Please select category below:
Normal Paper ☒
Student Paper ☐
Young Engineer Paper ☐

An Overview of Australian Defence Force Wear Debris Analysis

Dr Andrew Becker[1], SQNLDR James Walduck[2] and FLGOFF Paul Noceja[2]

[1] *Aerospace Division, Defence Science and Technology Group, 506 Lorimer Street, Fishermans Bend, Victoria, 3207 Australia*
[2] *Propulsion Systems Integrity, Defence Aviation Safety Authority, 661 Bourke St, Melbourne, Victoria 3000, Australia*

Abstract

Wear Debris Analysis (WDA) refers primarily to the analysis of metallic particulate recovered from aviation propulsion system lubrication systems via magnetic chip detectors, screens or filters. The aim of WDA is twofold: first to ensure the health of the critical load-bearing components serviced by the lubrication system (generally gears and bearings) and secondly to ensure engines and gearboxes are only removed when necessary, thereby saving significant overhaul and unplanned maintenance costs. The Defence Aviation Safety Authority (DASA) is responsible for this capability, however the Defence Science and Technology Group (DSTG) have been the custodian for several years. DSTG provide the specialist technical expertise, training and facilities to enable this specialised analytical laboratory to provide rapid feedback to any ADF aircraft operators. DSTG and DASA have also investigated the in-field analysis of wear debris for aircraft operating in remote locations, from ships at sea or hostile environments. This paper will explain the capability, facilities and current and near-term WDA activities relating to Australian Defence Force (ADF) aircraft.

Keywords: wear debris analysis, aviation, propulsion systems, in-field

Introduction

Wear Debris Analysis (WDA) refers to the analysis to determine the source and significance of metallic debris recovered from aircraft lubrication systems. WDA initially involves the recovery of metallic debris through in-built systems such as magnetic chip detectors (MCDs) or filters within an oil system. Effective WDA typically focuses on the quantity, size, elemental composition and morphology of the debris combined with an understanding of aviation propulsion systems. The results then enable an informed decision to be made regarding the immediate condition of critical load-bearing components in the propulsion system. The results may also support longer term reliability, diagnostic or prognostic aims. Similarly, analysis of debris from aircraft hydraulic systems is also conducted by this laboratory.

For the majority of aircraft applications an emphasis is placed on the identification of critical alloys used for load-bearing dynamic components such as bearings and gears. The ability to trace the origin of recovered debris to a particular component is made possible only through the use of specialised equipment that is able to determine elemental composition (e.g. Scanning Electron Microscopes). Results can be cross-referenced with 'metal maps' that are a list of the elemental composition of oil-wetted components provided by the propulsion system Original Equipment Manufacturer (OEM). In most cases the OEM also identifies the critical bearing and gear alloys in a flow chart contained in the maintenance manual.

There are three main benefits of WDA. Firstly, the ability to determine the serviceability of critical components directly links to improved safety outcomes through informed decision making. Secondly, WDA can be used to identify impending failures of critical components by way of analysing trends; this can assist with fleet planning and deployment of specific aircraft. Thirdly, being aware of the condition of load-bearing components means that life cycle costs can be reduced by avoiding the unnecessary and expensive replacement of components, or worse, execution of engine overhauls.

The WDA process detailed above has a significantly different focus when compared to routine oil analysis which typically employs Spectrometric Oil Analysis (SOA). While SOA also seeks to detect metallic particles in lubricated systems, its upper particle detection limit of approximately 10 microns means the value of this technique is severely compromised. Since contact fatigue is the primary (and life limiting) damage mode of gears and bearings, and the particle size range from a fatigue spall is typically in the 50-1000 microns range, WDA is more appropriate. The detection limitation of SOA results in uncertainty about the significance of the results and makes it difficult to make serviceability decisions. SOA results are therefore often limited to guidance or identification of longer term trends. It has also been shown that fine filtration of aircraft propulsion lubrication systems will also limit the effectiveness of SOA [1]. Aircraft OEMs have understood the criticality of accurately assessing wear debris for a long time, which is why strict limits are typically mandated for wear debris captured by MCDs and not SOA.

ADF Wear Debris Analysis

The Military Context

The nature of military operations presents particular challenges for the conduct of WDA. Factors that differentiate military WDA from commercial analysis include:

1. Overseas deployments (e.g. helicopter operating from a ship at sea).
2. Operations in remote or inhospitable environments (e.g. aircraft operating from remote airstrips); and
3. Significant time constraints for obtaining results (e.g. the expectation for aircraft to be serviceable on-demand during exercises or disaster relief efforts).

Combined with these factors is that there has traditionally been little or no in-field support for WDA, which has led to unfavourable scenarios when wear debris is actually detected. Experience has shown that debris may present itself at any time, location or operational context. Therefore the impact of not being able to make an informed decision about propulsion system serviceability has both cost and operational consequences. Some examples experienced by the ADF are presented later in this paper.

The Current ADF Approach

Metallic debris recovered from ADF aviation propulsion systems is currently analysed in a centralised laboratory at DSTG in Fishermans Bend, Victoria. The laboratory has been run by DSTG on behalf of the Defence Aviation Safety Authority (DASA) since 2015, following the closure of the Non Destructive Testing Standards Laboratory (NDTSL) Metallurgy Lab at RAAF Amberley. DSTG assumed this role as an interim solution as it possessed the skills and equipment required to conduct this analysis. At the time, an assessment of commercial services identified no viable alternatives and has resulted in DSTG continuing to provide this function. However, the capability is now currently being transitioned to industry. Most samples sent to the lab require immediate analysis to enable aircraft serviceability to be determined. The ADF WDA Lab has three priority timeframes:

1. 48 hours: this is the most common priority and results in an immediate analysis of the debris. Most samples with this priority are completed well within a few hours, however occasionally more complex samples are received and require the full 48 hours.
2. 7 days: this priority is used where a sample is important but may not necessarily be required for clearance of an aircraft to fly. For example, other unrelated circumstances mean the aircraft is not immediately required.
3. 14 days: This priority is typically only used where an aircraft has generated debris and is entering an extended maintenance period.

Being a centralised lab means the physical samples must be sent to the lab and this usually represents the primary delay in releasing results. Additionally, aircraft operating from ships at sea may have to wait until the next port to send the debris resulting in further delays.

Not only is the ADF WDA Lab highly focused and specialised, it also offers filter debris analysis (FDA) in accordance with ASTM 7898 [2], a service not offered in commercial labs. FDA involves extracting debris from filter elements (typically scavenge/return filters as they hold the most debris information) for analysis. Whilst cumbersome to remove from aircraft propulsion systems, filters capture the vast majority of solid debris and can provide high fidelity information about the presence and/or severity of incipient damage. When decisions have to be made regarding expensive and time consuming engine or gearbox removals, a filter element can provide additional confidence that the decision to remove the component is appropriate. However, a filter’s capacity to capture the majority of debris also makes the analysis more difficult and time consuming. Care must be taken during the extraction process to identify the significant debris amongst the general detritus. It is possible to undertake rudimentary FDA in the field with care; however, simply looking for debris in the filter element pleats is not sufficient and a proper extraction is required to produce high fidelity results.

A New Approach

While there will remain a need for a centralised lab with the requisite skills and technical knowledge for WDA, it became clear that improvements could be made. In 2018, DSTG and DASA agreed to investigate in-field options for providing WDA for ADF aircraft deployed or operating in remote locations. Primary criteria for any device to be selected for WDA in the field were:

1. It had to be portable to enable it to easily accompany aircraft operating in remote locations.
2. It had to identify the composition of the debris so that the likely origin could be identified and therefore, enable an accurate assessment of criticality.
3. It had to have a low training burden. In other words, it had to be intuitive to use without the need for an extensive training course.

A market survey identified three potential candidates that all used different technologies to determine composition.

The first to be rejected was a portable ruggedized X-ray Fluorescence device (XRF). This device had been developed for geologists to use in the field and used a narrow beam x-ray to excite specimens for spectroscopy. Whilst the technique provided composition information, it was rejected because even with a narrow beam x-ray, particle discrimination was problematic.

Additionally, the administrative and regulatory burden of an x-ray device was onerous. The spectral resolution of an XRF combined with poor light element detection were also considered negatives.

The second device to be rejected was a benchtop scanning electron microscope (SEM) specifically marketed for WDA. This device was assessed as being technically suitable for conducting WDA in a fixed laboratory environment (such as at a base) but was not considered feasible for deployments or operating in remote or hostile environments. Additionally, there were questions about the training of ADF staff who would use this intermittently.

The device selected for further evaluation was ChipCHECK, which uses Laser Induced Breakdown Spectroscopy to determine composition. This process uses a laser to ablate the first few nanometres of the particle's surface to enable spectroscopy to occur. Contrary to some misconceptions, the laser does not destroy the particle. Figure 1 shows some relatively soft silver (Ag) plating material recovered from a gearbox and shows that after analysis the particles are not significantly damaged; the small dots indicate where the laser has been applied. The ChipCHECK instrument is rated as a Class 1 laser device meaning there are no specific safety or regulatory requirements. Despite the device housing a Class 4 laser it is classified as a Class 1 as it is fully enclosed with multiple interlocks.

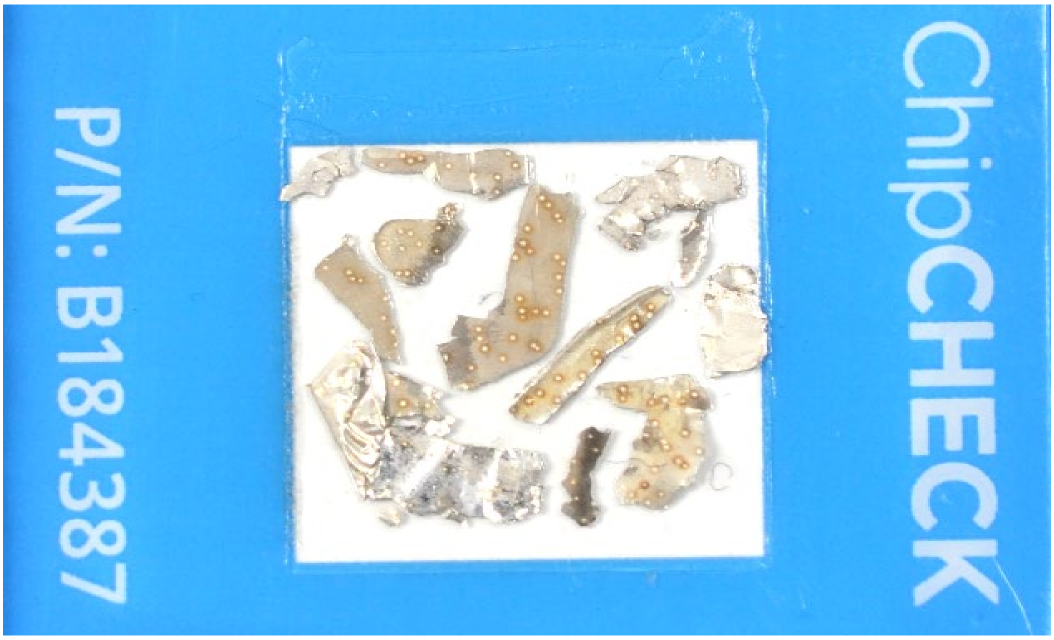

Figure 1: Sample of silver (Ag) plating showing where the laser has ablated the surface during analysis in the ChipCHECK.

The resulting spectrum is then automatically compared to a library of a limited number of critical alloys commonly found in aviation propulsion lubrication systems. This device is specifically designed to be portable for deployed operations and has a low training burden. The instrument also provides size, area and quantity details about the debris being analysed. For the first phase of the evaluation one unit was purchased and assessed using samples of known alloys in a size range comparable to typical wear debris (i.e. 200 to 1000 microns, noting that ChipCHECK can resolve down to 80 microns). The second phase involved an in-field evaluation where the device was used by ADF maintainers in various operational environments. For example, a ChipCHECK was used on-board one of the Royal Australian Navy's Canberra Class ships during Exercise Talisman Sabre. The instrument performed well and a separate report was written about experiences in the field.

DASA funded a second unit with the intention that one would be used at operational bases and the other used by DSTG. In fact both units have been extensively used in the field since acquisition, including support for aircraft operating during Victoria's 2020 bushfire emergency. Currently, one unit remains supporting MRH90 helicopters while the other unit is located at RAAF Amberley and available for use by aircraft based there as part of a six month trial. Both the Royal Australian Navy (RAN) and the Australian Army have now acquired several ChipCHECKs to support aircraft operating in remote locations.

Examples

The following examples demonstrate where an in-field capability provides (or would have provided) a significant benefit. The cost-benefit equation is very clear for aviation propulsion systems. Saving a single unplanned removal of an assembly (e.g. gearbox or engine) and overhaul will pay for the device. The removal, overhaul and reinstallation effort involved would typically run into the hundreds of thousands of dollars. Add to this the operational impact of having an aircraft unserviceable for an extended period of time and the need for in-field analysis to augment a centralised lab is further made obvious.

Example 1: RAN helicopter

While operating from a RAN frigate in the vicinity of Hawaii in 2020, a metallic chip was recovered from the magnetic chip detector fitted to a helicopter tail rotor gearbox. With no way of assessing the chip on board (apart from measuring the size) the aircraft remained grounded. Analysis of the chip was conducted by a local laboratory while the ship was alongside in Hawaii. The rudimentary analysis was inadequate and could not be used to make any maintenance or operational decisions (Figure 2). The technique used by the lab was X-Ray Fluorescence (XRF) and the reported results did not provide sufficient information to identify the alloy. Eventually the gearbox had to be opened for visual inspection revealing contact fatigue spall on the drive side of the input pinion tooth (Figure 3) requiring replacement of the gearbox. Had an in-field wear debris analysis capability been available, the alloy (a common aviation gear steel) would have been identified immediately, confirmed as a serious fault and would have saved several days of effort.

Analysis/Service Requested: Material Identification
Remarks: MH-60R, BUNO
Type of Analysis: Material Identification

Sample Number: C001
Laboratory analysis by QuantX-EDXRF per SOP-212 indicates that magnetic chip (0.140 x 0.090 inch) consists primarily of iron with lesser amounts of chromium, nickel, and copper.

Figure 2: Extract of chip analysis report obtained from a laboratory in Hawaii that proved to be inadequate. No substantive text has been left out – only the identifying details of the aircraft have been redacted.

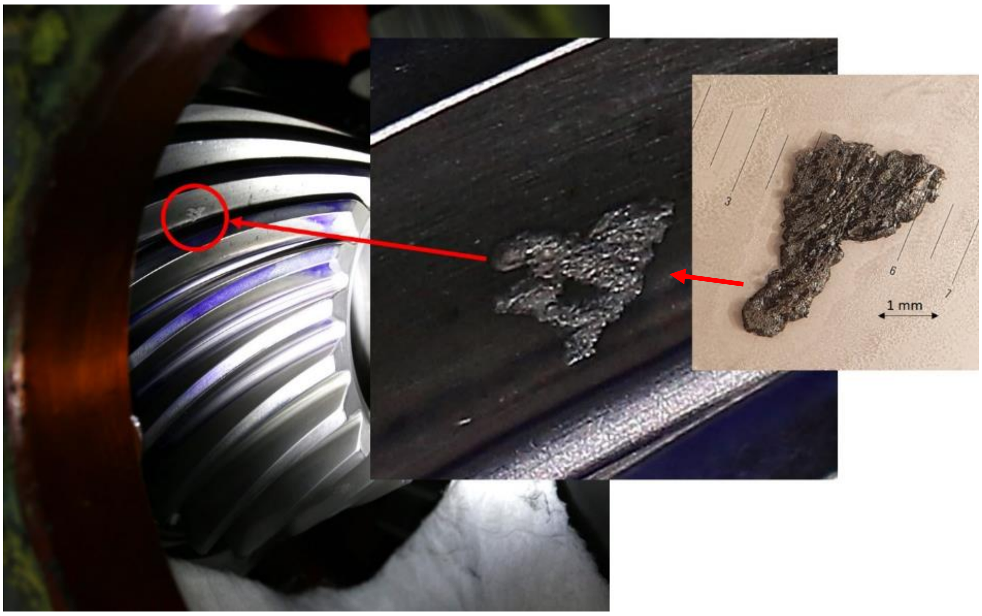

Figure 3: Spiral bevel pinion showing spalled tooth, magnified spall area and debris

Example 2: RAAF CFM56 Engine Debris

In 2020, the ADF WDA Lab completed wear debris analysis for a CFM56 engine fitted to a maritime reconnaissance aircraft. Three relatively large flakes were recovered from the Transfer Gearbox magnetic chip detector screen and filter element. Analysis of the debris clearly identified the debris as silver (Ag) plating material (Figures 4), likely to have been liberated from a bearing cage. The debris had been despatched via courier from RAAF Base Edinburgh to the ADF WDA Lab in Melbourne (more than 700 km away) and was processed immediately upon receipt. An in-field WDA capability located at the base would have identified the composition in hours, as opposed to the 3 days required for this sample. The engine OEM wear debris guidance mandates that any number of particles over 0.5 mm (which all of these were) must be sent for laboratory analysis. Until the results are obtained, the engine can remain on wing provided a 10 minute ground run is undertaken and the magnetic chip detector examined before every flight [3].

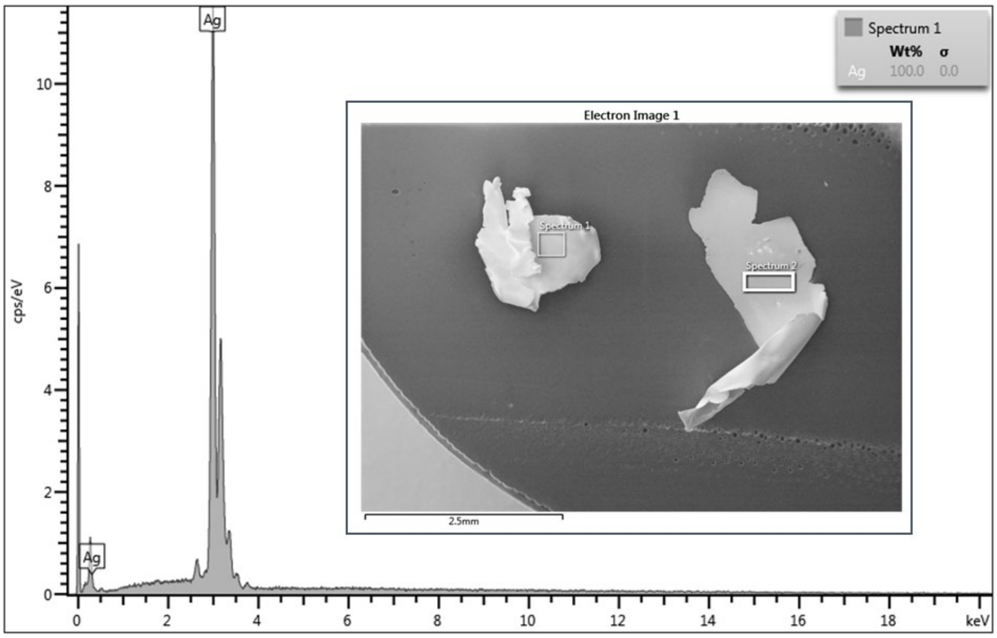

Figure 4: Scanning Electron Microscope spectrum and image (inset) of one of the particles analysed showing pure silver (Ag) typical of bearing cage plating material

Example 3: Australian Army Helicopter

The ADF WDA Lab has provided significant support for Australian Army helicopters over many years. In February 2019, a single chip was recovered from an Australian Army helicopter main rotor gearbox and sent to the ADF WDA Lab for analysis. The chip was a perfect example of a contact fatigue particle liberated from a gear tooth. The particle showed the characteristic smooth machined surface on one side and a rough surface on the reverse side (Figure 5) where the sub-surface fatigue crack had propagated. The rough surface also clearly showed the classic fatigue progression features often referred to as 'beach marks'. These marks appeared to radiate from an initiation point and were likely the result of an inclusion in the steel. Unfortunately the initiation cause could not be conclusively determined as the OEM requested the particle be immediately sent back to them. The material composition was confirmed as a gear steel for this aircraft type and after further investigation the gearbox was removed from the aircraft. A 'textbook' example of a fatigue particle is rare since they are invariably damaged by successive meshing teeth during liberation.

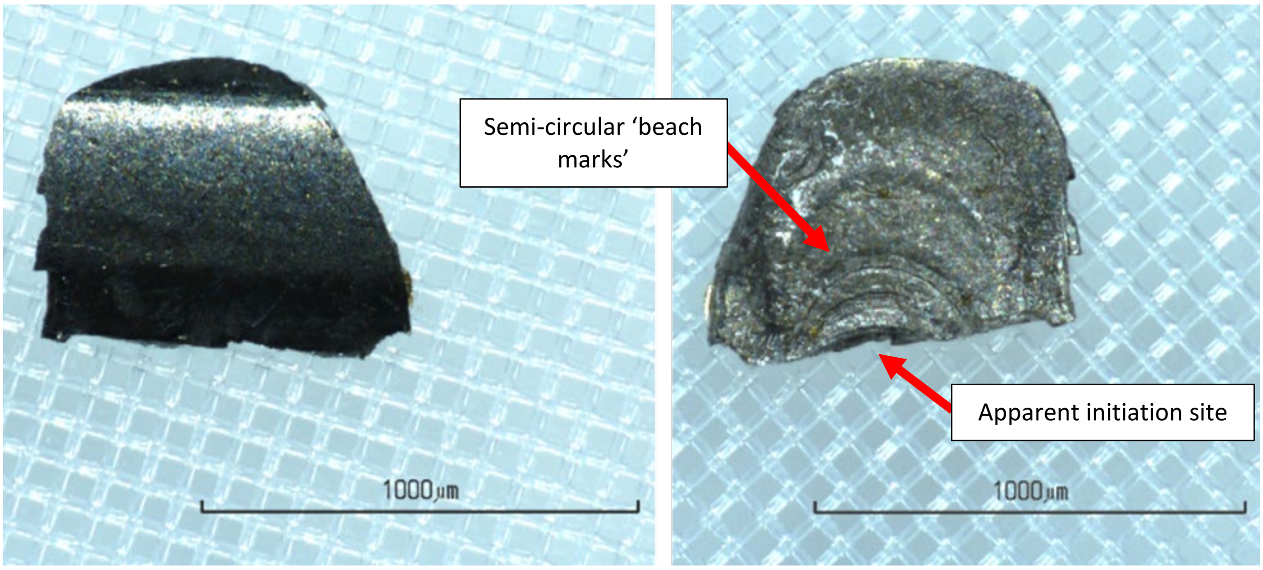

Figure 5: Image of the gear tooth chip showing the smooth machined surface (right) and the rough crack propagation surface (left) with classic fatigue 'beach marks' appearing to radiate from an initiation site.

Example 4: Filter Debris Analysis

In 2021, a blocked auxiliary lubrication filter from a main gearbox of an Australian Army helicopter was sent to the ADF WDA Lab to identify the cause of the blockage. Extraction of the debris revealed that the filter was blocked with a significant quantity of magnesium oxide particles, with traces of cadmium oxide particles (Figure 6). The presence of this type of particulate indicated corrosion was likely to be active inside the gearbox. Corrosion of internal gearbox components can be a result of water (e.g. condensation from the atmosphere) causing the polyol ester lubricants to revert to their constituent acids (known as hydrolysis). Gearboxes and engines are particularly susceptible to this process when stored or used infrequently. Any water inside the gearbox will only be driven out if the gearbox is operated at the normal operating temperature. The acids cause corrosion of internal components, including casings (structural components), plated surfaces, and dynamic components (e.g. gears or bearings) since the latter are not made of corrosion resisting steels.

The subject gearbox had high hours and had been in storage for several years prior to the current installation. Oil analysis results showed a high Total Acid Number of 3.5 mgKOH/g where the in-service limit is 2 mgKOH/g. Similarly, routine oil analysis results showed a persistently high magnesium (Mg) level (e.g. 67.2 mg/kg) where typically the concentration would be less than 1.0 mg/kg in a healthy gearbox. This example demonstrates the value of conducting FDA to provide high quality information on which to base maintenance decisions. Internal corrosion is out of sight and difficult to detect unless techniques like FDA are available.

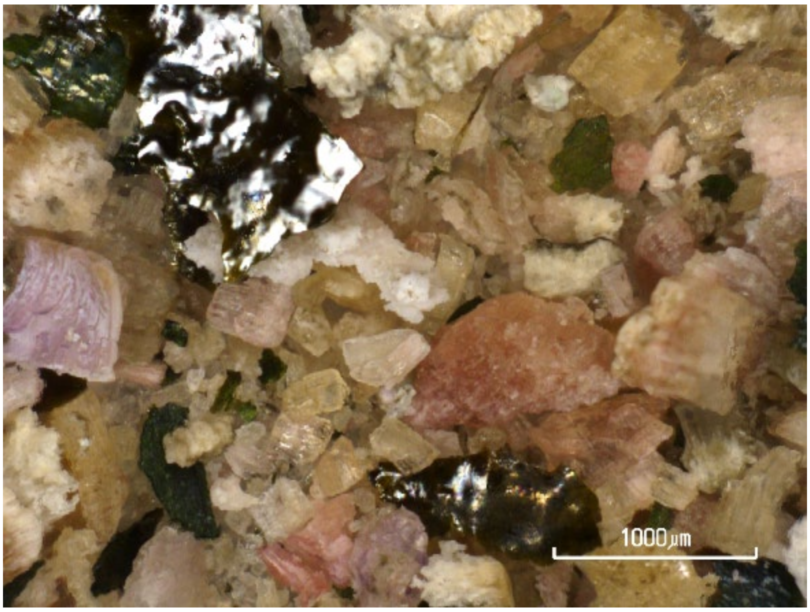

Figure 6: Magnified view of debris (primarily corrosion product) extracted from the auxiliary filter element (and after washing with isopropyl alcohol).

Where to next?

Although chip events are relatively rare, there have been instances where particular fleets have suffered inordinate indications that have caused significant operational difficulties. In one case, a particular helicopter fleet suffered 20 unplanned engine removals over a 6 year period due to chipping events that had a deeper more complex root cause. The ADF WDA Lab was able to support the rapid analysis of these chips and the subsequent investigation. In this case, an adverse reaction between the lubricant and another fluid was identified as the likely cause. FDA also played an important role in this case to provide high quality data and ensure engines were only removed if absolutely necessary. Even with a fully implemented in-field WDA capability, there will remain a need for a specialised laboratory to provide oversight of the in-field analyses and provide second tier analysis of unusual or inconclusive results.

At present, one capability ChipCHECK does not provide is high quality magnified images of the debris. The morphology (shape, surface features, colour, edge features etc.) can provide additional information about how the debris was formed. This is especially true where engines or gearboxes use traditional gear steels for other components. Morphological analysis can confirm that particles are from a fatigue event or otherwise. To enable high quality images to be taken in the field, a portable digital microscope is available to augment the ChipCHECK. The microscope selected was a Dino Lite USB microscope that is intuitive to use and has a maximum magnification of 200x, being suitable for most debris imaging requirements. This microscope has sufficient features to enable simple measurements to be made (e.g. Feret length or area) without being overly complicated. Ease of use was again a major consideration for this device.

Conclusion

WDA, when implemented effectively, is a key force enabler by way of supporting the unique demands posed by military operations. In particular, the need for effective and timely WDA becomes more critical when deployed in remote locations and when conducting shipborne operations. Several examples described in this paper demonstrate how a WDA capability (or lack thereof) has significantly affected Defence's ability to meet its objectives.

Recent developments in the market have enabled Defence to conduct in-field WDA, which focuses on the identification of critical alloys. The ability to quickly determine the characteristics of wear debris in the field (especially debris composition) is one that has not been available in the past. Examples one (RAN Helicopter) and two (RAAF CFM56 engine debris) illustrate where this capability would have had a direct positive impact to operations. DASA and DSTG are currently engaging with ADF units across the three services to establish an in-field WDA solution.

Even as new WDA technologies become more commonplace in Defence, it remains beneficial to have a dedicated laboratory that can retain corporate knowledge on the subject matter. Laboratories are also able to conduct deeper level analysis if needed (e.g. filter debris analysis) or provide confirmation of inconclusive in-field results. Examples three (gear chip liberation) and particularly four (conducting FDA) demonstrate where the ADF WDA laboratory involvement was appropriate and effective.

Finally, synergy is created between Defence and the ADF WDA laboratory through continuous identification of gaps and areas for improvement in the WDA capability. For example, it is likely that if a proactive relationship did not exist between a dedicated WDA laboratory and Defence, opportunities such as investigating potential in-field WDA solutions may not have been prioritised and actioned accordingly. Simply providing a material testing service is not enough in the military context. Therefore, by ensuring appropriate emphasis remains placed on (1) the maturation of an in-field WDA capability and (2) an ongoing positive relationship between Defence and the DSTG WDA laboratory, Defence can continue to benefit from timely and effective execution of WDA.

Acknowledgements

The authors would like to thank the following people:

- Mr Peter Stanhope (DSTG) for his continued technical support of the laboratory.
- CPO Chris Pickering (816 Squadron) for the chip images in Figure 3.
- Mr James Niclis (QinetiQ) for the images in Figure 6.
- FLTLT Dennis Schmidt and Mr Alvin Ng (both ex DASA PSI) for their assistance in evaluating ChipCHECK.

References

1. Becker, A., Abanteriba, S., Dutton, S., Forrester, D. and Rowlinson, G., On the impact of fine filtration on spectrometric oil analysis and inductive wear debris sensors, 2015, Journal of Engineering Tribology DOI: 10.1177/1350650115592917
2. ASTM 7898-14, Standard Practice for Lubrication and Hydraulic Filter Debris Analysis (FDA) for Condition Monitoring of Machinery, ASTM International, 2014.
3. Field Guide for Lubrication System Debris - Boeing Programs CFM56-2 CFM56-3 CFM56-7, GEK 119193, February 2018, page 28.