USING FILTER DEBRIS ANALYSIS TO IDENTIFY COMPONENT WEAR IN INDUSTRIAL APPLICATIONS

Allison M. Toms & Michael P. Barrett

Insight Services
216-251-2510 ext. 107   216-251-2515 (fax)
cell phone 216-272-1319
mike@testoil.com

GasTOPS Inc.,
4900 Bayou Blvd., Suite 107
Pensacola, FL 32503
Tel: 850-478-8512
Atoms@gastopsUSA.com

Abstract: Oil filters capture a tremendous amount of tribology information about the operation of a machine. Removal and analysis of the filter debris has proved to be an effective tool for engine health management by determining wear modes and observing failure progression providing long lead times for maintenance remediation. The process of manual debris removal and analysis in a laboratory, however, is tedious. An automated filter debris analysis system provides a repeatable process. The filters are automatically cleaned; the particles are counted and sized utilizing a quantitative oil debris sensor; and the debris is deposited on a patch for automatic analysis by energy dispersive x-ray fluorescence spectrometer. The system has been successfully applied to operational aircraft fleets with significant benefits realized. A repeatable process for extracting and analyzing filter debris is now available for industrial applications.

Key Words: Condition based maintenance; debris sensor; filter debris analysis (FDA); operational uptime; wear modes

History of Filter Debris Analysis: Fluid filters and strainers play an important role in capturing and removing the debris and contamination that can damage mechanical components. An increase in the effectiveness of the filtration corresponds to a decrease in secondary damage caused by abrasive wear. Filters also capture the history of component wear for the life of the filter and for the capture efficiency of the filter. With the installation of fine filtration [1] (less than 7 microns), traditional wear analysis techniques such as atomic emission spectroscopy (AES) and ferrography become less efficient at detecting the initiation of damage. These filters capture most of the debris that AES and ferrography require for reliable detection and analysis. However, removing and analyzing the deposited particulates from the filter can provide a comprehensive assessment of the wear the asset has undergone during the life of the filter element.

Filter debris analysis has been in use since the mid 1980's. When the Canadian Forces' Sea King helicopter was plagued with main gearbox debris problems, the Canadian Defense Research Establishment Atlantic (DREA) embarked on a research project to determine if the debris from the filters could be used to reliably evaluate the condition of helicopter gearboxes. [2] The project was so successful that Filter Debris Analysis (FDA) became an integral part of the maintenance program to determine Sea King gearbox health. [3, 4]

The Sea King senior aircraft maintenance officer tasked GasTOPS Ltd., Ottawa, ON, their health monitoring specialist contractor, to work with DREA to develop the FDA program into an automated tool for mechanics at the flight line. [5] The outcome of the project was the development and production of the FilterCHECK™ 200. This instrument was simple to operate and in 15 minutes, could efficiently clean a filter, quantitatively count and size the ferrous and non-ferrous debris via the in-line particle debris monitor [6, 7] and prepare a patch of the debris for SEMEDX analysis. The FDA instrument's expert system accurately and repeatedly determined the gearbox serviceability. [8] The patch however was still sent to an expert analyst for metallurgical analysis and this continued to be a lengthy process.[5]

The US military's Joint Oil Analysis Program Technical Support Center (JOAP-TSC), Pensacola, FL conducted testing of the FilterCHECK™ 200 and was impressed with its capabilities. However, the JOAP wanted a comprehensive first-line capability in a single, transportable instrument that included metallurgical analysis. In 1999, the JOAP initiated an application project to develop and include an energy dispersive x-ray fluorescence (EDXRF) capability in the FilterCHECK™ 200 unit. [10] Under the USAF productivity, reliability, availability and maintainability (PRAM) program, an alpha prototype & six beta prototype units were constructed that incorporated a miniature EDXRF system into FilterCHECK™. As a result of the JOAP-TSC PRAM project, the new FilterCHECK™ 300 unit cleans the filter, counts and sizes the ferrous and nonferrous particles, prepares a thin film patch of wear debris, determines the metallic composition and mass of the debris. The project went from prototype to production unit in one year. The FilterCHECK™ 300 is in the process of being upgraded to the FilterCHECK™ 400 to incorporate advances in XRF technology.

Counting and Sizing Debris: The debris is quantitatively counted and sized by ferrous and non-ferrous using an inductive sensor. This sensor employs the same technology as a commercially available sensor (GasTOPS Ltd.) used for on-line wear debris monitoring for aircraft engines and gearboxes, industrial gas turbines, wind turbine gearboxes, podded marine propulsion systems, etc. The on-line line sensor data can be compared to the counts and sizes obtained from the filter debris analysis sensor.

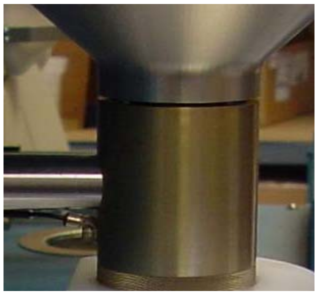


Fig. 2: Debris sensor

Metallurgy and Profiling: Particle type, size, count and wear metal limits needed to be established for the debris extracted from engine oil filters to enable automated diagnosis of abnormal wear. Since the debris extraction from the filter and deposition on the patch is automated, patches are prepared consistently, with the only variation being amount of debris due to **wear** and **time** on the filter.

The automated filter-washing instrument creates uniform and randomly dispersed populations of particulates for EDXRF analysis. The time on filter is taken into account during analysis of particulate size, mass, size-distribution and wear metals. Consequently, debris deposited on the patch is related to **wear modes** and **wear rates** in the machine. The remaining diagnosis is largely confined to determining the metal alloys present on the patch and relating the alloys present to engine components. The constituent alloy elements are reported as percentages (or can be calculated as mg/cm^2) and represent the percent of the particulates on the patch that is composed of that element. Elements and combinations of elements are used to identify alloys wearing in the component's system. Databases are constructed from a representative sampling of the components currently in service and are statistically analyzed to generate and maintain viable limits for condition assessment. [11] The statistically derived limits are validated by tear down inspection.

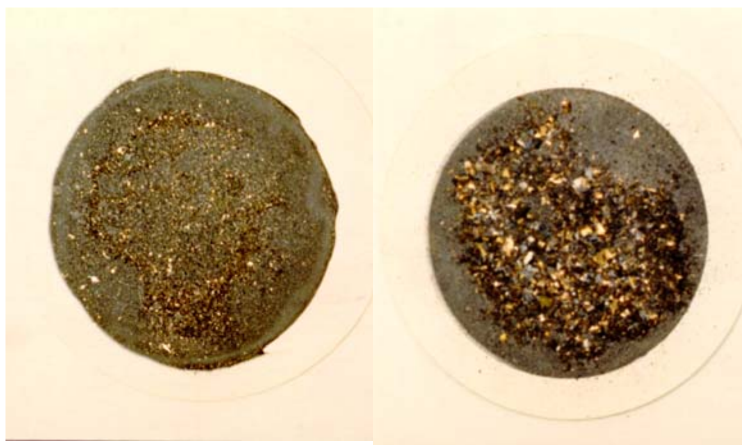


Fig. 3: Filter debris. Engine on left is operational; engine on right is in failure.

Success with Filter Debris Analysis: In the late 1990's, the EA-6B Pratt & Whitney J52-P-408 turbojet engines of NAVAIR's EA-6B Prowler fleet were experiencing one in-flight shutdown per month. The root cause of the failures was traced to a lack of lubrication of the #4 $^{1}/_{2}$ roller bearing, followed by the fracturing of the #4 $^{1}/_{2}$ bearing cage. During this failure mode, insufficient lubrication causes the bearing area to heat up causing the oil to carbonize. The carbonized oil then plugs the holes that feed lubricant to the bearing. The initial phase of the failure is removal of silver plating on the bearings, followed by bulleting (wearing) of the roller ends, simultaneously skidding all the bearings and finally causing the roller cage to crack. The complete failure of the bearing assembly can cause the shaft to warp. The excessive heat generated during the sliding phase has in some cases actually created a fire in the #4 $^{1}/_{2}$ bearing area.

The traditional means of identifying impending failures in the J-52 engine was via atomic emission spectroscopy (AES) of the engine's oil. The J-52 engines have their oil sampled every 10-flight hours. However, AES was not detecting the bearing failures, as the wear metal limits were never reached. The Navy Oil Analysis Program (NOAP) performed a statistical analysis of the AES results for the fleet's J-52 engines and found that seven of eleven prior failures could have been detected if the AES limits were lowered for iron and silver. [The bearings are M50 alloy (iron, chromium, molybdenum and vanadium) with silver plating.] But what about a means of detecting the other five failures? Part of the problem was that the filters were not changed at specific intervals. On some engines, this resulted in a large quantity of carbonized oil debris trapped in the filter that, in turn, resulted in higher filter efficiency and fewer wear metals to analyze in oil samples. A means of analyzing the filter debris would restore the detection capability and thus eliminate in-flight shut-downs.

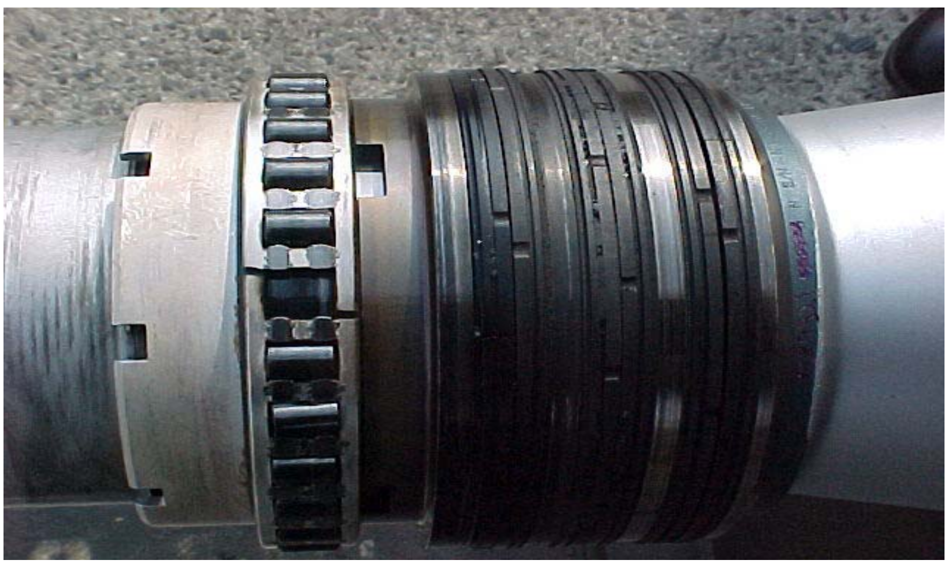


Figure 4. Broken #4 ½-bearing cage

The automated filter debris analysis system has been an overwhelmingly successful for advanced fault identification and early failure warning, often greater than 100 flight hours. Chief of Naval Operations (CNO) ordered FilterCHECK™ 300 units placed on every carrier (CV and CVN). Navy shore based facilities supporting the EA-6B also have the automated filter debris analysis units. In the first six months, FDA successfully diagnosed six #4 ½ bearing failures (verified by engine tear down) for which other monitoring techniques had no indication of any abnormality.

FDA technology has been credited with keeping the J52 aircraft operational and functional during the Afghanistan and Iraq conflicts. “Filter debris analysis meets all of the criteria established by the SAE Standard for a condition monitoring task.” [13]

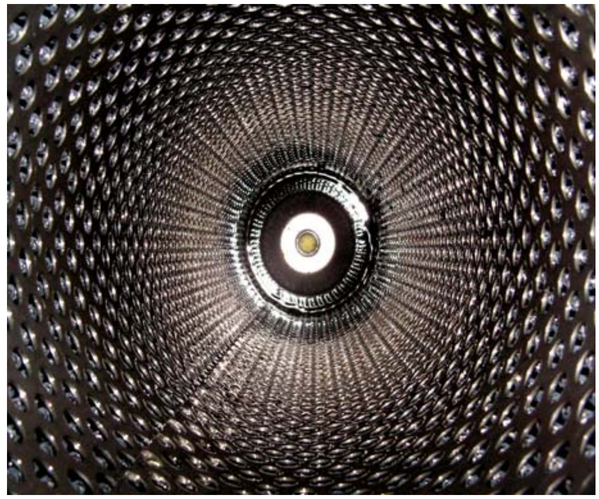
Transferring FDA Technology to Industry: Advanced warning of abnormal wear in critical operational assets provides decision makers valuable insight on the health of their rotating equipment. Armed with this information, the uncertainty behind maintenance decisions is eliminated enabling the proper scheduling of maintenance actions, ultimately, saving money by avoiding operational upsets and minimizing maintenance costs.

As companies employ finer filtration to extend the life of their most critical rotating equipment more debris is captured in filters and less remains in the oil. Wear debris analysis through oil analysis is no longer enough to predict impending failure. The next generation of wear debris analysis requires Filter Debris Analysis (FDA) to uncover the wealth of information buried in your filter and gain a comprehensive assessment of machine wear.

Industrial Filter Debris Analysis: Insight Services, working with GASTOPS, has developed a systematic process to wash and analyze industrial size filters in a similar fashion employed by the military. The FDA instrument is a self-contained unit which employs an automated method for filter washing to extract representative debris from the filter with high repeatability and reproducibility. A used filter is placed in the system wash chamber and debris is removed from the filter using a solvent wash. The wash fluid carrying the filter debris passes through a MetalSCAN sensor which quantifies and sizes the amount of ferrous debris. The fluid then runs through a filter patch where the sample of debris is captured for further metallurgical analysis by X-ray fluorescence (XRF). XRF analysis provides the elemental composition of the sample that can be correlated to the wear debris of interest.

In traditional oil analysis, the only particles available for analysis are those circulating in the oil (smaller than the filter size) or immediately released in the oil prior to filtering. Given the fine filtration used in rotating equipment today to produce longer life cycles, 95% of the wear debris that could provide useful insight into machinery condition is caught in the filter and never ends up in an oil sample. Typically, all the debris is discarded with the filter. Increasingly, fine filtration is making conventional monitoring techniques less effective at providing reliable indication of machinery component wear. FDA captures this lost information and identifies the specific components that are wearing, providing improved diagnostic and prognostic information about impending failures.

- FDA fills a gap left by atomic emission spectroscopy and analytical ferrography with improved diagnostic and prognostic information about impending failures.
- FDA captures valuable data lost by fine filtration.
- FDA provides a fingerprint of what has happened since last filter change.
- FDA allows accurate quantification of elemental particle debris without interference from the oil.



Conclusions: Filter debris analysis is an effective technique for determining wear modes and observing failure progression, thereby providing long lead times for maintenance remediation. Previous applications, primarily in the military, utilizing this technology have seen considerable successes including early warning on catastrophic failure, increased operational uptime, extended periods between scheduled repair, decreased maintenance costs, etc. The FDA technology is now available for industrial applications in the form of a reproducible and repeatable test that can be used by maintenance personnel for in-service maintenance support for assessing critical asset health.

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