Wear evaluation methods for friction units of aircraft GTE oil systems: the lab-based methods

A Y Hodunaev

Irkutsk National Research Technical University, 83 Lermontov Str., Irkutsk, 664074, Russia

E-mail: alex.hodunaev@gmail.com

Abstract. The problems before reliable wear evaluation using traditional lab based methods, such as ferrography, x-ray and spectrography, are discussed. One of those problems is that only a subset of wear debris features is measured by each method, which does not allow one to determine wear type. Filter sample analysis technology must be developed, because oil sample is devoid of diagnostic information due to fine filtration. The solution to aforementioned problems is proposed in the form of a newly developing microwave plasma method.

1. Introduction

The common consideration is that the wear process can be described by rate, type, location and severity. These features can be determined through measurement of concentration, size, morphology and elemental composition of the wear debris [1-6]. Relationship between wear and debris features [1] is shown in table 1, where “×” means related.

| Debris feature | Wear feature |
|----------------|-------------|
|                | Severity    | Rate | Type | Location |
| Concentration  | ×           | ×    |      |          |
| Size           | ×           | ×    | ×    |          |
| Morphology     | ×           | ×    | ×    |          |
| Composition    |             |      | ×    |          |

The most important task in wear evaluation is determining the wear type. Without clear understanding of the wear type, relationship between debris features “concentration” and “size” and wear “severity” cannot be established. For example, in case of non-periodic pulse generation of debris, the oil sample won’t show significant increase of the debris “amount”. Debris “size” too won’t give much information.
2. Results
Metallic debris that appear in the engine oil system can be described by multiple wear types [8]. It’s considered that using ferrograph measurements it’s possible to identify wear type using sizes and morphology of the debris [9].

Four most common wear types are normal (rubbing) wear, cutting wear, fatigue wear and sliding wear. The issue is that debris morphology often intersect between different wear types [1, 10]. As such, both rubbing and fatigue wear types may exhibit debris that take shape of flat thin scales [10]. Intersections like this complicate correct identification of wear type and prognosis of its development.

Another example is spherical debris of 2-5 micrometers in size that appear in ferrographic measurements and are considered to be feature, commonly associated with scuffing of roller bearings [11] and occur from welding, cavitation or likewise processes [5]. During prolonged tests of D30-KU154 gas-turbine engine, spherical debris of 2-5 in diameter were found [12]. Yet, there were no issues with bearings. Engine teardown showed no scuffing, and the reassembled engine was operated without bearing issues at least 7972 hours.

Therefore, debris morphology is not reliably tied to wear type and other debris features must be considered.

Regarding particle size, the results are ambigious too. There is information that debris size is related to wear type [5, 12]. Normal wear generates scale-shaped debris less than 15 micrometers in size, and bigger debris are related to excessive wear [5, 10, 12]. On other hand, debris of larger sizes generated on test machines do not relate to excessive wear [13], see figure 1.

![Figure 1](image1.png)

**Figure 1.** Spur rig experiments a) debris sizes after pitting damage was observed b) debris sizes without observable damage
The figure from work [13] shows that both with and without observable pitting damage, maximum debris size is >450 micrometers. The main difference between a) and b) figures is that amount of the debris increases in every class when the damage becomes visually detectable.

Further complications arise in the system of a real engine. When multiple wear processes coexist, the debris mix together. That can lead to “drowning” of excessive wear process within multiple normal wear processes. As such, work [13] states that “oil debris alone cannot discriminate between bearing and gear fatigue damage when both share a common lubrication system”.

Figure 2 shows distribution of the average debris diameter with relation to presence of excessive wear. The data is accumulated through microwave plasma measurements of the filter sample of different D30-KP gas-turbine engines [14]. The averaging is performed within each sample. The top curve represents distribution for engines exhibiting normal wear, the bottom curve – engines exhibiting excessive wear with confirmed damage.

![Figure 2. Distribution of average debris diameter within gas turbine engine samples](image)

The data shows that the wear process can develop among generation of debris in a wide size range – from tens to hundreds of micrometers. Therefore, the feature “debris size” should be used carefully through wear evaluation. To distinguish wear sources for debris mixed within one sample, the information on elemental composition of the debris is required.

Distinct sets of debris characteristics from table 1 can be measured using ferrography; x-ray and atomic emission spectral methods. Diagnosis reliability of D30-KP/KU/KU154 gas turbine engines using x-ray spectral measurements of oil samples does not exceed 5-7%, according to data of PJSC “UEC-Saturn” [15]; the damage of PS-90A engine high pressure turbine roller bearing was not ever identified using atomic-emission and ferrographic ground measurements [16]. Similar picture was observed for diagnostic of J52 4 1/2 bearing – atomic-emission measurements weren’t able to identify the damage of the bearing even at 10-day sampling period [17, 18].

Therefore, diagnostic miss is highly probable while using only a subset of debris features from table 1. Exception to this rule is when wear process is a frequently repeating one with continuous increase in concentration of metallic debris in the oil system. In this case, spectral methods can give fairly complete understanding about wear state of friction pairs in the system. Even more so - predict the remaining lifetime. As such, the damage of the high turbine bearing and middle compressor bearing of the AL-7F-1 engine was identified and monitored up to pre-failure state using atomic-
emission method with 92% reliability [19]. More than 280 engines were removed from operation prior to catastrophic failure.

The discussion above was relevant wear evaluation of friction pairs of gas-turbine engine oil system using spectral and ferrographic analysis of the oil sample. Another problem is raised by operation of 15-micrometer fine filters in the engine oil system. The fine filtration increases lifetime of oiled engine units by order of magnitude [20], but leaves the oil sample with no diagnostic information. More than 95% of the wear debris are deposited on the filter [21].

The analysis of the oil sample allowed one to use absolute-value features for diagnostics, such as concentration or debris count [22]. Yet, for the filter sample, these and other absolute-value features generally depend on filter operation time, engine operation environment, filter washing technique and other non-accountable conditions.

In work [23] the problem was solved as follows. An automatic filter wash system was developed. A washed filter sample was put through MetalSCAN debris counter and deposited on the 20-micrometer fine membrane filter. By-percent elemental composition of the membrane debris was determined using x-ray spectral analysis. This machine (FilterCHECK 300) and the developed technology allowed one to identify the early signs of the wear degradation of 4 ½ bearing in J52 engine with 95% reliability [18, 24, 25]. In words of one of the authors, Gary Humphrey, the developed technology allowed one to “save 58 units of EA-68 Prowler aircraft, which equates to $765 million and 116 air crew” [26].

However, the information about the application of this technology for other units of J52 engine or other types of engine isn’t there. Most probably, the developed equipment has narrow specialization.

The same was true for AL-7F-1 bearing wear evaluation technology. When transferred to D30-KP/KU-154, the reliability of the early wear identification dropped from more than 90% to 5-7%. Same could be said for IVU-1M, ultrasonic equipment which allowed to detect the damage D30KP/KU/KU-154 intershaft bearing, undetectable using traditional spectral methods. The damage of other bearings (high pressure turbine, compressor) couldn’t be identified using IVU-1M.

Therefore, repeatable wear processes is the simplest way to perform reliably diagnosis. In this case, most probably, a single wear type dominates, which allows one to find effective diagnostic feature and monitor the damage up to a pre-failure state.

There is one more problem that is barely discussed in engine tribodiagnostics literature. Some elements in the oil or filter sample can be present simultaneously as both wear particles and oil additives. For example, molybdenum is a common anti-scuffing additive that is also present in M50 bearing steel; silicium is used as anti-foam additive and can appear into the oil system from environmental dirt; latter is also true for Al₂O₃ and other chemical compounds. An aforementioned problem mixes wear and non-wear sources for some of the debris, confusing the diagnosis.

3. Conclusion

The diagnost possess in their toolbox several laboratory methods that allow measurements of sets of specific features, such as wear debris concentration, size, morphology and elemental composition. Long history of employment of these methods shows not enough reliability in wear evaluation. There is several problems that need to be solved for reliable:

1. Wear type identification, which decides further diagnostic actions.
2. Measurements of debris amount and elemental composition among their whole size range.
3. Separate acquisition of information about chemical elements that are present both in shape of wear debris and oil additives.
4. Filter sample diagnostic features must be found for engines that are equipped with fine oil filters that capture most of the wear debris as the diagnostic information.

These problems are currently being solved with newly developed equipment.

One example of such equipment is the new microwave plasma atomic-emission method [14]. The method employs ten to thirty minutes long analysis of the filter/oil sample. The method allows one to determine size and elemental composition of each registered debris that consists of Al, Fe, Cr, Ni, Mg, V, Ti, Mo and the elemental dictionary is being expanded. Partial solution of the aforementioned
problems allowed the method to reach 90% diagnosis reliability for D30-KP/KU/KU-154 engines.

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