Propulsion System Health Monitoring

An Insight into Wear Debris Analysis

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Auckland, New Zealand

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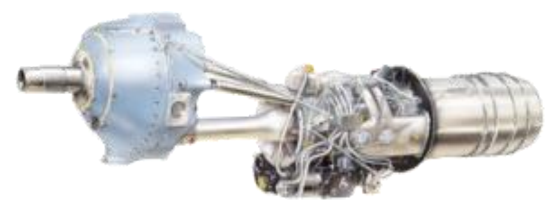
dta
Defence Technology Agency

New Zealand DEFENCE FORCE
Te Ope Kātua O Aotearoa
NAVY NZ ARMY AIR FORCE

DTA Propulsion System Health Monitoring

- Provide advice to the RNZAF to:
  - Support continued airworthiness
  - Prevent flight safety events
  - Increase aircraft availability/reduce cost of ownership

- Propulsion systems:
  - Gas turbine engines/gearboxes/helicopter drivetrains



NZDF Context - Motivation

- Small fleets - U/S aircraft - high impact on capability
- Deployed A/C – minimal facilities and spares available
  - E.g. Antarctic Flights, helos embarked on ships, austere environments, in-theatre ops etc.
- Need for increased warning lead-time to required maintenance intervention
- Oil-wetted component defects significant driver for unscheduled maintenance

Wear debris analysis identified as one area requiring enhancement



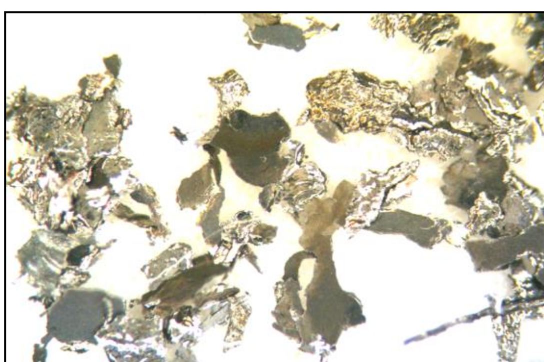


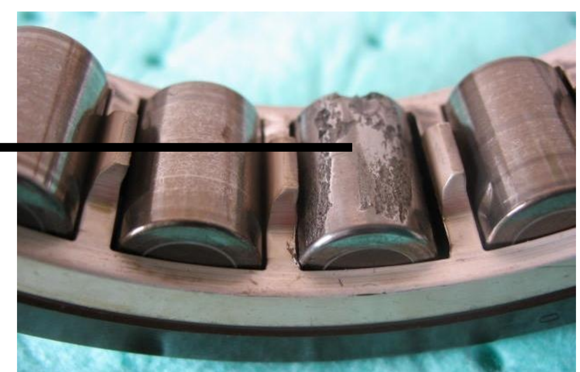



Wear Debris Analysis - Definition

- Wear Debris Analysis infers the health of oil-wetted components from debris liberated from wear modes within the system

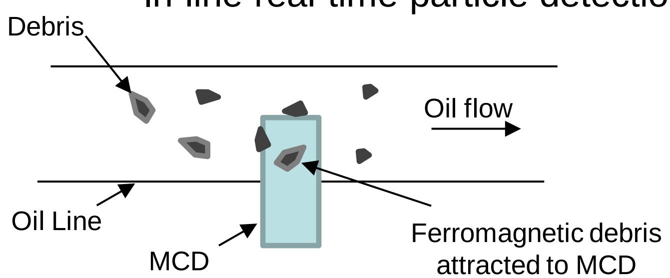
- Provides data on:
  - Wear modes
    - Morphology
  - Origin of debris
    - elemental composition
  - State of defect progression
    - Size/quantity
    - Debris rate

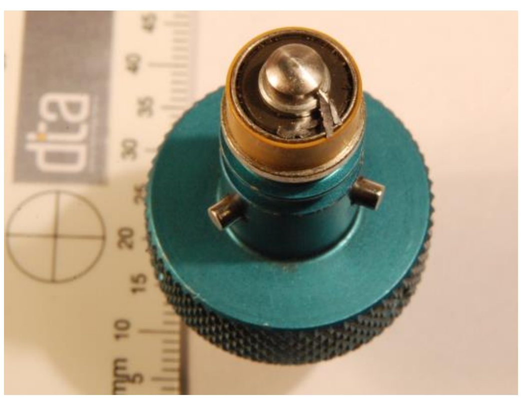




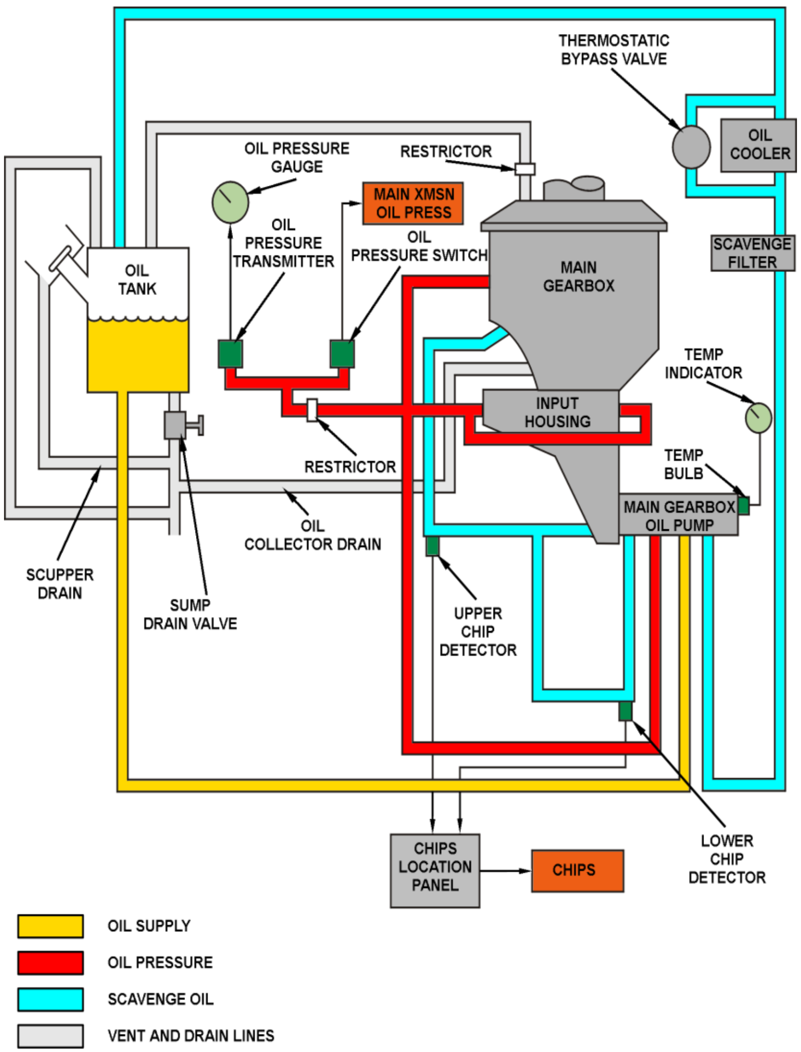
Wear Debris Analysis – Typical Aircraft Systems

- WDA employed by OEMs as a prime means of detecting oil-wetted component defects
  - In-line Magnetic chip detectors (MCDs) – indicating/passive
  - Filter debris analysis
  - In-line real-time particle detection (very limited application)

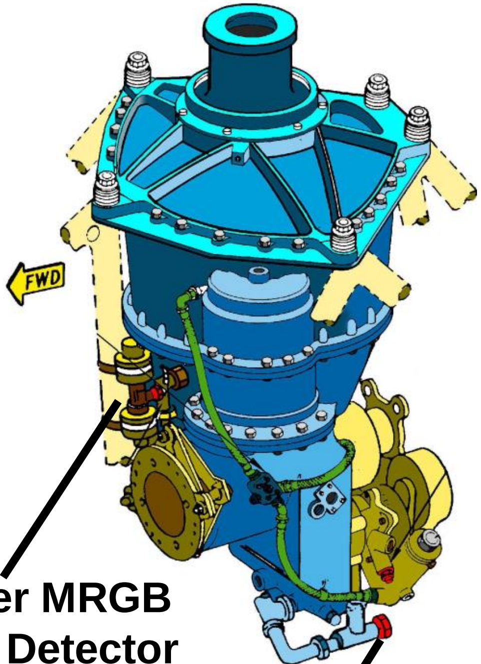




Wear Debris Analysis – Typical Aircraft Systems

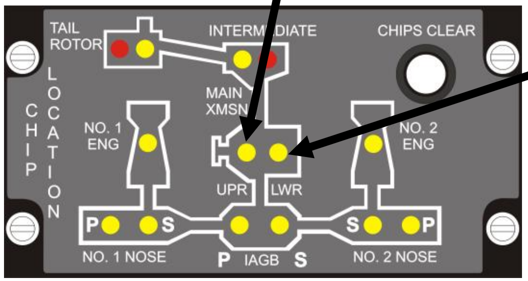


Efficacy of MCDs vary between various designs



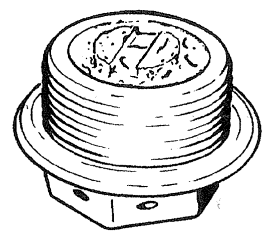
Upper MRGB Chip Detector

Lower MRGB Chip Detector

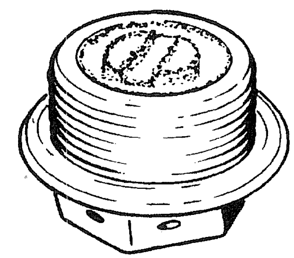


Wear Debris – Serviceability Assessment

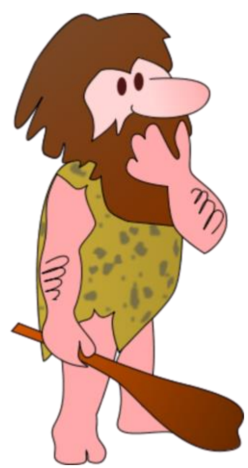
- OEMs provide AMM inspection criteria for wear debris
- First Line assessment visual inspection process has changed little over time
- Inspection guidance can be ambiguous/open to interpretation
  - Often no detail on inspection method
  - Often no detail on filter debris inspection
- First Line assessment visual inspection:
  - Quantity and size
  - Morphology
- Within limits - no further review
  - Sample may not be retained
- Out of limits
  - Requires engineering review
  - Possibly laboratory analysis

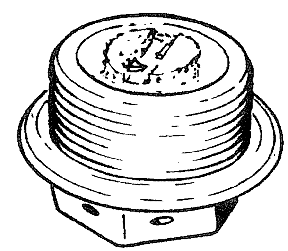


HAIR-LIKE SLIVERS - MAGNETIC PLUG ACCUMULATION



NORMAL MAGNETIC PLUG METAL ACCUMULATION





METAL CHUNK, ACTIVE FAILURE MAGNETIC PLUG ACCUMULATION

Wear Debris – Serviceability Assessment

Example of generic AMM serviceability criteria for wear debris

Type	Qty/size	Prob Cause	Action
Steel	Fuzz, fine hair-like particles or granular form	Normal wear	None
	Particles in splinter form	Usually indicates failure	Perform serviceability check
	Thin flakes not exceeding 0.031 inch (0.78 mm) in diameter and 0.25 inch (6.35 mm) in length. Qty not to exceed 20 flakes	Small qty will not cause bearing failure	Perform serviceability check
	More than 20 flakes not exceeding 0.031 inch (0.78 mm) in diameter or any Qty of flakes exceeding the above dims	Usually indicates failure	Perform serviceability check

How do you measure this in the field?

Wear Debris – Serviceability Check Example

Generic procedure for a helicopter main rotor gearbox

- Indications
  - MCD chip light – Assess iaw AMM criteria
  - Filter bypass
  - Other (high vib etc.)

- Perform serviceability check
  - Perform 30 min ground run at flight RPM – if OK
  - Perform 30 min hover check

  - Inspect MCDs
    - if QTY of particles increased – Reject gearbox OR
    - If QTY is less – assess debris and repeat serviceability check OR
    - If QTY is Nil – continue in service

Wear Debris – Engineering Review

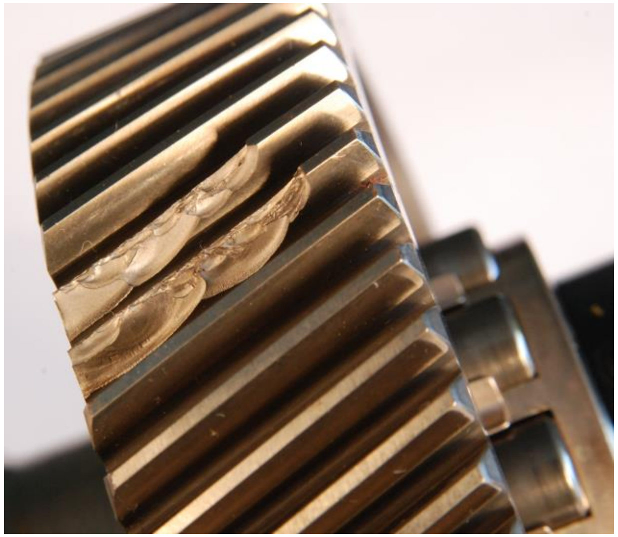
- Inputs to serviceability assessment:
  - Lab analysis of wear debris sample – composition, morphology
  - Maintenance history
  - Known and predicted wear modes
  - Engineering data – e.g. metal map
  - Trend data – wear debris and other e.g. vibs
  - Engineering judgement

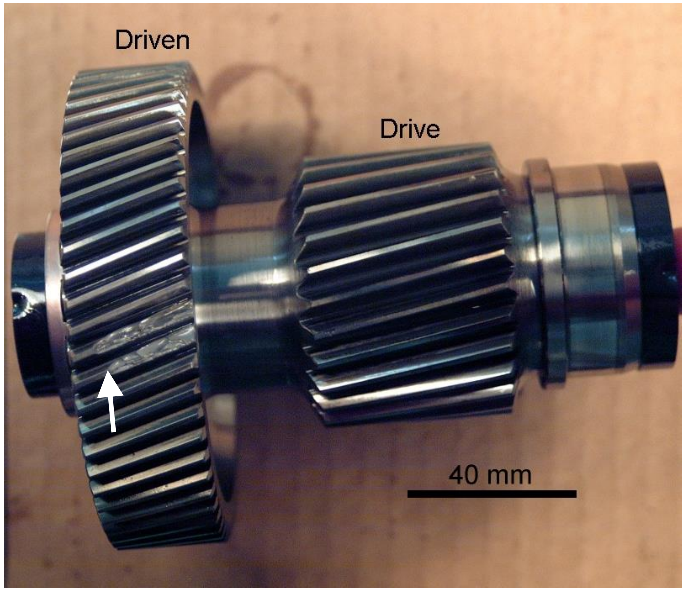
- Output:
  - Diagnosis: Go/No-go (based on AMM criteria)
  - Prognosis: time until required maintenance intervention
  - Mandated inspections/monitoring if remaining in service

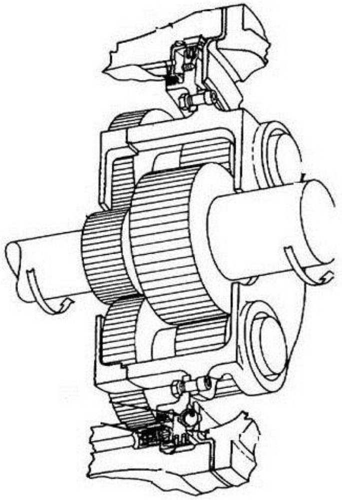
- Issues
  - Data for engineering review may not be available
  - SMEs may be remote from samples – delay in analysis
  - Variable experience of personnel in WDA

Case Study –Iroquois T53 gearbox

- Multiple MCD indications over period of 100+ hours – all assessed as ‘S’
- Final in-service MCD indication – serviceability check
  - Further MCD indication 3 min into 20 min hover check
  - Teardown found 2 fractured gear teeth, abnormal wear on gear surfaces
  - Wear debris precursors not detected

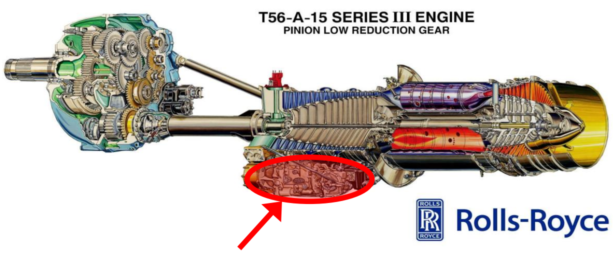




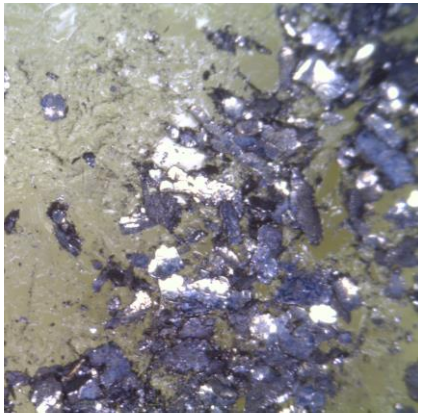


Case Study – T56 Accessory Gearbox (AGB)

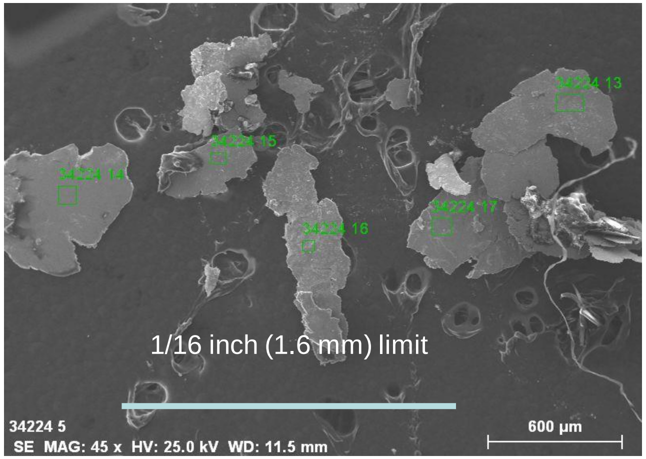
- Aircraft deployed on operation
- Mag plugs checked – Accessory Gearbox Mag plug had debris
- Debris assessed as ‘fuzz’ and within limits – sample sent to DTA slow time for review
- Results:
  - ‘Fuzz’ shown to be fatigue spall flakes of bearing material
  - Particles <1/16th inch limit
- Engine changed



AGB Lower mag plug: Visual



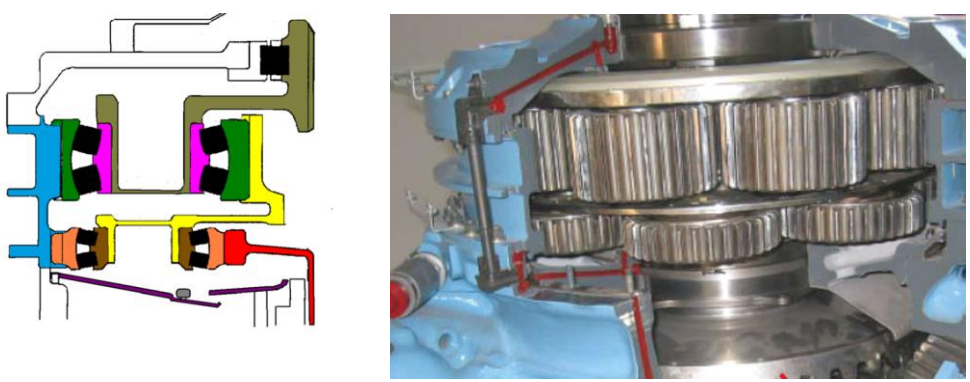
AGB Lower mag plug: Macro lens photo



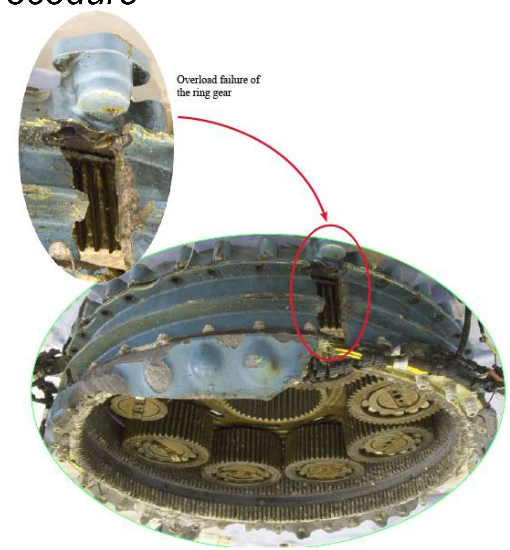
Lower mag plug: SEM image

Case Study: Super Puma G-REDL 2009

- Eurocopter AS332L2 Super Puma G-REDL main gearbox failure 2009 [1], [2]
- Ruptured planet gear caused catastrophic failure of gearbox
- Main rotor separated – fatal accident 16 killed
- Wear debris precursors were present – incorrectly diagnosed
- Noted from report on the AMM WDA process: *"No illustrations or photographs of representative particles, to aid the process of identification, are included in the procedure"*



Eurocopter AS332L2 Super Puma main gearbox epicyclic gear set

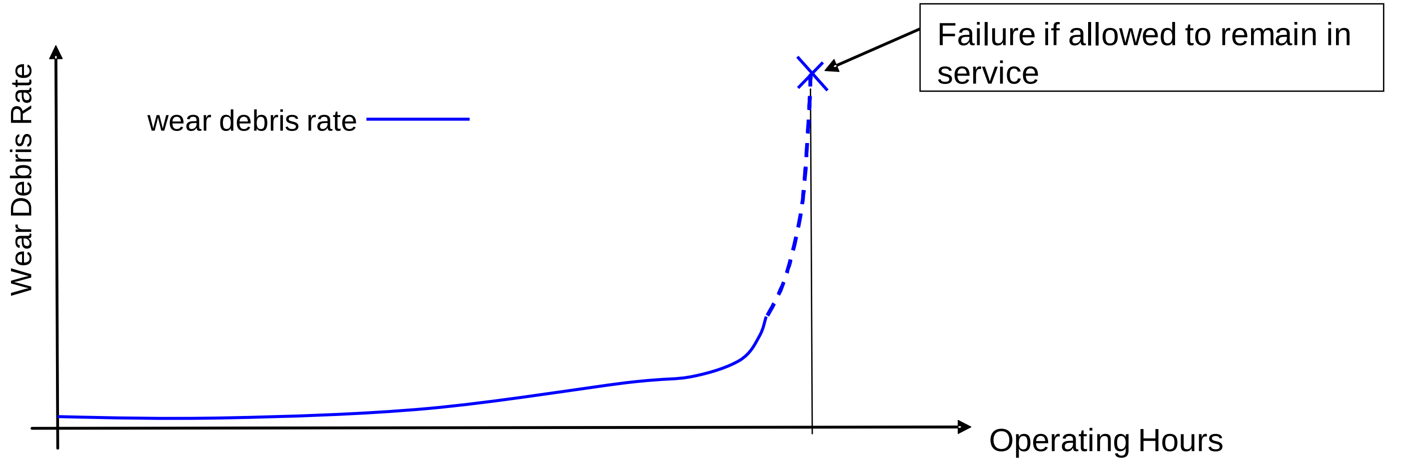


Failed Eurocopter AS332L2 Super Puma G-REDL main gearbox

[1] UK AAIB Special Bulletin: 5/2009 – Eurocopter AS332L2 Super Puma, G-REDL, North Sea, 2009.
[2] UK AAIB Aircraft Accident Report 2/2011: Report on the accident to Aerospatiale (Eurocopter) AS332 L2 Super Puma, registration G-REDL 11 nm NE of Peterhead, Scotland on 1 April 2009.

Summary Serviceability Assessment

- Primarily based on MCD findings
- Inspection criteria can be ambiguous
- In general, basic WDA systems and serviceability focus on confirmation of failures in late stages
- Refinement of process is operator dependent



DTA Development – Filter Debris Analysis

- Filters contain valuable wear debris data
- Potential to provide significant lead time to failure over MCDs alone [3]
- Advantage – applicable to all fleets without modification
- FDA under utilised
  - Time consuming
  - Limited guidance
  - Lack of capability to extract and analyse debris
  - Visual inspection of filter pleats inadequate to reliably detect bearing spall particles (200 µm)

[3] Toms, A., GasTOPS Inc., Jordan. E., and Humphrey, G., "The Success of Filter Debris Analysis for J52 Engine Condition Based Maintenance", AIAA-2005-4338, 41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Tucson, Arizona, July 10-13, 2005.

FilterCHECK FC400

- RNZAF procured GasTOPS FC400 in 2009 on DTA advice
  - Automatic debris extraction
  - Quantifies debris (Inductive sensor)
  - Produces debris patch for further analysis (if needed)
  - XRF system can provide aggregate composition (NOT used)

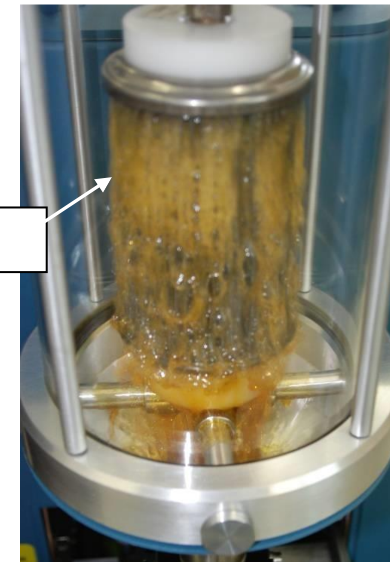
- DTA developed analysis processes/limits [4]

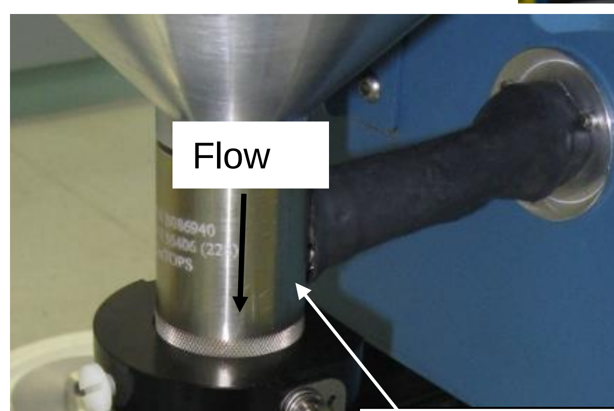
- RNZAF routinely sample filters for trending
  - Reduced inspection interval trending if defects detected

[4] Weller, A.J. Defence Technology Agency, New Zealand Defence Force, “Enhancing Propulsion System Condition Monitoring for the RNZAF”, AIAC14 Fourteenth Australian International Aerospace Congress, Melbourne, Victoria, Australia, 2011.

FilterCHECK FC400 -Debris extraction

- Consistent extraction method - Only variables are:
  - Time on filter
  - Amount of debris
- MetalSCAN sensor output:
  - Particle count
  - Particle size / Type (Ferrous or Non Ferrous)
- Debris rate derived from hours on filter
  - Primary trend metric

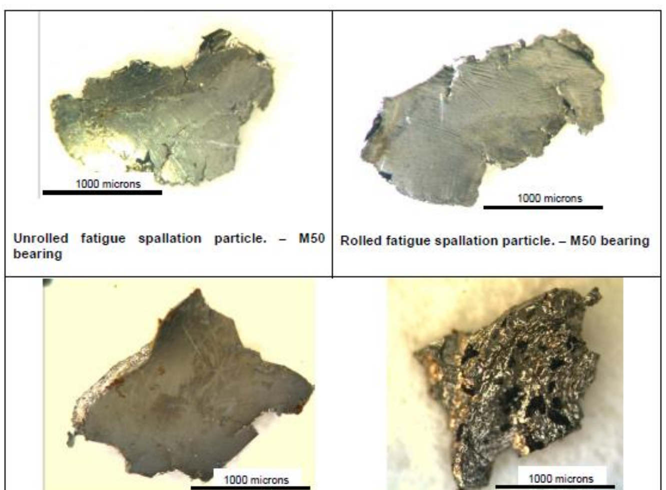




FilterCHECK FC400 –Debris Patch

- All debris collected above 60 µm in size on filter patches

- Debris Patches reviewed by RNZAF
  - Morphology inspection via optical microscope
- DTA developed visual inspection guidance used

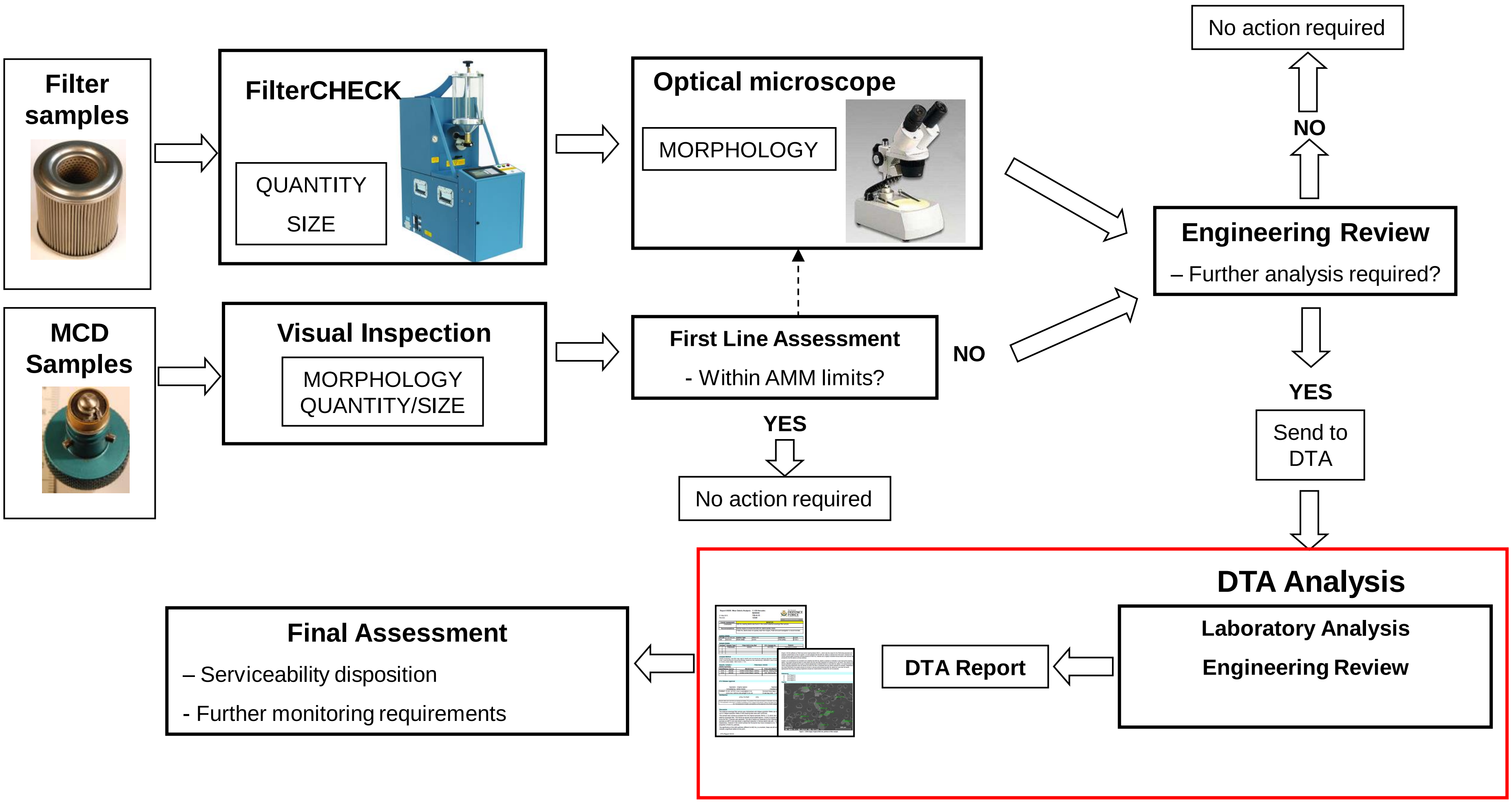


Unrolled fatigue spallation particle. – M50 bearing

Rolled fatigue spallation particle. – M50 bearing

Unrolled fatigue spallation particle. – M50 bearing
Left: showing original bearing surface. Right: showing opposite side fracture surface.

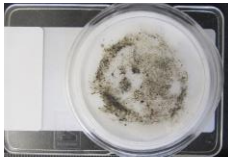
RNZAF/DTA Wear Debris Analysis Process

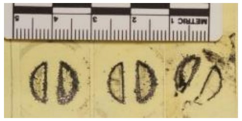


DTA Wear Debris Analysis Process

Sample received

- Filter patch
- MCD sample
- Sample details

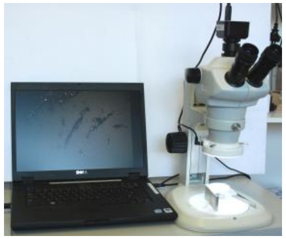




Optical Microscope

Detailed assessment of Morphology (50 X)

Remarkable debris present?



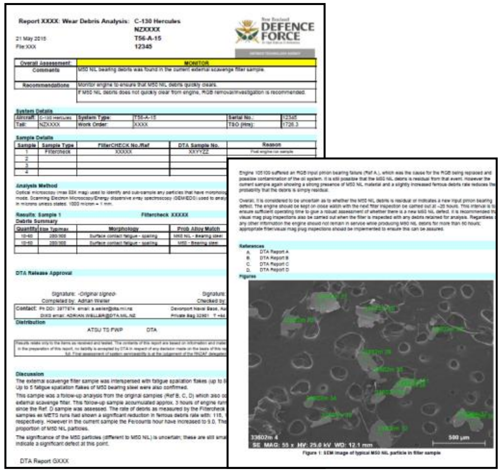
NO

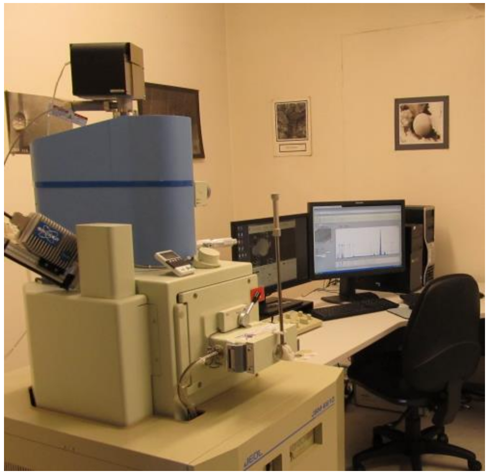
DTA Report

- Nil remarkable debris

YES

Extract representative subsample for SEM/EDS analysis


Report XXXX: Wear Debris Analysis: C-130 Hercules



SEM

Detailed assessment of Morphology

EDS

Composition of each particle assessed

Determine match to component Metal Maps

DTA Corp Knowledge

Physics of failure

System specific data

Failure case studies

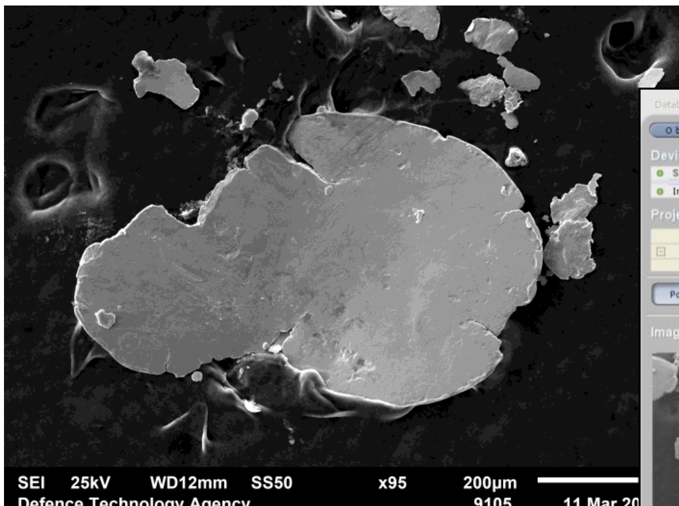
Mechanical and materials engineering

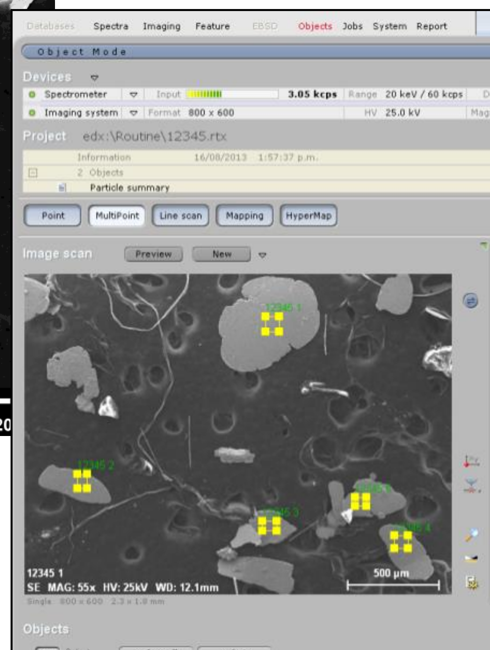
DTA Report

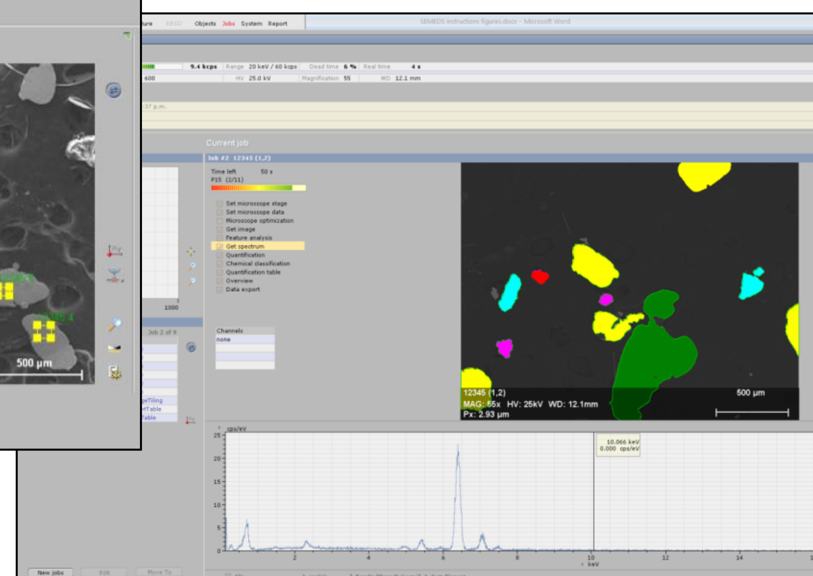
Detailed debris Summary

DTA Wear Debris Analysis Process

- Scanning Electron Microscope (SEM) - morphology analysis
- Energy dispersive x-ray spectroscopy (EDS) - elemental composition



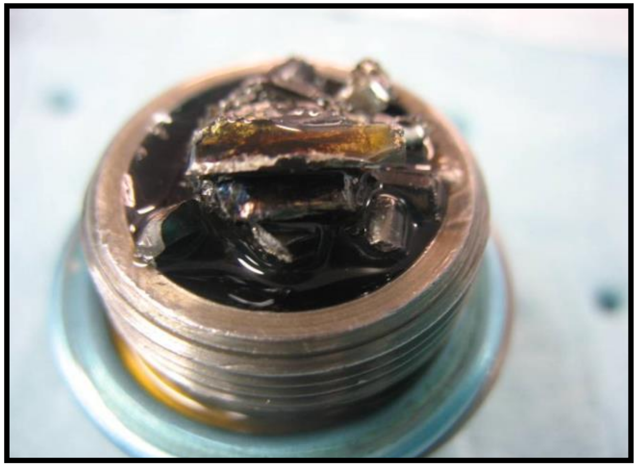


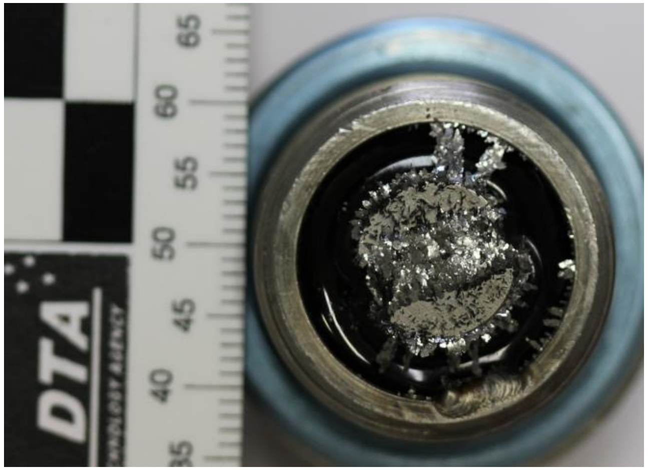


Case Study – T56 Reduction Gearbox (RGB) Pinion Bearing

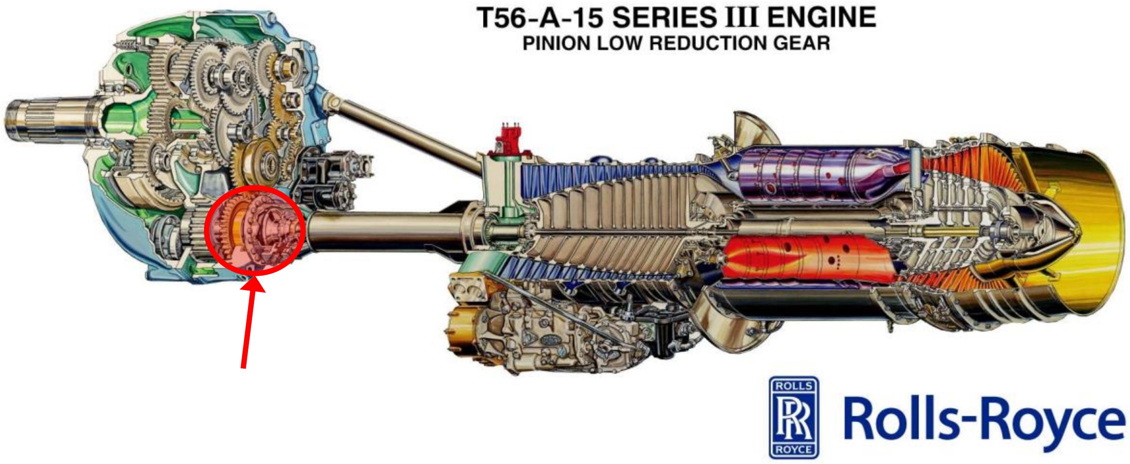
- Cruise FL280
- No. 1 engine Torque and RPM fluctuations
- Excessive red fluid streaming from engine
- Engine shutdown – return to origin
- Un-eventful landing after 4 hours on 3 engines

Case Study – T56 RGB pinion bearing



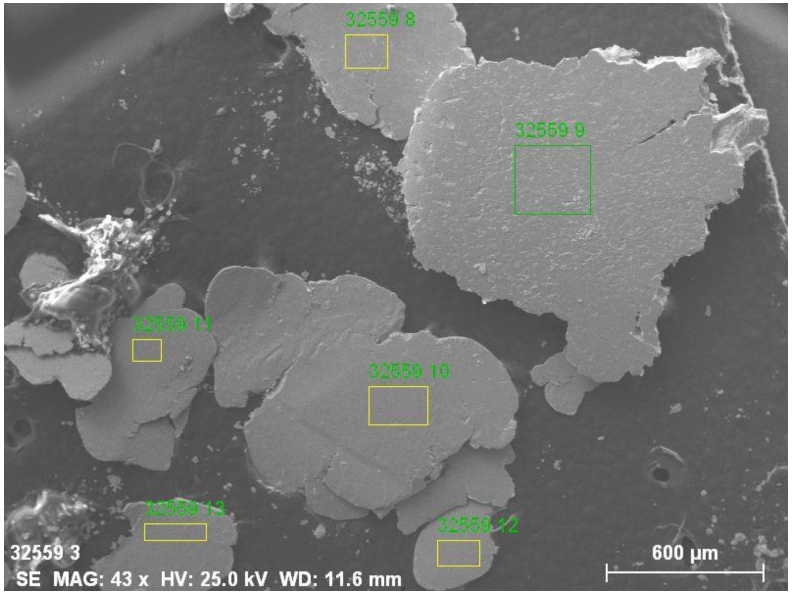


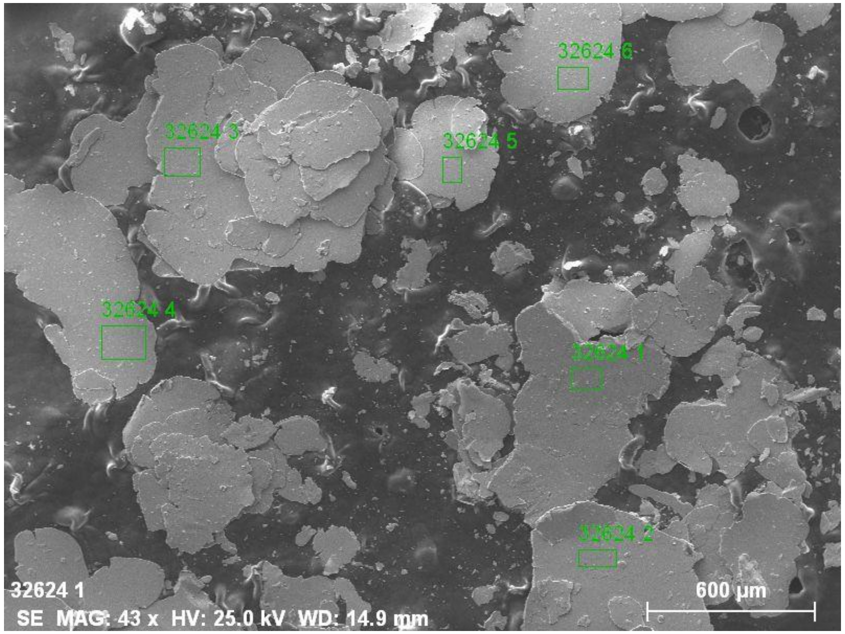
Magnetic Chip Detector Debris (Post Failure)



Case Study – T56 RGB pinion bearing

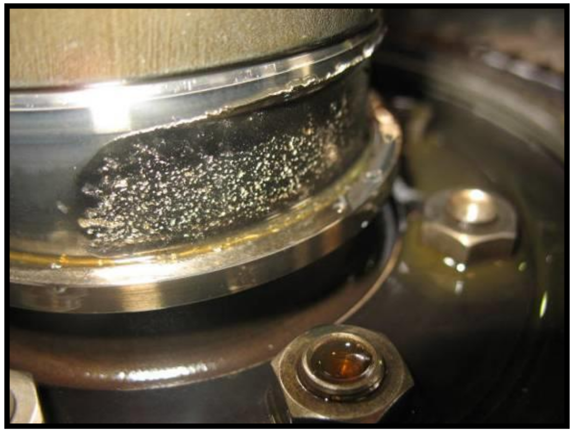
- SEM/EDS Analysis sample at failure:
  - M50 NiL bearing steel (AMS6278) – Match to pinion bearing
  - 9310 (AMS 6265) gear steel fragments





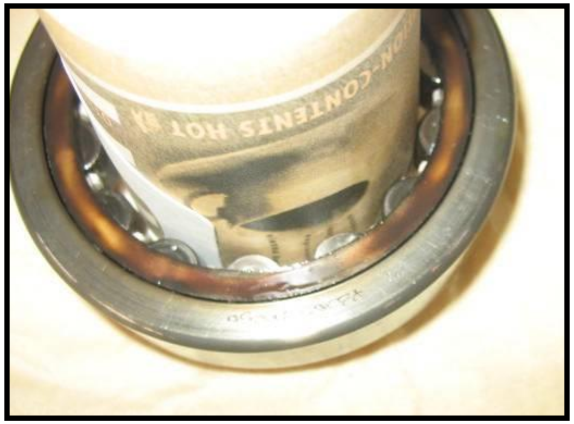
Magnetic Chip Detector Debris (Post Failure)

Case Study – T56 RGB pinion bearing



Rear Pinion Bearing Inner Race

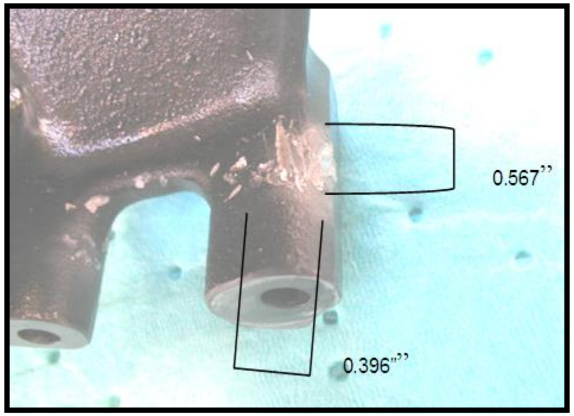
Pinion Rear Bearing



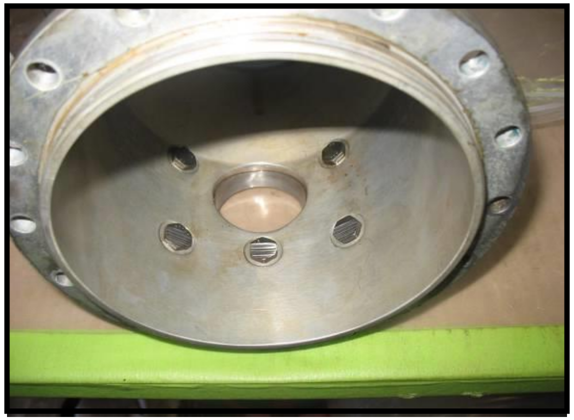
Bearing Cage Heat Damage

Pinion Rear Bearing Rolling Element

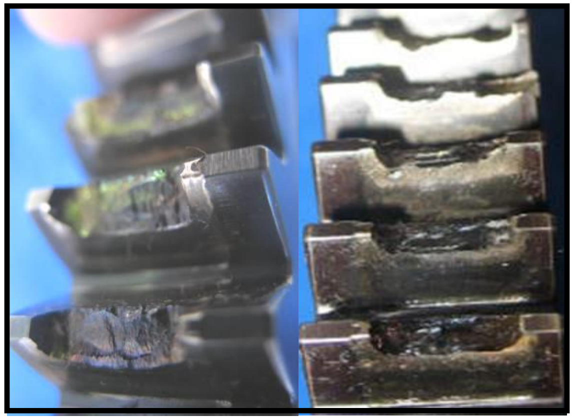
Case Study – T56 RGB pinion bearing



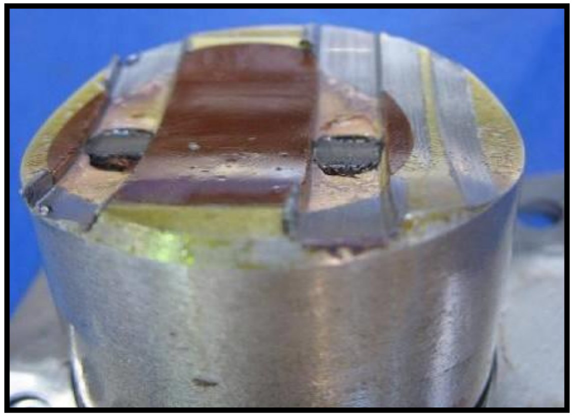
Inner Diaphragm Damage



Torque-meter Housing



Main Accessory Gear Damage



Torque-meter Pickup Gouging

Case Study – T56 RGB pinion bearing

- SEM/EDS analysis 250 hours prior to failure
  - Mag plugs assessed as within limits

Report [redacted]: Wear Debris Analysis: C-130 Hercules

[redacted]

T56-A-15

[redacted]

File: [redacted]

Defence Technology Agency

Overall Assessment:	**ADVISORY**
Comments	M50 NiL bearing debris was found indicating a surface contact fatigue defect. M50 NiL material is only known to be used for the RGB input pinion bearing.
Recommendations	Investigate source of debris.
	Review all maintenance data including any other mag plug inspections/samples to isolate source of debris or determine if debris is residual from previous event etc.

System Details

Aircraft:	C-130 Hercules	**System Type:**	T56-A-15	**Serial No.:**	[redacted]
Tail:	[redacted]	**Work Order:**	[redacted]	**TSO (Hrs):**	1478.6

Sample Details

Sample	Sample Type	FilterCHECK No./Ref	DTA Sample No.	Reason
1	Filtercheck	[redacted]	[redacted]	FilterCHECK: Advisory Morph
2				
3				
4				

Analysis Method

Optical microscopy (max 50X mag) used to identify and sub-sample any particles that have morphology indicative of a potential critical wear mode. Scanning Electron Microscopy/Energy dispersive x-ray spectroscopy (SEM/EDS) used to analyse individual particles in detail. Size listed in microns unless stated. 1000 micron = 1 mm.

Results: Sample 1 **Filtercheck** [redacted]

Debris Summary

Quantity	Size Typ/max	Morphology	Prob Alloy Match	Comments
100+	200/1000	Surface contact fatigue - spalling	M50 NiL - Bearing steel	
1-10	500	Surface contact fatigue - spalling	SAE 9310 Gear/shaft Steel	

Figures

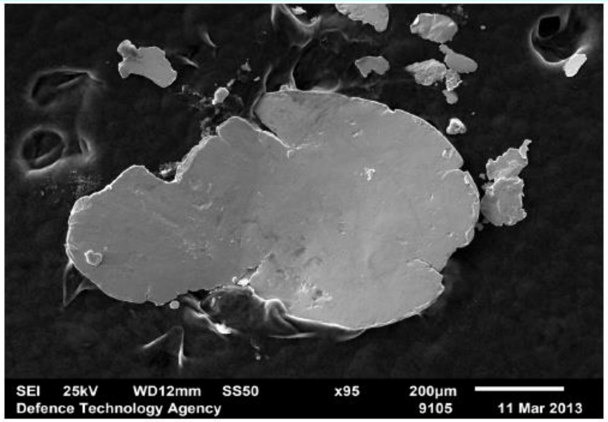


Figure 1: SEM image of largest M50 NiL particle

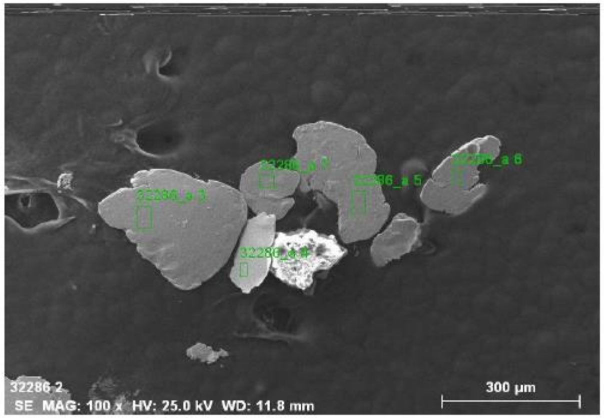
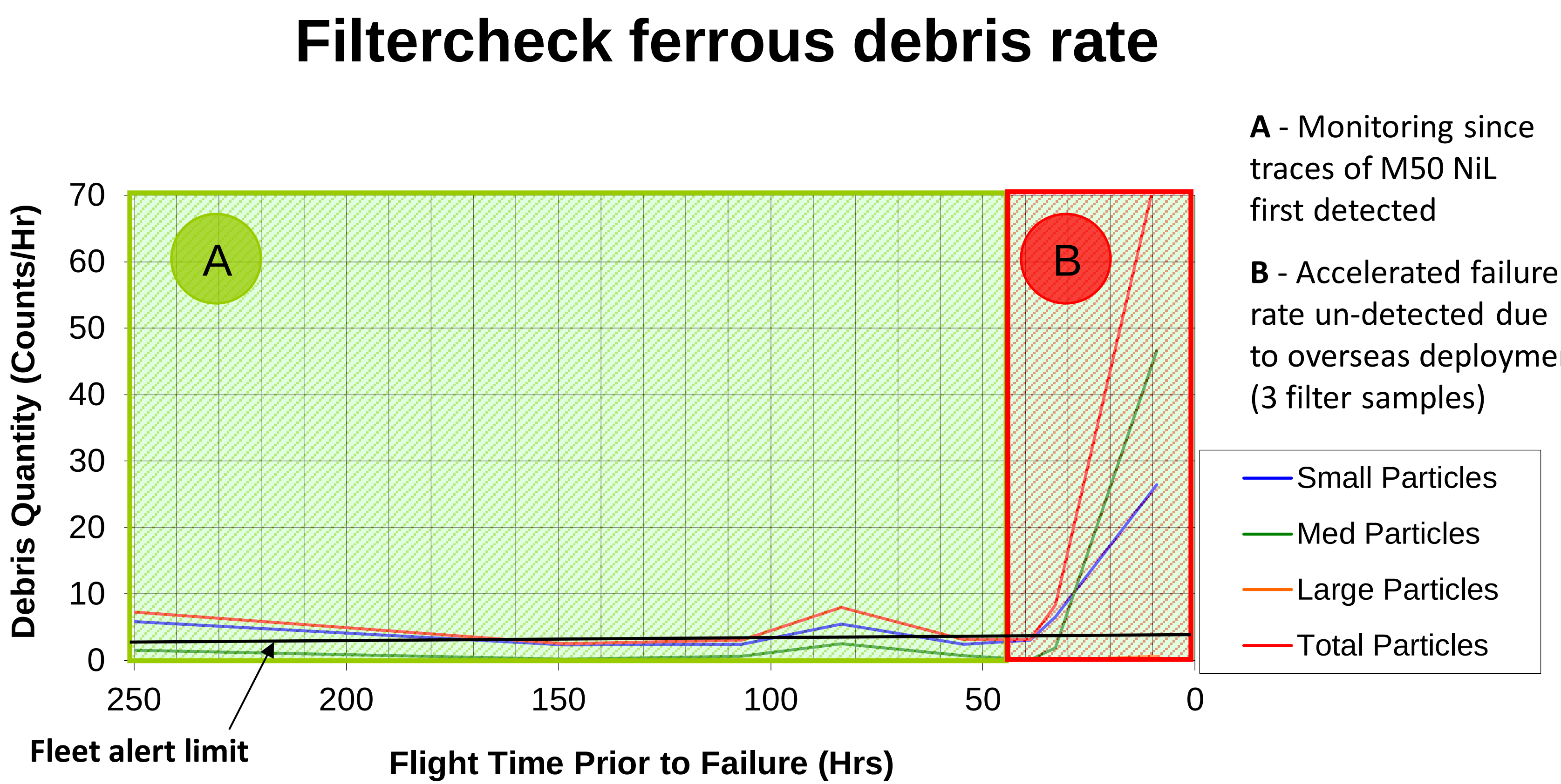


Figure 2: SEM image of typical M50 NiL debris

Case Study – T56 RGB pinion bearing



Fleet alert limit

σ + 3 S.D

A - Monitoring since traces of M50 NiL first detected

B - Accelerated failure rate un-detected due to overseas deployment (3 filter samples)

FDA Case Studies – Examples of catches

- RB211-535 – Detected power take off shaft steady bearing failure
  - Allowed repair on-wing
- RB211-535 – Pre first B757 Antarctic flight - detection of major bearing defect
  - Avoided flight safety risk/unscheduled engine change
- T56 – multiple reduction gearbox defects detected allowing scheduled intervention
- T56 – numerous cases detecting starter magnetic seal failures
  - Allowed on-wing repair
  - Avoided unnecessary engine removal

DTA Work: Advancing WDA

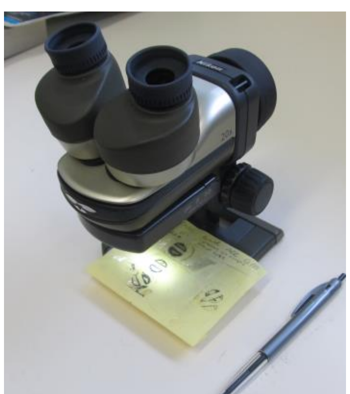
- Desire to standardise WDA to:
  - Allow more robust assessment of component health
  - Give guidance to operators
  - Provide standard means of analysis for laboratories
  - Provide a basis for OEMs to standardise AMM methods and inspection criteria
- DTA through TTCP nations produced FDA guidance document
  - None existed prior
- Covers:
  - Robust methods for debris extraction from filters
  - Analysis methods and requirements for detection of component defects
  - Interpretation guidance

DTA Work: Advancing WDA

- TTCP FDA document adapted and published by ASTM (2014)
  - Designation: D7898 − 14
  - “Standard Practice for Lubrication and Hydraulic Filter Debris Analysis (FDA) for Condition Monitoring of Machinery”
  - Covers debris extraction, analysis and reporting
  - Intended for aircraft systems (also applicable to wider machinery)
  - Includes simple manual methods and automated methods
- Future work planned to develop more comprehensive standard practice for all wear debris analysis

DTA Work: Advancing WDA

- Reviewing new analysis technology to enable deployed WDA
  - Strong need to have accurate serviceability assessment without delays
- Portable elemental analysis
  - X-ray fluorescence
  - Laser-induced breakdown spectroscopy (LIBS) based
- Portable microscope image capture systems
  - Compact microscopes
  - Digital imaging techniques



Summary

- Legacy MCD based AMM inspection methods/criteria:
  - Robustness of assessment heavily dependant on operator competency
  - WDA assessment process is variable between OEMs
  - Generally aimed at confirming late stages of a failure (Often insufficient warning to prevent unscheduled maintenance)
  - Inspection criteria is typically vague and can lead to incorrect assessment
  - Delay in accurate analysis can incur flight safety risk
- RNZAF WDA programme
  - Underpinned by DTA SEM/EDS capability and corporate knowledge
  - Augmented by filter debris analysis - has proven to detect significant proportion of defects with increased lead time
  - Future work to focus on enhancing deployed WDA capability
- DTA WDA Advancement Recommendations
  - Industry wide standards needed to improve and standardise WDA best practice amongst OEMs and operators
  - FDA ASTM standard D7898 − 14 is now in place
  - Civil aviation is encouraged to participate in future WDA standards development work!
- Failure investigations
  - Consider MCDs and filters and residual internal debris Fe and Nfe – very few failure modes produce no wear debris
  - Ask the question was robust WDA conducted?