Remote Location Wear Debris Analysis for Aircraft

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Abstract

When aircraft propulsion machinery starts to deteriorate, tiny particles are liberated from load bearing surfaces (such as bearings and gears) into the lubricant. Being able to detect and analyse these particles is essential for making informed maintenance decisions. Informed decisions using this type of information typically have a significant positive impact on aircraft availability and safety in particular. Military aircraft are often required to operate for extended periods in remote locations such as at sea or from a forward operating base far removed from significant laboratory support services. In this context, it is therefore necessary to provide some enhanced tools that can quickly and accurately determine the significance of metallic wear debris recovered from aircraft magnetic chip detectors, screens or filters. This paper describes some work that has commenced to enhance the information available to maintenance staff operating aircraft in remote locations.

Keywords: wear debris analysis, remote location.

Introduction

The first rigorous analysis of metallic debris specifically for the detection of failures in machines dates back to the early 1970's [1, 2]. Since then, the extraction and analysis of metallic wear debris from lubrication systems has been shown to be highly effective for the identification of incipient failures of oil-wetted component [3-5]. Wear Debris Analysis (WDA) is the process of analysing the size, quantity, morphology and composition of these particles to provide an indication of system health. For the common failure mode of rolling contact fatigue there is a direct correlation between the severity of damage and an increase in the size and quantity of wear debris. Morphology of the debris such as surface features, shape, edge features and discolouration can also provide an indication of the failure mode.

As different metal alloys are used for different applications, the elemental composition of wear debris is extremely useful for determining the origin of wear debris and therefore the significance. Being able to determine the significance of wear debris particles can prevent many costly hours of unplanned maintenance or conversely provide low ambiguity confidence that maintenance is actually required. In an aviation context, WDA has a direct relationship to propulsion system reliability and safety, which explains why manufacturers universally publish mandatory wear debris analysis limits for debris. The difficulty has always been how to accurately analyse debris in the field when no laboratory support is available. For example, composition has not traditionally been done in the field (or even at an operating base) and has instead relied on expensive laboratory instruments and centralised analysis. For military aircraft operating at small to medium bases or in a remote location, this results in an inherent delay (typically days at best) in getting results to maintenance staff and therefore has a major impact on aircraft availability.

What’s Important?

One of the primary indicators of aircraft propulsion system health remains the detection and analysis of metallic particles retrieved from lubrication systems [6, 7]. When aircraft dynamic components such as gears and bearings start to deteriorate, they shed particles typically in the 50-1000+ µm range into the lubricant. These particles can then be detected by either magnetic chip detectors, filter debris extractions or draining the sump oil through a porous medium such as a filter patch. The size of particles liberated by contact fatigue generally exceeds the detection range of Spectrometric Oil Analysis used in most commercial oil analysis programs [8], however they could be collectively detected using a bulk inductive technique such as PQ Index[1]. Some modern aircraft are now fitted with inductive wear debris sensors (IWDS) that count and size individual particles and can form part of a Health and Usage Monitoring System.

Both size and quantity of wear debris are directly related to the severity of the damage, particularly where contact fatigue is the dominant failure mode. Figure 1 shows a comparison of wear debris size and quantity for a rolling contact fatigue spall at both an early and advanced stage of ball bearing failure. During this test, the debris was detected by an IWDS that counted and sized all debris in the 100-1000 µm range. The “Early Damage” distribution relates to the point where approximately 46 ferromagnetic (Fe) particles had been liberated from the inner race of a seeded fault test bearing [9]. “Advanced Damage” refers to where approximately 302 Fe particles had been liberated and represented the termination of the test. The plot clearly shows that both the quantity and size increase as the extent of damage progresses. It is therefore clear why size and count are typically used for assessing the serviceability of aircraft propulsion machinery. Accurately assessing the size and quantity of debris, however, is only now becoming a reality, with some work by the authors focused on novel applications of IWDS as aircraft ground equipment rather than permanently installed.

Although size and quantity are important WDA measures, composition is essential for determining the significance of the recovered debris. An accurate composition can enable the likely source of the debris to be identified and therefore allow the significance to be determined. When analysing the composition of wear debris, the critical information comes from the alloying elements and their respective quantities. For example, Figure 2 shows the spectrum for a flake of AISI M50 bearing steel obtained from a Scanning Electron Microscope using Energy Dispersive Spectroscopy (SEM EDS). For the alloy steels that are

[1] Particle Quantification (PQ) Index is a measure of the total ferromagnetic debris present.

typically of interest, the important information comes not from the large iron (Fe) peak, but from the alloying elements and their relative quantities. It is these alloying elements that are essentially unique identifiers. Confidently knowing where debris has originated from can therefore enable the significance of the debris to be determined and provide maintenance engineers with unambiguous justification on which to base maintenance decisions. Typically gear and bearing alloys are identified by aircraft manufacturers as being significant and if detected in sufficient quantity require replacement of the engine or gearbox.

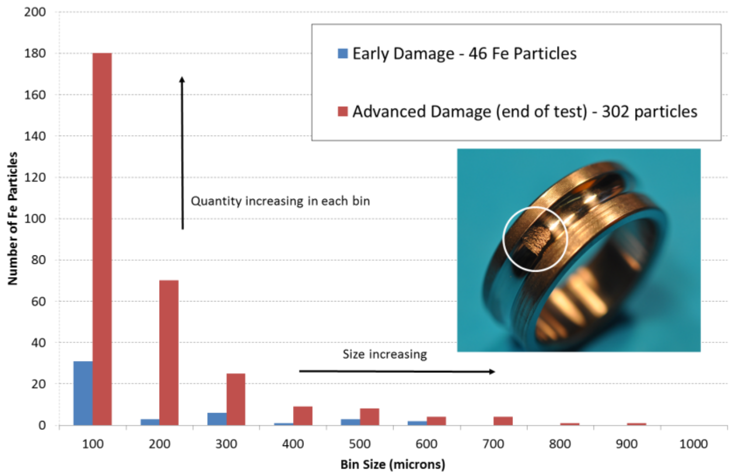

Figure 1: Comparison of size and quantity of wear debris at an early and advanced stage of damage for a rolling element bearing. Image shows "Advanced Damage" of inner race.

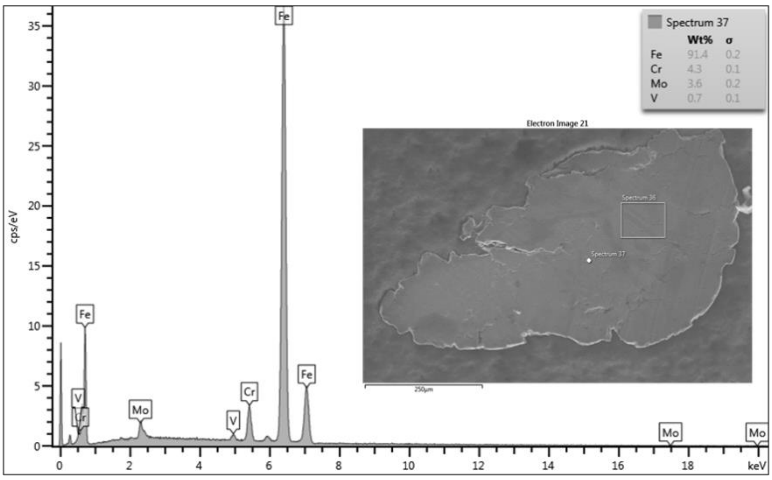

Figure 2: SEM EDS spectrum of a M50 bearing steel particle showing the principle alloying elements of Chromium (Cr), Vanadium (V) and Molybdenum (Mo).

Why is it Important?

The analysis of wear debris recovered from aircraft propulsion systems represents a direct and unambiguous insight into the health of the propulsion system if done correctly. The reason that WDA has persisted in aviation is that bearings and gears are inherently life limited by fatigue. While designers can predict the life of components (e.g. B_{10} life), this is a probability and by definition a small proportion of components may fail before the predicted life. Added to this are in-service operating conditions such as ingress of hard particle debris or lubricant degradation that can initiate or accelerate the deterioration of bearings and gears. While contact fatigue progresses over some time in rolling element bearings and gears, early and accurate detection is clearly the desirable aim for aviation propulsion systems.

For operations in remote locations (e.g. military aircraft at sea), the ability of maintenance staff to accurately assess wear debris is currently limited. Even the seemingly basic task of assessing size and count of debris is still done in a very rudimentary fashion. At best, it may involve the physical transportation of debris back to a laboratory for detailed analysis, however this is not always feasible. Providing maintenance staff with techniques or equipment to accurately conduct WDA with confidence can therefore provide a material benefit to aircraft availability and safety. Additionally, overhaul costs for engines and gearboxes are typically in the range of $100k to $1M and WDA is one of the few non-intrusive activities that provides confidence that removal of the assembly is in fact needed.

RNZAF Example

The Royal New Zealand Air Force (RNZAF) regularly deploys a single C-130H Hercules for operational missions to remote locations where laboratory based WDA does not exist. The RNZAF has a robust WDA programme aimed at preventing aircraft with defects from being deployed. However, with a relatively small fleet of C-130's, operational pressures at times require aircraft to be deployed with engines that are being more closely monitored. In these cases a reduced WDA inspection interval is employed and in-field WDA is a critical component of risk management.

The inadequacy of current in-field WDA inspection tools was highlighted when an RNZAF C-130 was deployed with one engine being monitored for generation of debris. The subject engine had been tracked using the RNZAF filter debris analysis programme, which typically detects defects well in advance of the maintenance manual rejection criteria. Although a small quantity of particles were identified prior to deploying the aircraft, the quantity was less than the mandated rejection criteria. The aircraft was therefore deployed for various operational and logistics reasons. To mitigate the risk of failure, a 25 hour visual inspection of the Reduction Gearbox (RGB) magnetic chip collectors (MCC) and the external scavenge filter were mandated.

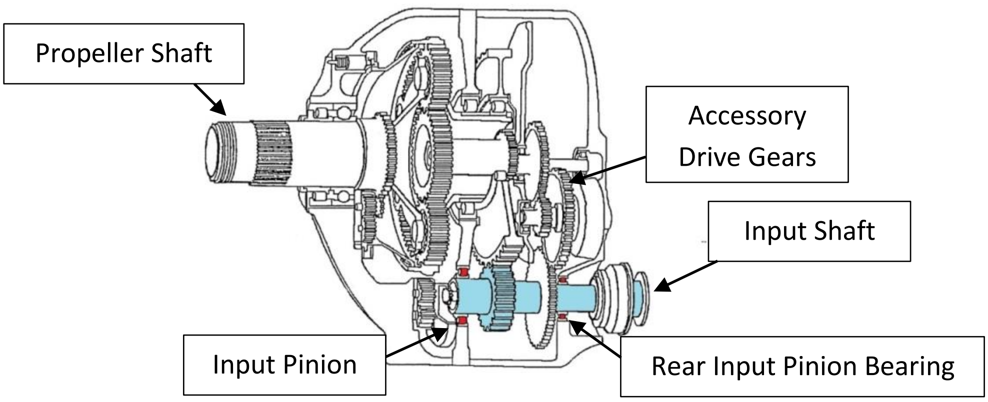

Figure 3: Section of T56-A-15 Reduction Gearbox (RGB)

After a period of operational flying, the aircraft was returning to New Zealand from the United States via Hawaii. Three hours after departure from Hawaii, engine #1 showed excessive RPM and torque fluctuation with evidence of red fluid streaming out of the engine nacelle. The engine was shut down and the aircraft returned to Hawaii on three engines. Subsequent inspection indicated the #1 engine RGB had experienced significant damage of the RGB rear input pinion bearing and collateral failure of accessory drive gears (Figure 3). Whilst the engine had been shut down in time to prevent a more serious catastrophic failure, significant collateral damage and airworthiness risk still occurred.

Had a robust in-field WDA inspection technique been available, the aircraft would not have been released to service and an engine change could have been carried out. Post failure analysis of the filters elements clearly showed a significant increase in debris rate (see area “B” in Figure 4). Due to the RGB internal component damage that occurred, the overhaul cost was significantly higher than a standard engine change. This example provides a clear case for improved in-field WDA tools as legacy visual inspection is not sufficiently reliable to mitigate risk.

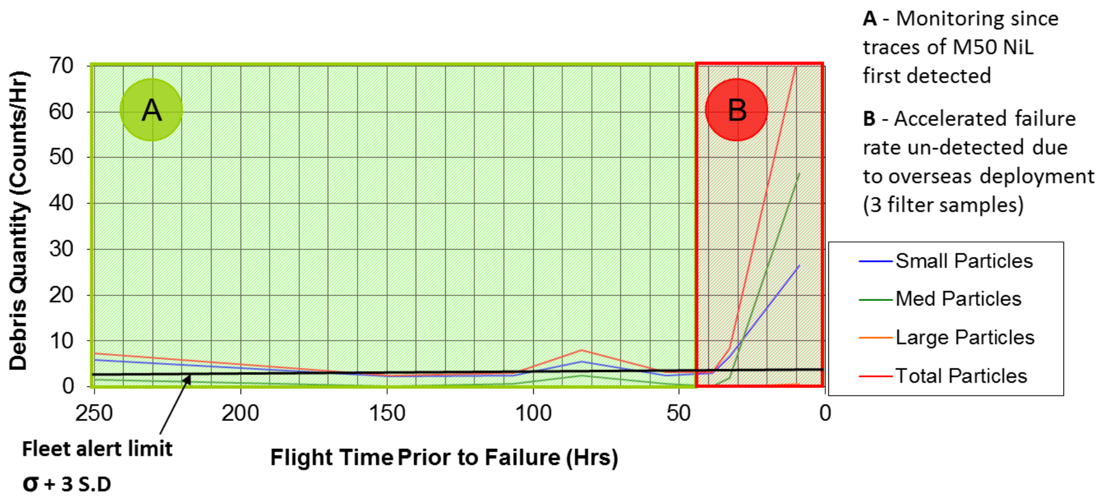

Figure 4: Ferrous filter debris trends for the subject engine. Area “B” analysed post failure.

What can be done?

One example of work currently being done in this area is the assessment of in-field devices that can determine the composition of debris. A survey was conducted of available portable X-ray Fluorescence (XRF) instruments to identify any that were sufficiently robust to cope with operations away from home base, had low training burden and could analyse individual particles. The Thermo-Scientific Niton FXL series of XRF instruments appeared to meet all of the criteria and was selected for further assessment. The FXL XRF (Figure 5) is a ruggedized portable XRF narrow beam device that incorporates a digital camera to identify what the X-ray beam is analysing. The device has an intuitive touchscreen menu, two physical buttons (start and stop) and a joystick for fine adjustment of beam location.

Figure 5: Niton FXL XRF Overview

Most XRF instruments do not have this capability and instead apply a broad beam to energise the specimen for bulk analysis of the sample. For WDA, a narrow beam pointing at a specific particle was required and this particular instrument had a minimum of 1mm diameter beam which was considered satisfactory. While other XRF instruments have narrower beams, they were not considered to meet the other requirements (in particular training burden and robustness). Testing of this XRF continues, however preliminary results show that the device can detect the important alloys required. The results shown in Table 1 were obtained using pseudo-standards of the various aviation propulsion alloys that covered the entire beam width. The three tests represent different locations on the same sample. Also shown is the "Match" value that indicates the confidence of identification; the scale varies from 0 (perfect match) to 5 (no match). Current work involves testing small particles of the alloys, shown in Table 1, to determine the minimum particle size (area) that the 1mm beam will reliably identify correctly. It should be noted that aluminium alloy detection was not considered essential for aviation propulsion applications; aluminium samples were, however, predominantly identified as the correct series (e.g. 7075 was detected as a 7000 series aluminium alloy). Magnesium is practically the lightest element detectable by most XRFs (without a helium atmosphere) and this explains the poor identification of ZE41A.

Table 1: Sample of results for common aviation alloys tested in Niton FXL XRF

Sample	XRF Reported Alloy					
	Test 1		Test 2		Test 3	
	Reported As	Match	Reported As	Match	Reported As	Match
302 Stainless Steel	Stainless	2.1	Stainless	1.3	Stainless	1.0
M50 Bearing Steel	M50	1.8	M50	1.8	M50	2.0
9310 Gear Steel	9310	1.2	9310	0.9	9310	1.2
52100 Bearing Steel	52100	2.2	52100	2.3	52100	1.9
4130 Steel	4130	1.7	4130	1.7	4130	1.5
4340 Steel	4340	1.9	4340	2.5	4340	2.2
7075 Aluminium Alloy	AA 7XXX	0.0	AA 7XXX	0.0	AA 7XXX	0.0
6061 Aluminium Alloy	AA 6XXX	2.1	AA 6XXX	3.4	AA 3XXX	2.2
Ti-6Al-4V	Ti6Al4V	2.3	Ti6Al4V	1.7	Ti6Al4V	1.9
ZE41A Magnesium Alloy	AA 7XXX	2.2	AA 7XXX	2.3	AA 7XXX	2.5

Other technologies besides XRF are also being considered, such as Laser Induced Breakdown Spectroscopy (LIBS). LIBS has one significant advantage in that it avoids radiation safety regulations. While LIBS based systems are currently less mature than XRF products, at least one OEM (GasTOPS) has released a LIBS system to the market capable of composition analysis specifically for aviation wear debris. Future work will likely include assessment of the Gastops LIBS product for deployed WDA.

Conclusion

This paper has discussed the need for in-field analysis of wear debris retrieved from aircraft propulsion lubrication systems operating in remote locations where no significant support is available to maintenance staff. A clear definition of what wear debris analysis means and what factors are important has also been discussed in the context of military aviation where significant operational time can be spent away from traditional laboratory support. The importance of wear debris size, quantity and composition in particular have been discussed. An example was provided to demonstrate the potentially significant impact that enhanced remote location WDA could provide. Work currently underway to enable wear debris composition to be determined in remote locations was described. The ability to accurately analyse wear debris when operating in remote locations has the potential to result in significant savings as well as increased availability and safety by enabling fully informed maintenance decisions.

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