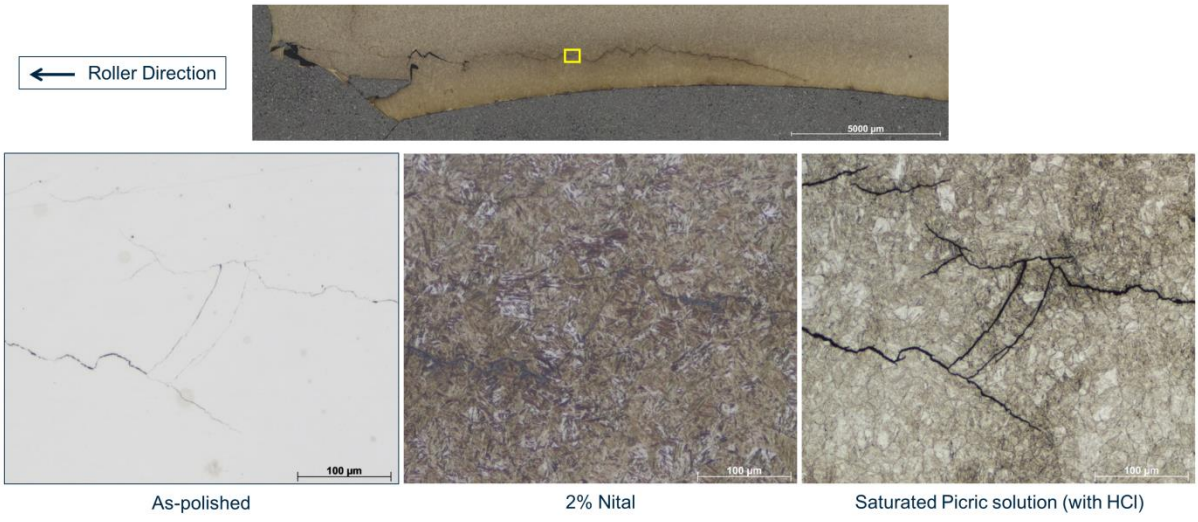
Fractured 2nd Stage Planet Gear
Typical Example of Subsurface Crack Propagation – FE14228 (9.1mm)



As-polished | 2% Nital | Saturated Picric solution (with HCl)

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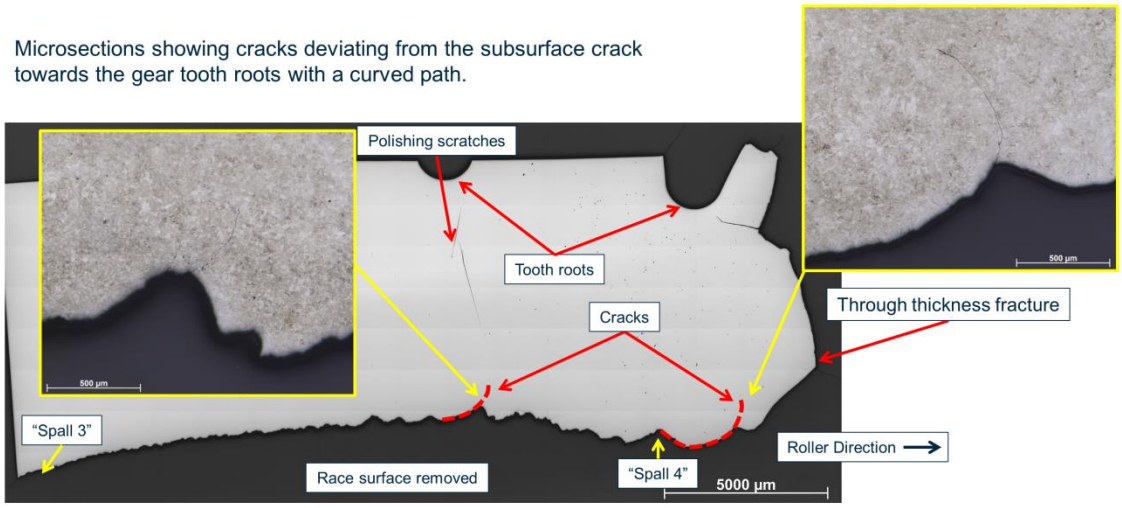
Fractured 2nd Stage Planet Gear
Sample FE13961 – Microsection 15.0mm From Upper Edge

Microsections showing cracks deviating from the subsurface crack towards the gear tooth roots with a curved path.



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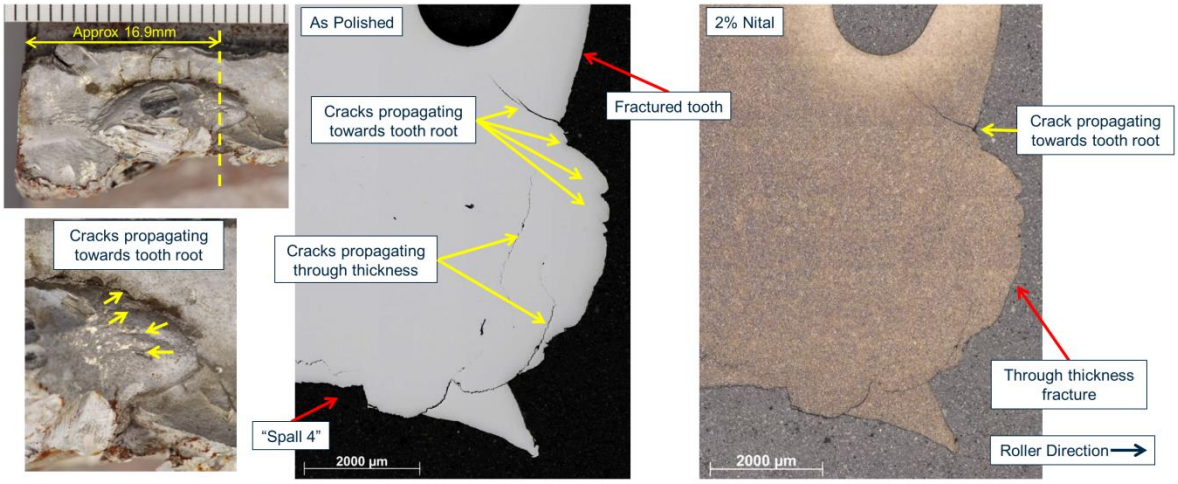
Fractured 2nd Stage Planet Gear
Sample FE14227 – Microsection 16.9mm From Upper Edge



Microsections showing a number of cracks deviating from the subsurface crack and propagating through thickness.
A number of cracks also observed propagating towards the tooth root.

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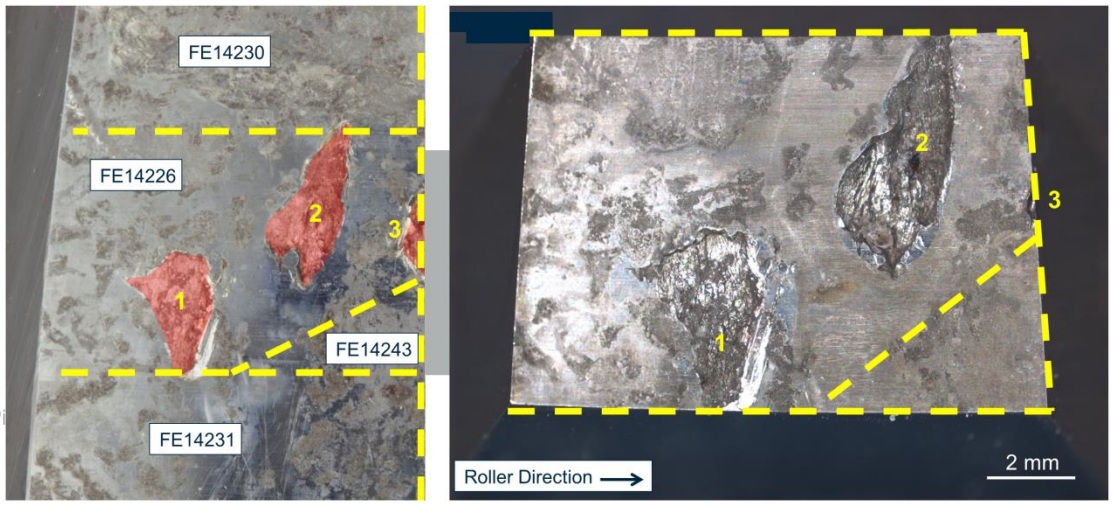
Fractured 2nd Stage Planet Gear
Sample FE13961 – Cutting Plan Spall 1 to Spall 3



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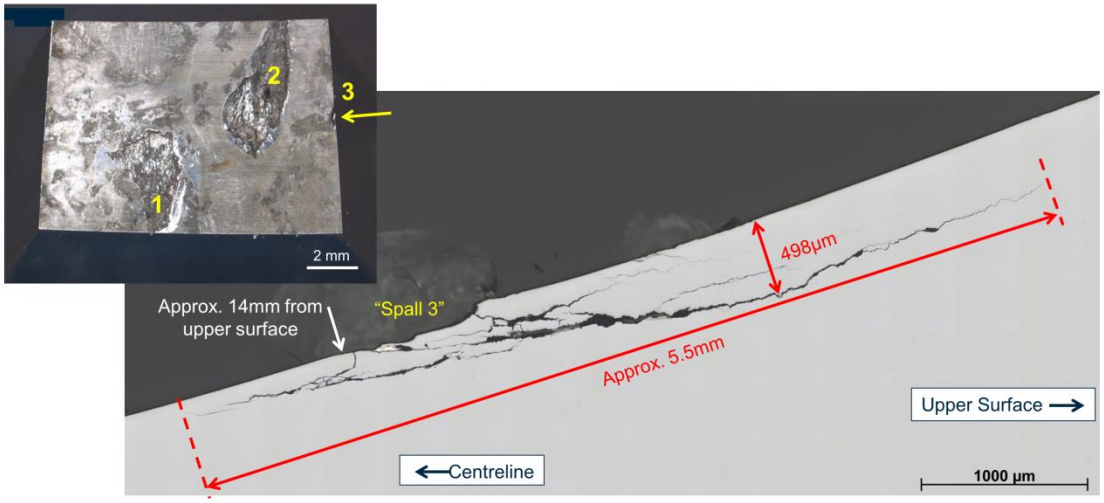
Fractured 2nd Stage Planet Gear
Sample FE14226 - Transverse Microsection Spall 3



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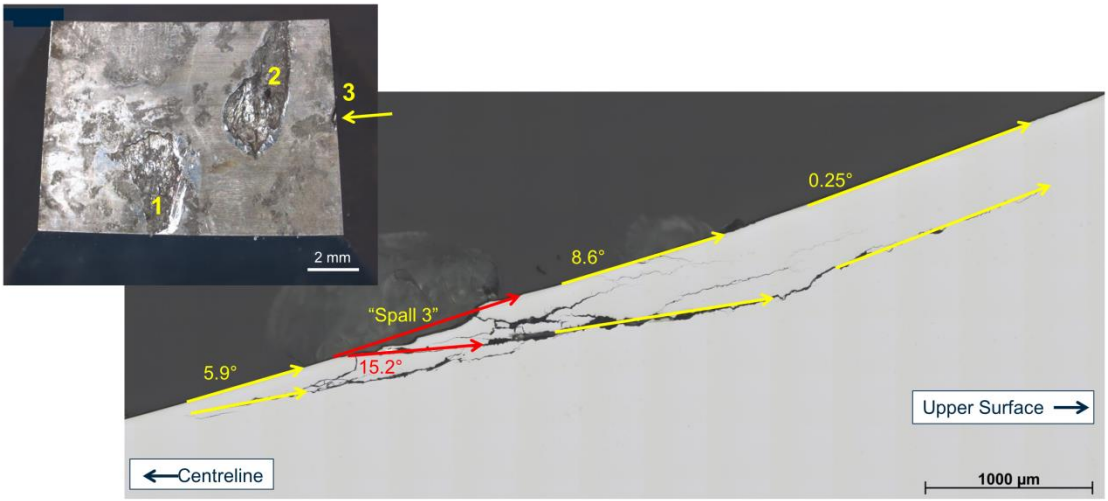
Fractured 2nd Stage Planet Gear
Sample FE14226 - Transverse Microsection Spall 3



46 LN-OJF EC225 Super Puma Accident - Summary of the Metallurgical Examination of the Epicyclic Gearbox Components at QinetiQ
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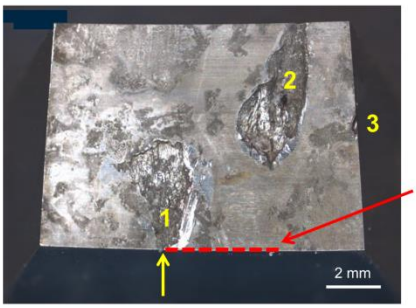
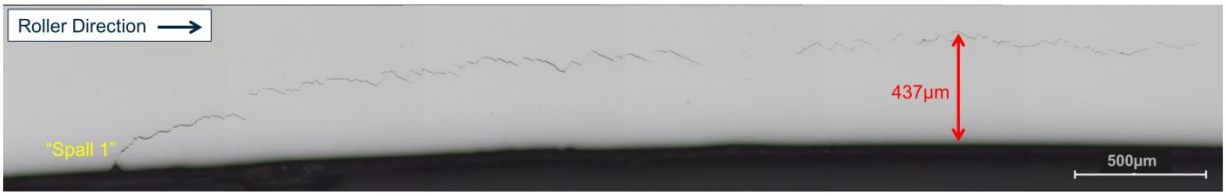
Fractured 2nd Stage Planet Gear
Sample FE14226 - Longitudinal Microsection Spall 1



Extent of crack from spall 1 on this microsection

Main crack path length = 5.18mm
Main crack length along race surface = 4.19mm



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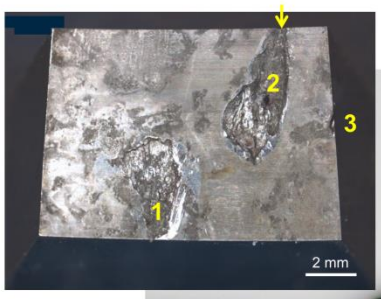
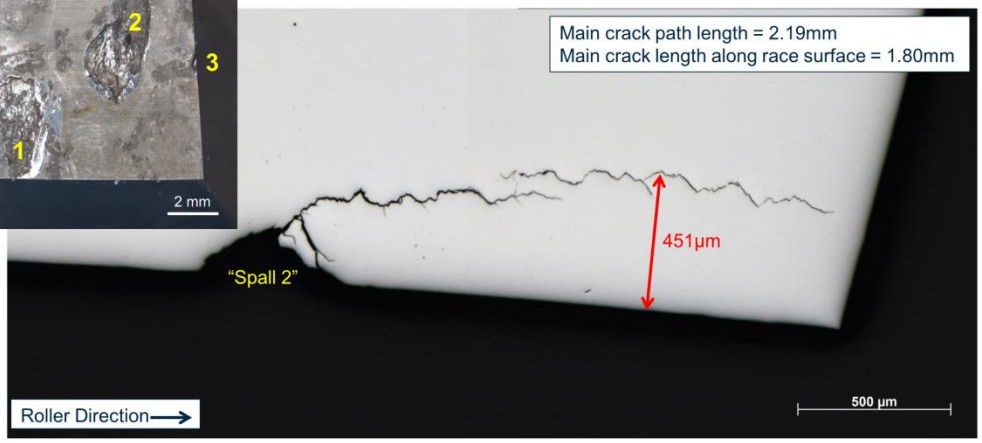
Fractured 2nd Stage Planet Gear
Sample FE14226 - Longitudinal Microsection Spall 2



Main crack path length = 2.19mm
Main crack length along race surface = 1.80mm



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QINETIQ/18/00263/1.0 | January 2018 | © QinetiQ

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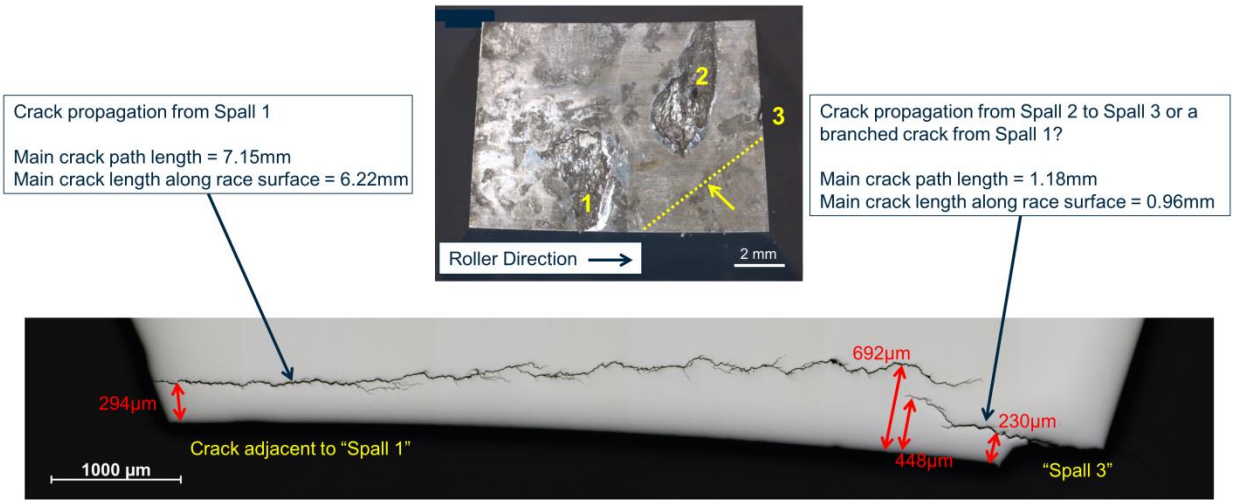
Fractured 2nd Stage Planet Gear
Sample FE14226 - Angled Microsection Between Spall 1 and Spall 3



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Fractured Second Stage Planet Gear S/N 10-1292
Microsections Through Micro-Pitting

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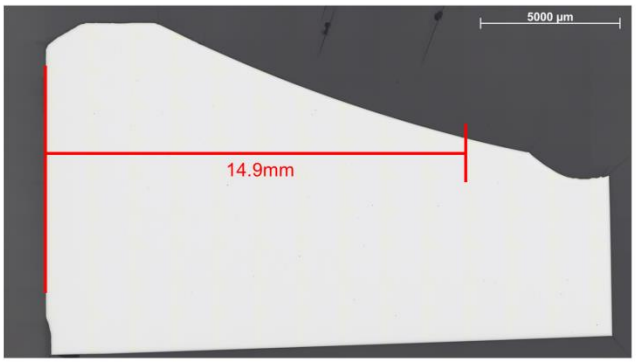
Fractured 2nd Stage Planet Gear
Sample FE13962 – Race Surface Micro-Pitting; Transverse Microsection



Sequential grinding & polishing of transverse microsection to reveal micro-pitting and cracking

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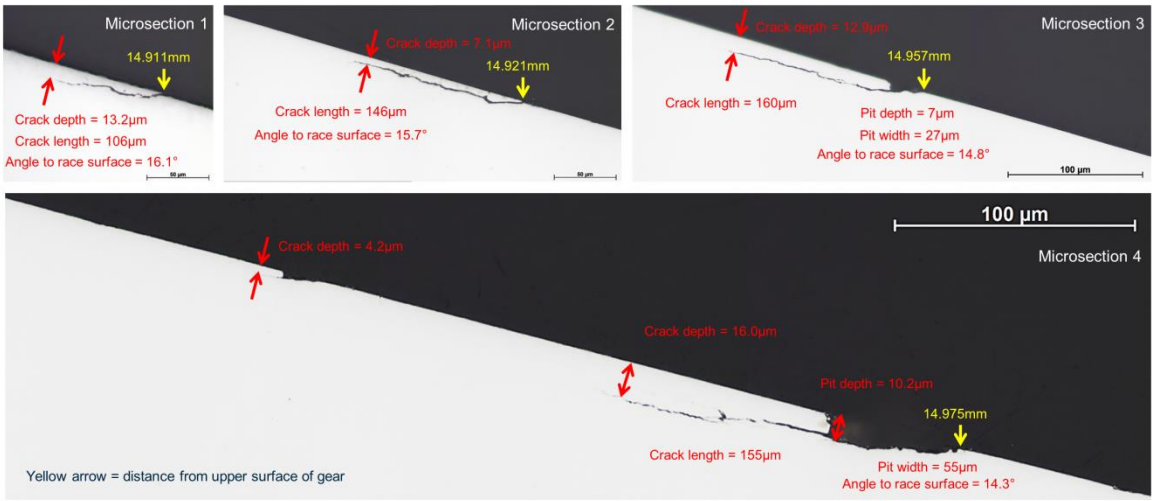
Fractured 2nd Stage Planet Gear
Sample FE13962 – Transverse Microsections Through Micro-Pitting



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Fractured 2nd Stage Planet Gear
Sample FE13962 – Race Surface Micro-Pitting; Circumferential Microsection

Sequential grinding & polishing of circumferential microsection to reveal micro-pitting and cracking

Microsections examined at 15.8mm, 15.1mm and 14.9mm from upper surface of gear

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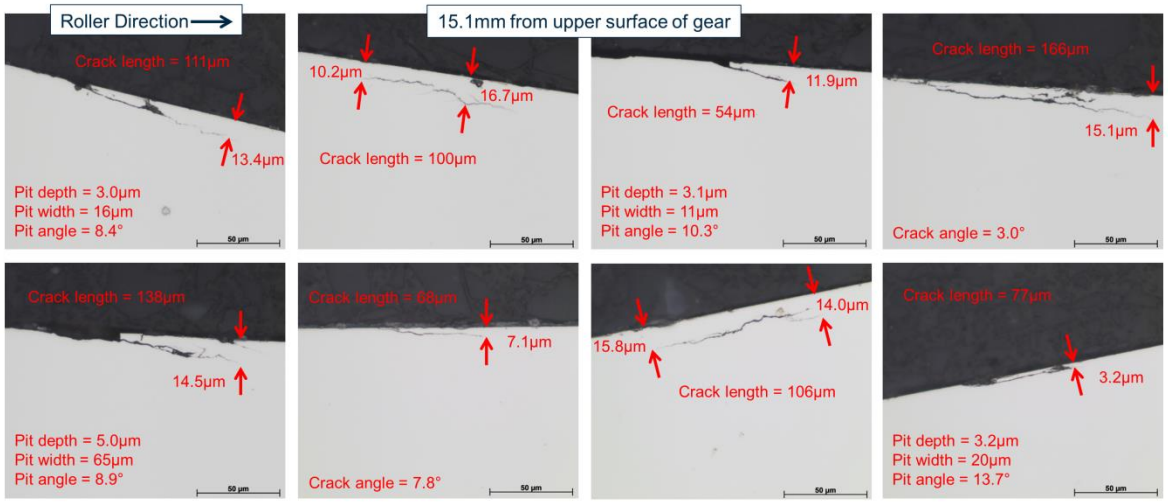
Fractured 2nd Stage Planet Gear
Sample FE13962 – Circumferential Microsections Through Micro-Pitting



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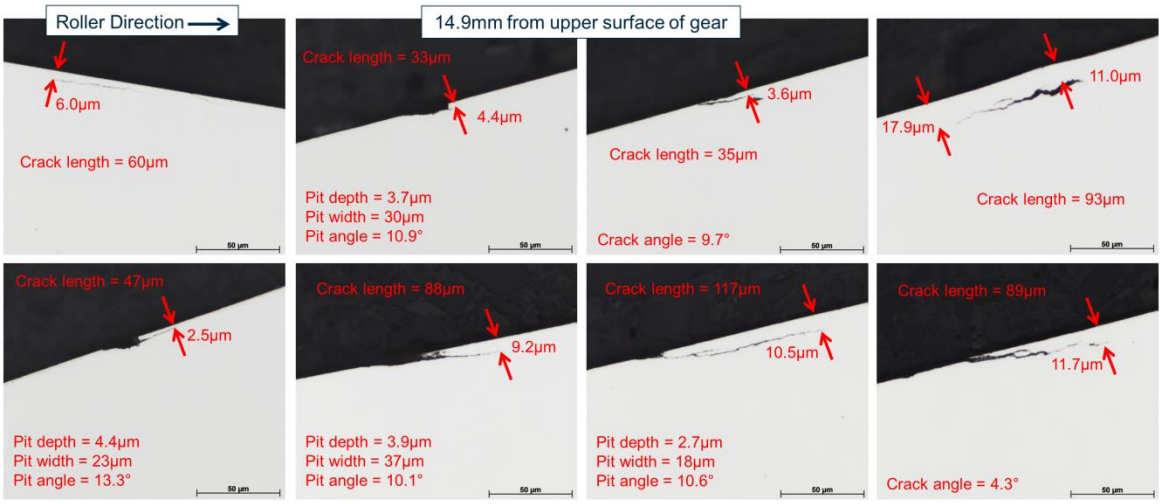
Fractured 2nd Stage Planet Gear
Sample FE13962 – Circumferential Microsections Through Micro-Pitting



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Fractured Second Stage Planet Gear S/N 10-1292
Fractography of Subsurface Cracks

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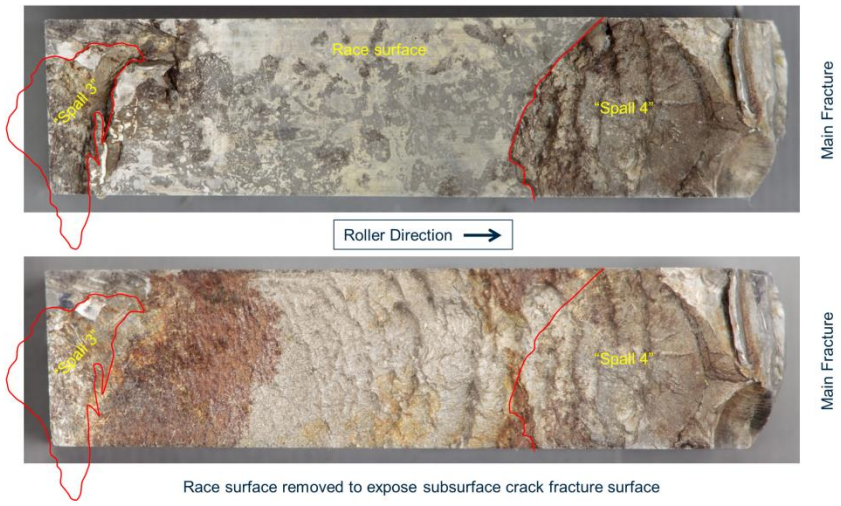
Fractured 2nd Stage Planet Gear
Sample FE13961 – Spall 3 to Main Fracture



Race surface removed to expose subsurface crack fracture surface

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Fractured 2nd Stage Planet Gear
Sample FE13961 – Opened Up Fracture

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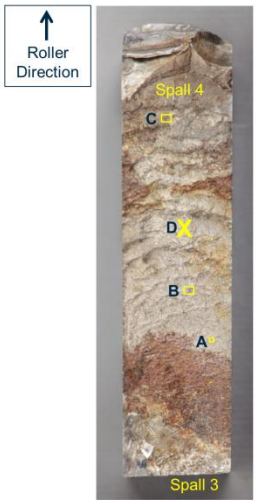
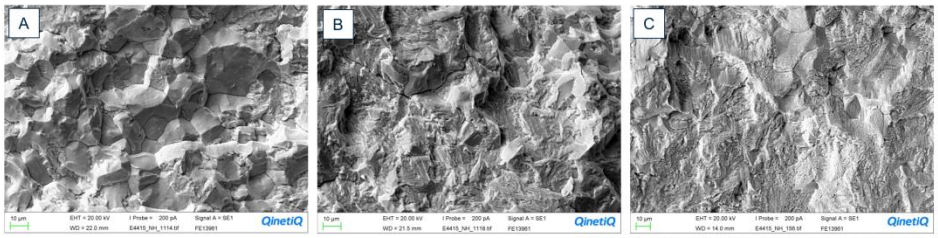
Fractured 2nd Stage Planet Gear
Sample FE13961 – Fractography Spall 3 to Main Fracture

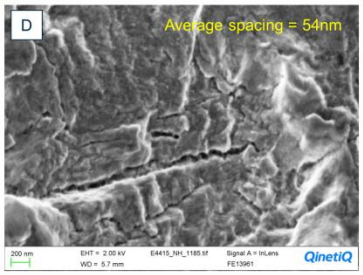




Micrographs A to C show a decreasing amount of intergranular fracture as the subsurface crack propagates deeper into the material.

One localised region (D) contained features consistent with striations.

Insufficient evidence to determine the crack growth rate from striation spacing measurements.



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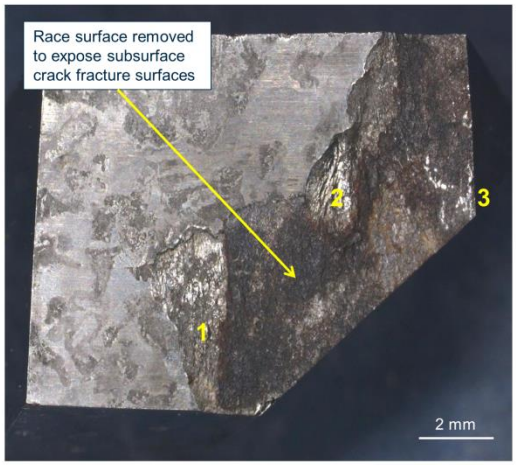
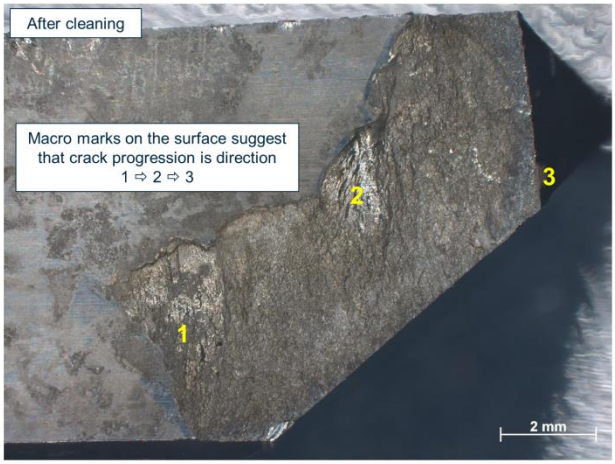
Fractured 2nd Stage Planet Gear
Sample FE14226





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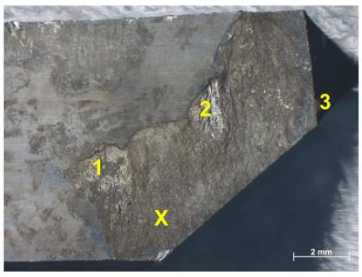
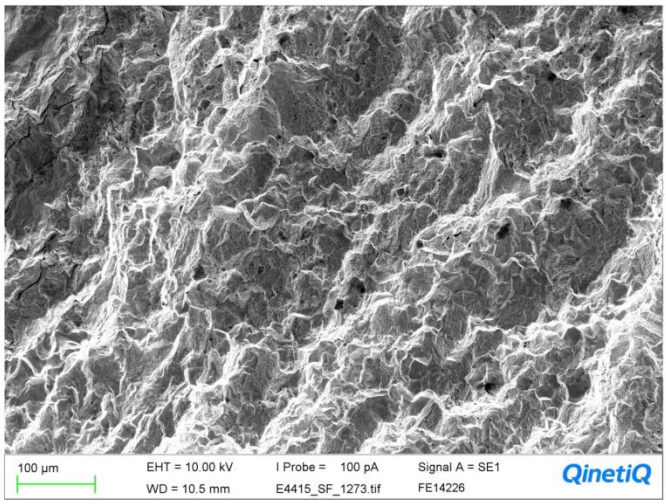
Fractured 2nd Stage Planet Gear
Sample FE14226 – SEM Fractography



Subsurface crack has a predominantly intergranular fracture surface.



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Fractured Second Stage Planet Gear S/N 10-1292
Sequential Polishing Through Spalls 1 - 3

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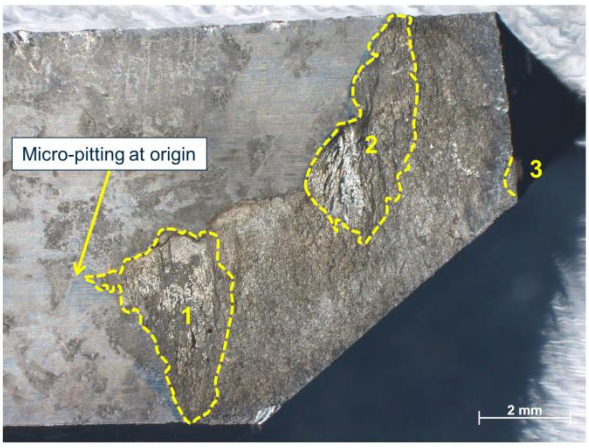
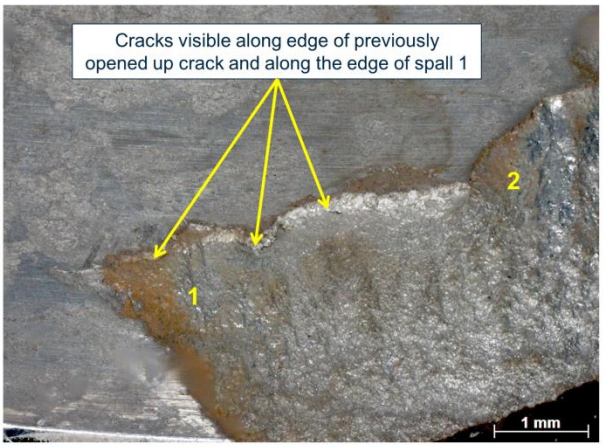
Fractured 2nd Stage Planet Gear – Sample FE14226





Objective: To determine the extent (length and depth) of subsurface cracking between spall 1 and spall 2, plus examine the micro-pitting at the origin of spall 1.

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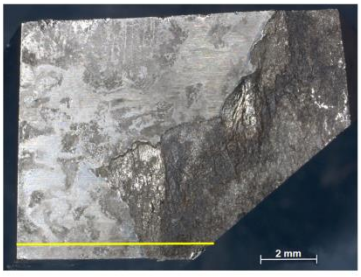
Fractured 2nd Stage Planet Gear – Sample FE14226 Sequential Polishing



Sequential polishing to determine the extent of subsurface cracking and location of micro-pitting near the origin of spall 1.

Yellow line indicates the location of the slice shown below. A total of 19 slices were examined.

17.6mm from upper surface of gear

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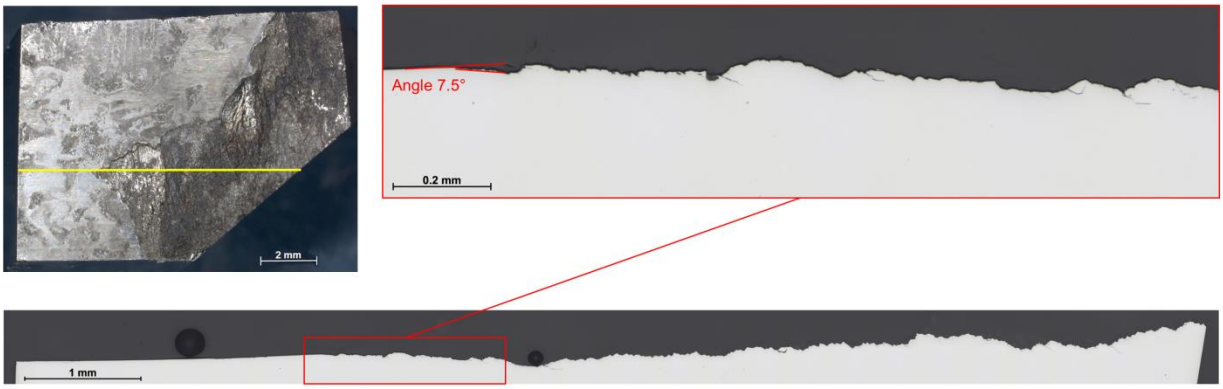
Fractured 2nd Stage Planet Gear – Sample FE14226 Sequential Polishing



15.1mm from upper surface of gear

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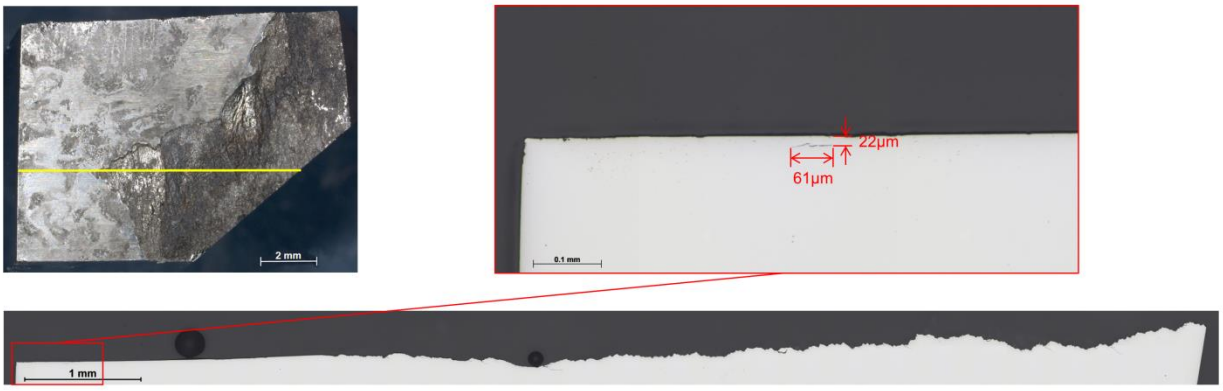
Fractured 2nd Stage Planet Gear – Sample FE14226 Sequential Polishing



15.1mm from upper surface of gear

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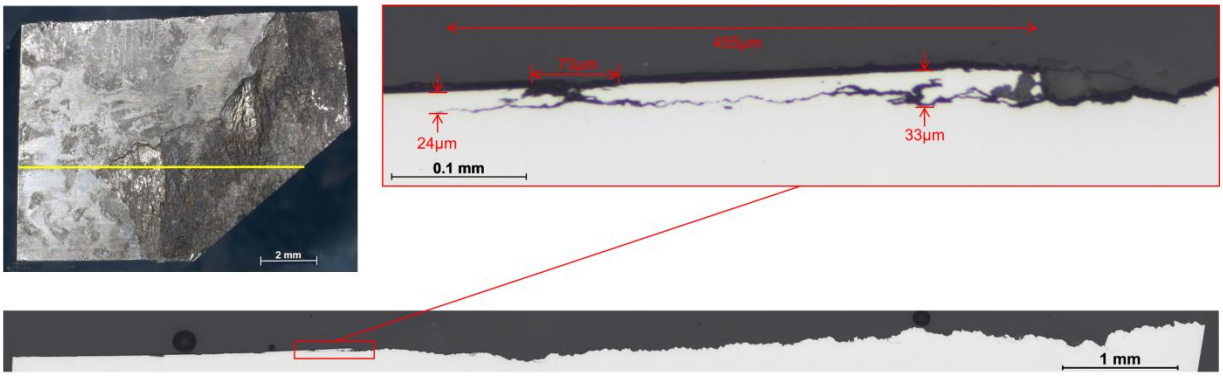
Fractured 2nd Stage Planet Gear – Sample FE14226 Sequential Polishing



15.0mm from upper surface of gear

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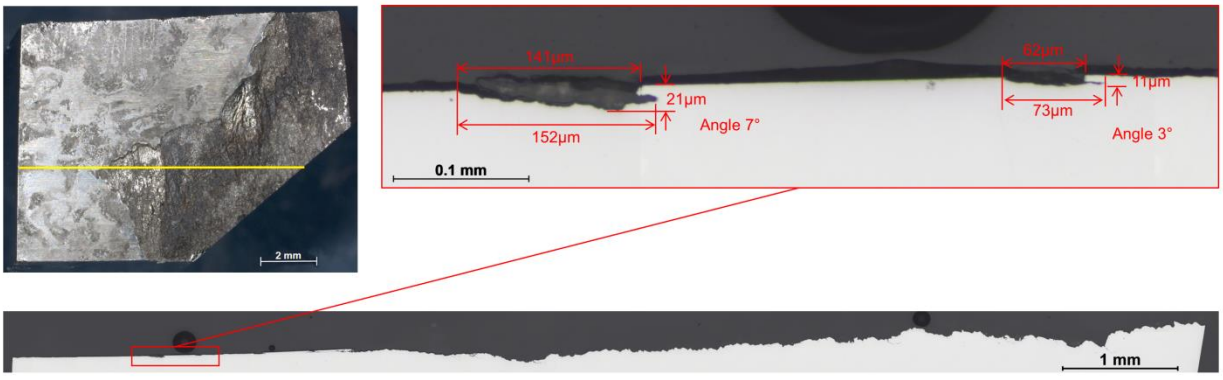
Fractured 2nd Stage Planet Gear – Sample FE14226 Sequential Polishing



15.0mm from upper surface of gear

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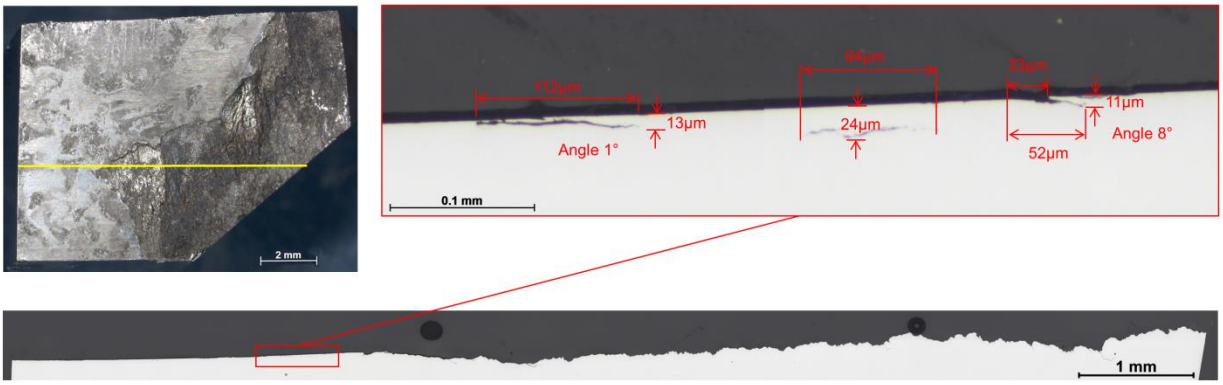
Fractured 2nd Stage Planet Gear – Sample FE14226 Sequential Polishing



14.9mm from upper surface of gear

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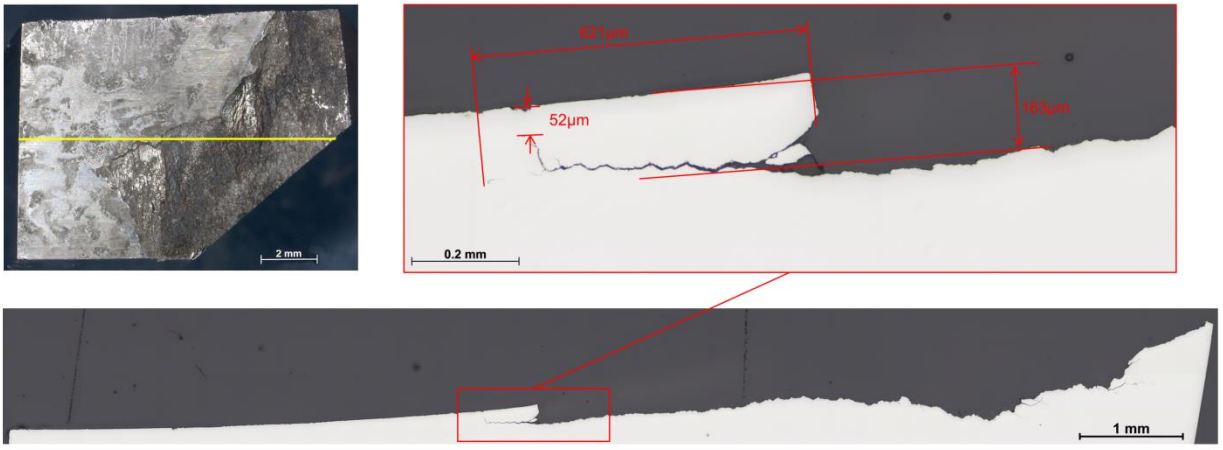
Fractured 2nd Stage Planet Gear – Sample FE14226 Sequential Polishing



14.1mm from upper surface of gear

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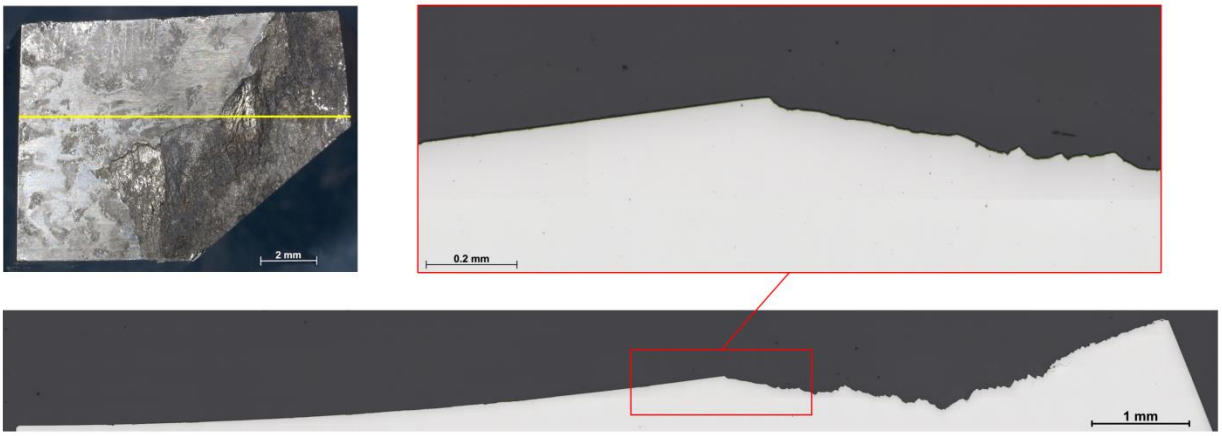
Fractured 2nd Stage Planet Gear – Sample FE14226 Sequential Polishing



13.3mm from upper surface of gear

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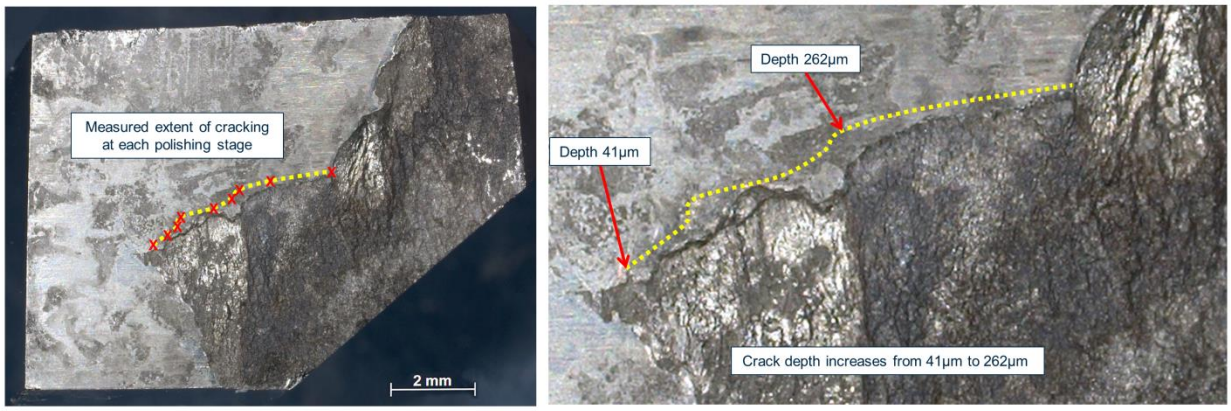
Fractured 2nd Stage Planet Gear – Sample FE14226



Approximate location of subsurface crack

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Fractured Second Stage Planet Gear S/N 10-1292
Materials Conformity

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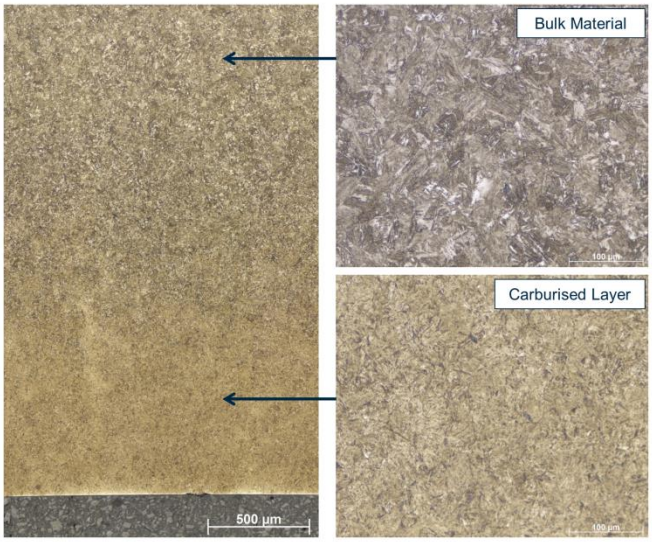
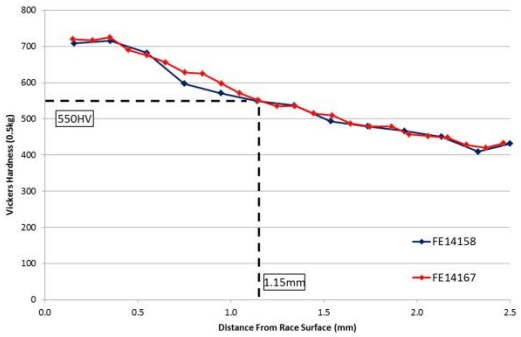
Fractured Second Stage Planet Gear
Materials Conformity – Microstructure & Case Depth





Average measured carburised layer depth on race surface = 1.25mm
[11 measurements; min 1.14mm, max 1.47mm]
(Specification 0.85 to 1.70mm) "ER" value for this gear = 1.11mm

Measured surface hardness of race = 725HV10
(Specification min 660HV10)
[micro-hardness profiles show 688–740HV0.5 near surface]

Composition consistent with 16NCD13

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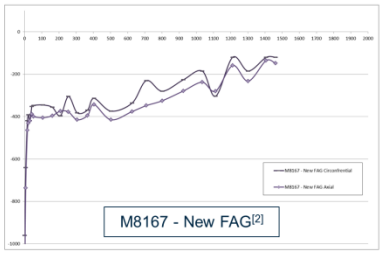
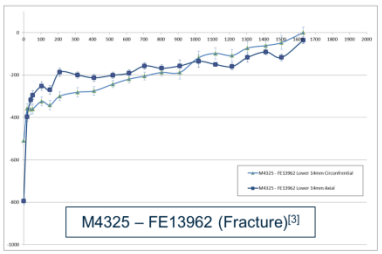
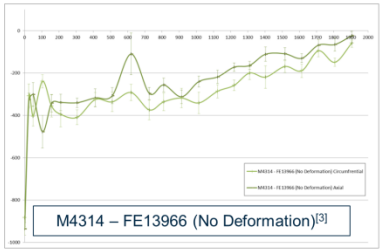
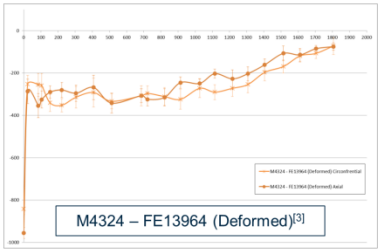
Fractured Second Stage Planet Gear
Materials Conformity – Residual Stress









Comparison of the measured residual stress profiles from the outer race surface of three planet gears recovered from the LN-OJF accident, including the failed gear M4325, with the profile obtained from a new FAG planet gear outer race.

The residual stress profiles obtained from the LN-OJF gears were as expected.

Residual stress measurements performed by Airbus Helicopters

[2] FAG-New Manuracturing.xlsx, email from Airbus Helicopters, 16 August 2016.
[3] LN-OJF _ Export Profils Contrainte.xlsx, email from Airbus Helicopters, 15 September 2016.

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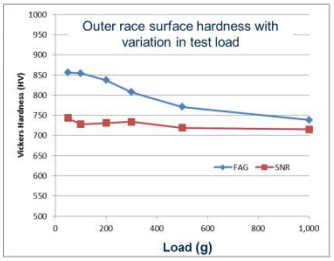
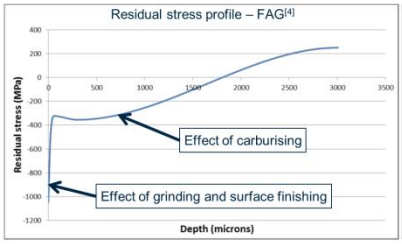
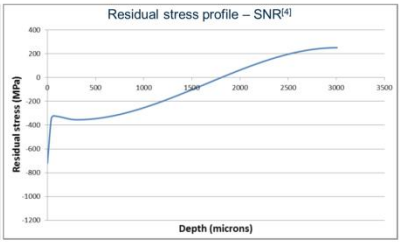
Fractured Second Stage Planet Gear
Materials Conformity – Surface Hardness and Residual Stress Comparison

Load (g)	Vickers Hardness	
	FAG [M4325; FE13961 Fracture]	SNR [M5362;Heli-one]
10,000	725	701
1,000	738	715
500	771	719
300	807	734
200	837	731
100	854	728
50	856	743







Vickers hardness measurements made on the outer race surface using a decreasing test load shows an apparent increase in surface hardness on the FAG planet gear as the indent sampling depth decreases.

Residual stress profiles measured on new FAG and SNR outer race surfaces shows a greater compressive residual stress at the surface (<50µm) of the FAG gear compared to the SNR.

These results are consistent with the differences in final finishing operations employed by the two suppliers.

Residual stress measurements performed by Airbus Helicopters

[4] Super Puma Bearing Sizing Stress Comparison, Airbus Helicopters, 332A056057-B, 5 September 2016..

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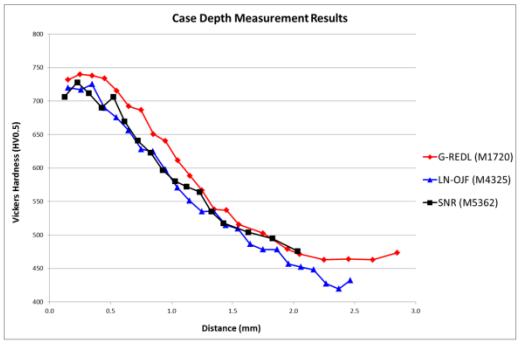
Fractured Second Stage Planet Gear
Comparison of Second Stage Outer Race Hardness Values with G-REDL Data

Measurement	G-REDL [M1720]	LN-OJF [M4325]	SNR [M5362]
Depth of carburised layer (Specification 0.85 – 1.70mm)	Most reliable data = 1.3mm (min 0.9mm, max 1.5mm)	Average = 1.25mm (min 1.14mm, max 1.47mm)	1.28mm
Outer race surface hardness (Specification min 660HV10)	755HV10	725HV10	701HV10
Core hardness (Specification 340 – 410HB)	453HV30 (Approx 447HB)	399HV30 (Approx 394HB)	414HV30 (Approx 409HB)



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Second Stage Planet Gear Inner Race S/N 10-1292

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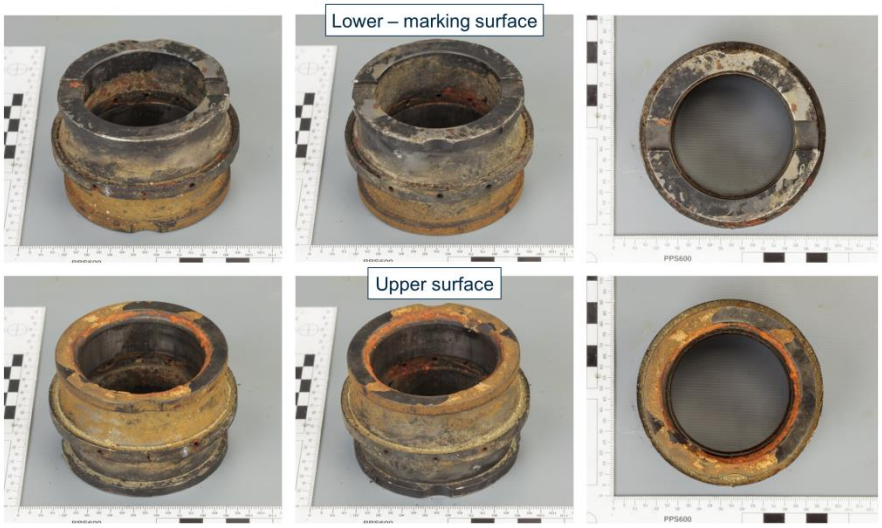
Second Stage Planet Gear Inner Race 10-1292
As-Received



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Second Stage Planet Gear Inner Race 10-1292
After Cleaning

Circumferential "wear" bands observed on the inner-race surfaces

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Second Stage Planet Gear Inner Race 10-1292
After Cleaning – Upper Race Surface

Micro-pitting observed within a small region of the “wear” band on the upper inner-race surface.

No evidence of micro-pitting observed on the lower inner-race surface.

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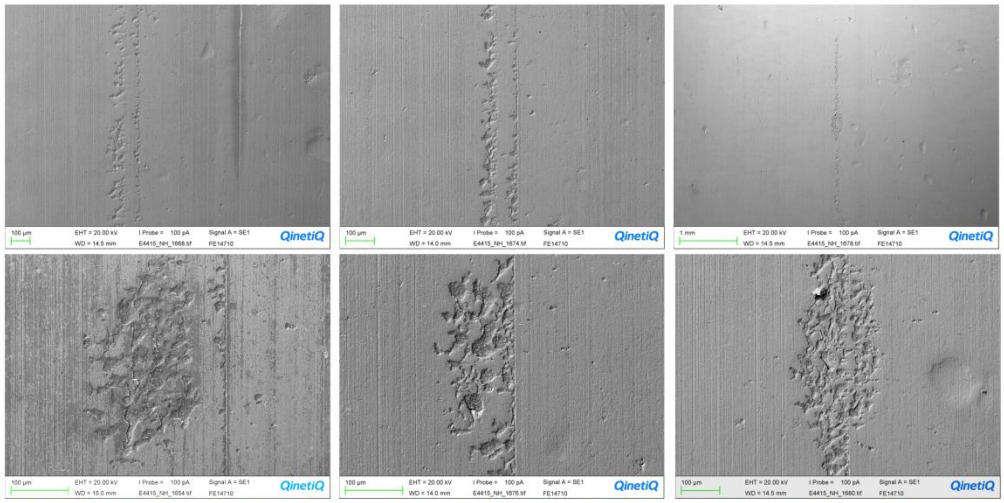
Second Stage Planet Gear Inner Race 10-1292
After Cleaning – Upper Race Surface



SEM examination of the micro-pitting on the upper inner-race surface shows features similar to the micro-pitting observed on the outer race.

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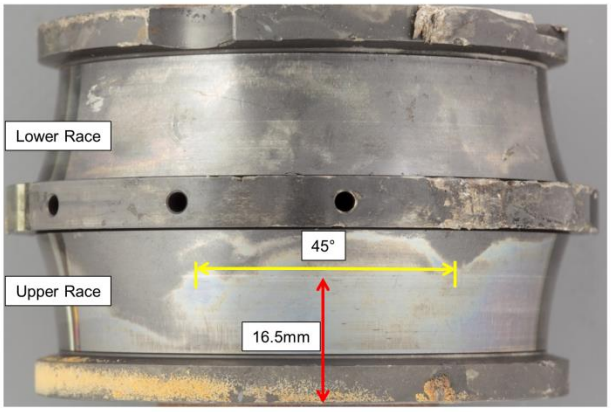
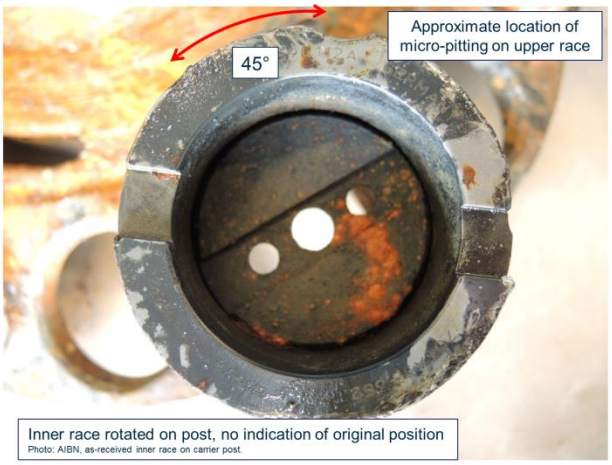
Second Stage Planet Gear Inner Race 10-1292
After Cleaning



Location of micro-pitting on the upper inner-race surface



Inner race rotated on post, no indication of original position
Photo: AIBN, as-received inner race on carrier post.

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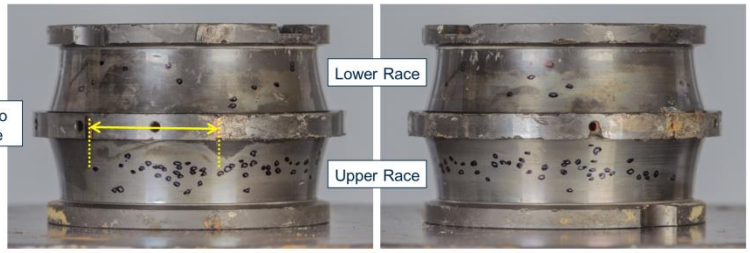
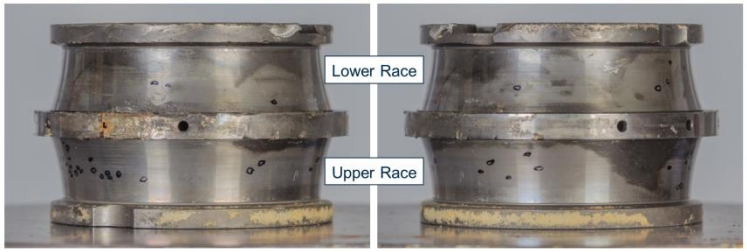
Second Stage Planet Gear Inner Race 10-1292
After Cleaning – Location of Small Impressions on Race Surfaces

Approximate location of micro pitting on upper race surface

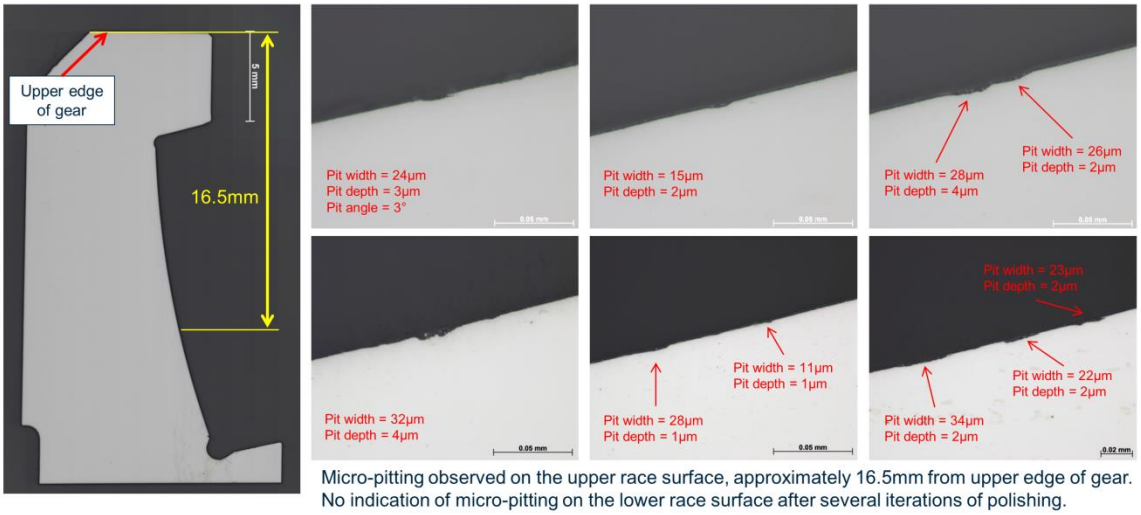




Location of small impressions on race surfaces suspected to be associated with debris particle imprints; mechanical damage and larger indents consistent with roller impacts due to breakup not identified.

QINETIQ

Second Stage Planet Gear Inner Race 10-1292
Upper Race Transverse Microsection



Micro-pitting observed on the upper race surface, approximately 16.5mm from upper edge of gear.
No indication of micro-pitting on the lower race surface after several iterations of polishing.

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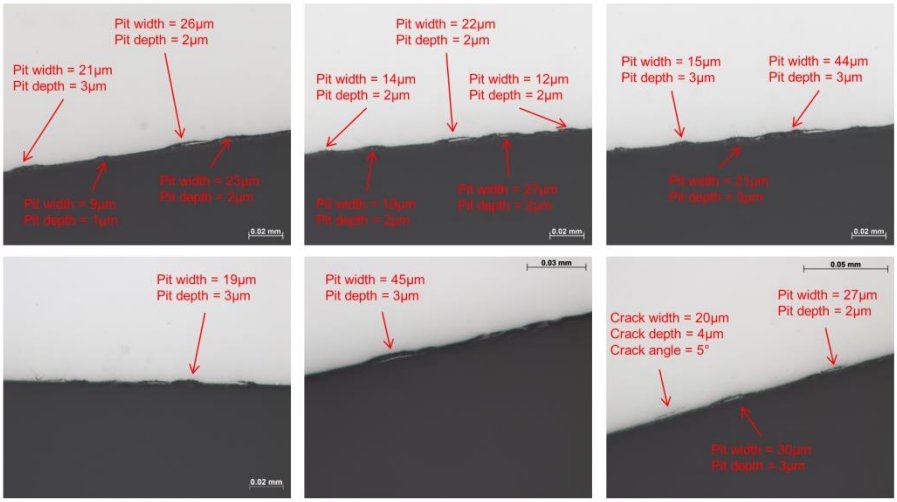
Second Stage Planet Gear Inner Race 10-1292
Upper Race Circumferential Microsection



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Second Stage Planet Gear Carrier

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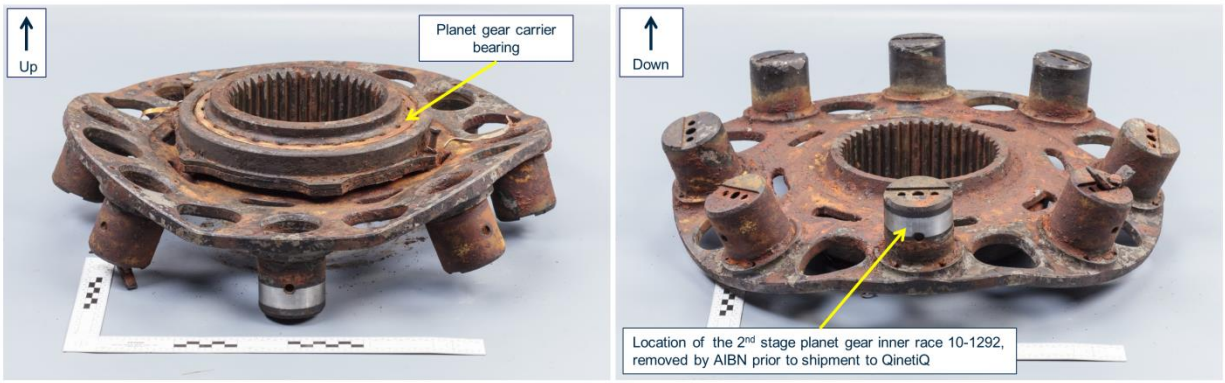
Second Stage Planet Gear Carrier As-Received



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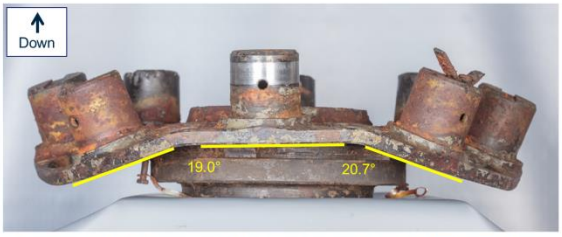
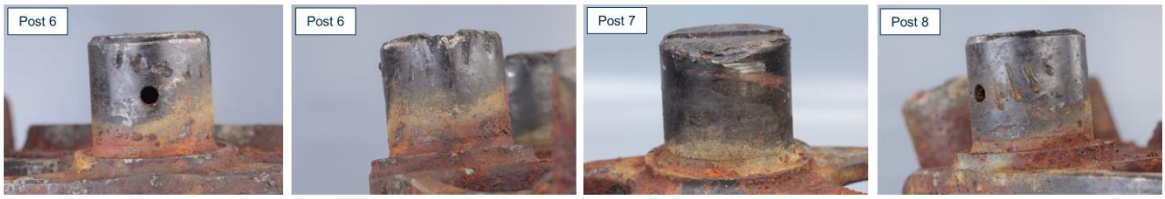
Second Stage Planet Gear Carrier
As-Received – Deformation and Post Damage



Symmetrical deformation of carrier around post of fractured gear

Only one of the planet gear locking tabs remaining attached



Mechanical damage consistent with gear teeth impressions on three posts

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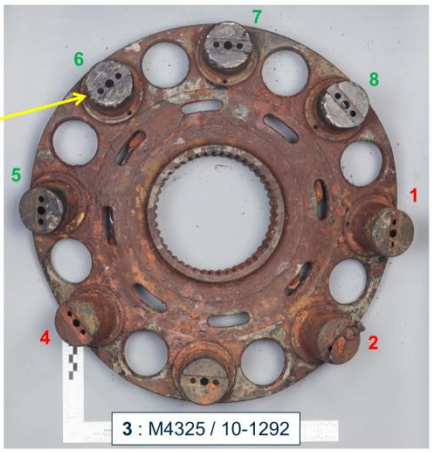
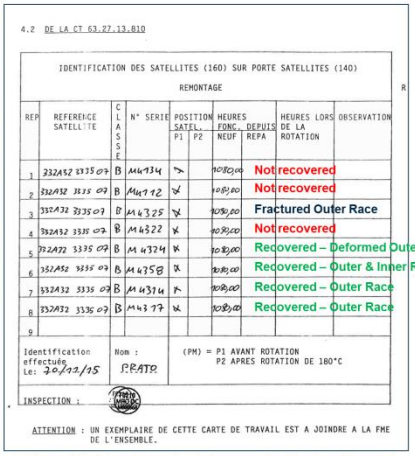
Second Stage Planet Gear Carrier
As-Received – Post Identification

Hand engraved post numbers identifiable on some posts





4.2 DE LA CT 63.27.13.810

IDENTIFICATION DES SATELLITES (160) SUR PORTE SATELLITES (140)

REMONTAGE

REP	REFERENCE SATELLITE	CLASSE	N° SERIE	POSITION SATEL. P1	POSITION SATEL. P2	HEURES FONC. DEPUIS NEUF	HEURES FONC. DEPUIS REPA	HEURES LORS DE LA ROTATION	OBSERVATION
1	332A32 3335 07	B	M4734	X		10810,00			Not recovered
2	332A32 3335 07	B	M4712	X		10810,00			Not recovered
3	332A32 3335 07	B	M4325	X		10810,00			Fractured Outer Race
4	332A32 3335 07	B	M4322	X		10810,00			Not recovered
5	332A32 3335 07	B	M4324	X		10810,00			Recovered – Deformed Outer Race
6	332A32 3335 07	B	M4758	X		10810,00			Recovered – Outer & Inner Race, 24 Rollers
7	332A32 3335 07	B	M4314	X		10810,00			Recovered – Outer Race
8	332A32 3335 07	B	M4377	X		10810,00			Recovered – Outer Race
9									

Identification effectuée Le: 20/12/95 Nom : PRATO

(PM) = P1 AVANT ROTATION
P2 APRES ROTATION DE 180°C

INSPECTION :

ATTENTION : UN EXEMPLAIRE DE CETTE CARTE DE TRAVAIL EST A JOINDRE A LA FME DE L'ENSEMBLE.

Airbus Helicopters build record attached to epicyclic module log card after Australian car accident repair

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Second Stage Planet Gear Carrier
After Plastic Media Cleaning

Mast splines show no major mechanical damage, corrosion of the splines has removed any surface detail.

91 LN-OJF EC225 Super Puma Accident - Summary of the Metallurgical Examination of the Epicyclic Gearbox Components at QinetiQ
QINETIQ/18/00263/1.0 | January 2018 | © QinetiQ

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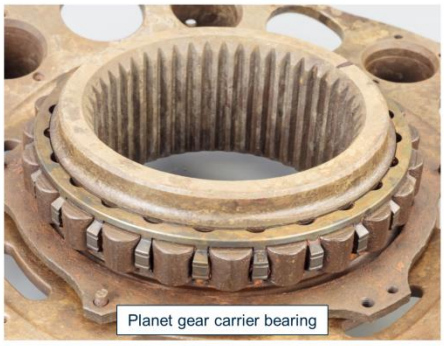
Second Stage Planet Gear Carrier
Dismantling of Carrier Bearing



Dismantling of carrier plate bearing shows significant corrosion of race surfaces, bearing cage and rollers. Surfaces are too corroded to observe any wear pattern.

All of the rollers exhibit a channel (groove) on their upper surface, this is suspected to be associated with corrosion of the exposed surfaces of the roller between the cage and outer race

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