Technical state evaluation of oil-lubricated parts and units of aircraft gas turbine engines using microwave plasma method

V G Drokov¹, V V Drokov¹, N A Ivanov², V V Myrishenko¹, Y D Skudaev¹ and A Y Hodunaev¹

¹Irkutsk State University, 20 Gagarin Blvd., Irkutsk, 664003, Russia
²Irkutsk National Research Technical University, 83 Lermontov Str., Irkutsk, 664074, Russia

E-mail: viktor.drokov@gmail.com

Abstract. The method for technical state evaluation of oil-lubricated units of aircraft gas turbine engines using measurement of wear particle parameters and the microwave plasma method is suggested. Diagnostic features accounting for quantity and composition of wear particles in oil samples and oil filter wash samples have been discovered. Parameter levels for non-defective engines are evaluated. Reference statistical models for non-defective engines, which take into account engine type and engine operating time, are calculated. Distribution laws of parameter values are evaluated, and value normalization functions were found. Actual validity with accuracy up to a unit has been estimated to be 85%, which is confirmed by factory disassembly study of engines, removed from operation by the results of evaluation.

1. Introduction

There are multiple ways to develop a diagnostic method. One of them compares the "character" of the engine in question with the reference average-value non-defective engine of the same type. The reference engine is formed according to the statistical processing of data from the non-defective engines currently on operation. The difference between the reference and the evaluated engines is attributed to the probable change in their technical state [1-3].

In the current paper, the attempt is made to develop a new method to evaluate the technical state of the oil lubricated units and assemblies of gas turbine engines by the results of the wear particle parameters measurement in the oil sample and the oil filter wash sample using the microwave plasma analyzer [4]. The method is developed by the example of evaluating the state of D30KP/KU/KU-154 engines.

The reference statistical models for the non-defective engines which take into account the engine type and operating time since the last repair (further will be referenced as "operating time") are developed to help in decision making on the matter of disallowing/allowing the further engine operation. 2194 total engine samples are used as a model basis for the D30KP/KP-2 engine, and 1819 samples are used for the D30KU-154 model. The models account for more than 100 parameters.

2. Engine data

The sampled engines quantity distribution by operating time is presented in table 1.
Table 1. Quantity distribution of the engines, evaluated using the microwave plasma method according to the operating time.

| Operating time, h | Quantity of non-defective and defective engines, evaluated using the microwave plasma method |
|------------------|-----------------------------------------------------------------------------------------------|
|                  | D30KP/KP-2 | D30KU-154 |
| 0-500 h          | 63         | 56        |
| 500-1000 h       | 58         | 56        |
| 1000-2000 h      | 92         | 65        |
| 2000-3000 h      | 56         | 80        |
| More than 3000 h | 44         | 108       |
| Total:           | 313        | 365       |

The statistical model of the non-defective engine by results of the oil sample analysis was developed using these parameters:

Measured parameters:
- Total quantity of wear particles, containing the particular element.
- Quantity of "simple" particles, containing only one particular element.
- Mass concentration of elements in the sample determined by the dissolved component.
- Mass concentration of elements that are a part of wear particles.

Calculated parameters:
- Quantity of "complex" particles, containing two and more elements.
- Average wear particle size.
- Element wear coefficient, defined as ratio of "complex" particle count, containing a particular element, to count of the "simple" particles only consisted of that element.

Integral parameters:
- General wear coefficient - ratio of total "complex" particle quantity to the total "simple" particle quantity.
- Total registered compositions of the complex particles.

The work [5] shows that parameter measurement error using the microwave plasma method with 1 ml is mostly caused by the sample non-uniformity error, which may be above 100%. The error can be lowered using standard method - by conducting multiple parallel measurements. The error will decline as $\sqrt{n}$ [6]. As such, it has required more than 100 measurements to develop a "snapshot" (statistical model) of non-defective engine. If a sample is taken every 50 flight hours, then engine operating time will total in 5000 h. The model of the particular engine, accounting for its peculiarities, will be statistically accurate concerning the engine working resource exhaustion.

On the other hand, there are three known periods in the non-defective engines operation which vary in dynamic of wear particle parameters [7]. Relatively short period (0-500) is characterized by increased wear particle parameters, lengthily second - by relatively lower parameters and, during the third, last period parameters increase again [1,4,5,8]. Thusly, the model of the non-defective engine must consider at least three these periods, which suggests that it is impossible to create a statistically accurate model ("snapshot") of the non-defective engine, accounting for its peculiarities, using the discrete engine state evaluation method.

The next important moment is figuring out threshold values for wear particle parameters, that denote whether it is advisable to further operate the engine. In an ideal situation, where one has both statistical data set on the defective and non-defective engines, solution becomes trivial. But during the effective time, it is impossible to gather the statistical data for the defective and pre-failure engines in the sensible time frame, which accounts for the engine type, wear type and operation period. Thus, the next approach was applied.
The models were developed on the basis of the non-defective engines currently in operation, accounting for their type and operation time. It's clear that non-defective engines for a particular type and range of operation time feature parameter spread, caused by differences in overall wear, which depend on operation conditions, alloy quality, part manufacturing quality, assembly quality etc. Analysis result error also takes its part in $\sigma$ values. Using the formal dispersion addition:

$$\sigma^2 = \sigma^2_{\text{wear}} + \sigma^2_{\text{analysis}}$$  \hspace{1cm} (1)

where $\sigma^2$ - parameters distribution dispersion for non-defective engine, $\sigma^2_{\text{wear}}$ - parameters distribution dispersion, caused by engine wear, parameters distribution, $\sigma^2_{\text{analysis}}$ - dispersion, caused by equipment error [9].

The experience in the technical state evaluation of the friction units of the aircraft engines shows that microwave plasma measurements accuracy is acceptable even when the measurement result is taken as mean from just two parallel measurements, i.e. $\sigma_{\text{wear}} > \sigma_{\text{analysis}}$. With that said, it's possible to state that parameter value range from 0 to $(\bar{x} + \sigma)$ includes $(68 + 32/2)$% of the non-defective engines, range from 0 to $(\bar{x} + 2\sigma)$ includes $(95 + 5/2)$% of non-defective engines. And above $(\bar{x} + 3\sigma)$ - $(99 + 0.3/2)$% threshold, non-defective engines are virtually impossible. Generally speaking, values calculated using the above-mentioned approach are inexact pre-failure threshold values. They can be corrected with accumulation of the statistical data on the defective and pre-failure engines.

One more issue is the value distribution law of particular parameter. It defines the final values for threshold values.

The microwave plasma method provides comprehensive information about the wear particles. The next important step is to make rationale for the engine wear criterion choice and their efficacy evaluation out of all diversity of the measured parameters.

3. Parameter values distribution

The development of the technical state evaluation method for of the D30KP/KU/KU-154 engine friction units totals in these tasks:

- accumulation of enough statistical data on non-defective engines to build reliable reference model of non-defective engine;
- study of value distribution laws of the parameters measured using the microwave plasma method;
- search for function, which transforms value distribution of particular parameter to normal distribution (normalization function);
- development and application of statistical model building algorithm, which accounts for particular parameter value law distribution;
- selection of the most efficient engine wear criterion;
- comparison of the results of the technical state evaluation using the microwave plasma method to results of factory disassembly study of engines of discontinued operation.

As was pointed out above, the estimation of the value distribution law is required for establishing parameter threshold values. When a parameter value crosses the threshold, the engine should either be operated in the strict check mode or be considered faulty. One-side (exceeding) $2\sigma$ and $3\sigma$ above mean values were used correspondingly as these thresholds.

Usually researchers encounter normally distributed values. In that case, the calculation of mean value, standard error and confidence margins of the measured parameter poses no problem. When the distribution laws are different from normal, multiple approaches could be taken. It's possible to find a transform function on the independent variable which converts distribution to normal, or use special statistical approaches to analyze such data.
The tests for normality of parameters, measured using the microwave plasma method, were performed using Kolmogorov-Smirnov test. The resulting distributions below were obtained using "Statistics 5.5" program [10].

For example, in figures 1 and 2 the distribution histogram of Cu particle count and comparison to normal distribution is shown. The shape of histogram suggests log-normal distribution law, since pronounced maximum of distribution is positioned near the first groups, gradually declining to the right.

**Figure 1.** The distribution histogram of NCu and natural logarithm of NCu. NCu is a total count of particles, containing Cu, measured using microwave plasma analyser. On abscissa axis, histogram groups are shown, on ordinate axis, count of samples containing parameter value in the specific group is shown.

**Figure 2.** The comparison of NCu, Ln(NCu) distribution to normal distribution using Kolmogorov-Smirnov test. NCu is total count of particles, containing Cu, measured using microwave plasma analyser. The closer data points are to line, the closer empirical distribution to normal.

Such data could be shown for all the parameters, measured using the microwave plasma analyser. The results of the study of the value distribution laws of parameters, measured using the microwave plasma analyzer, show that multiple parameters behave according to log-normal distribution, and before construction of statistical model, their values need to be normalized using $y = \ln(x)$ transform function. These parameters are all particle counts, mass concentrations and all average particle sizes. The general wear coefficient parameter too is distributed log-normally on the condition that the samples with $W_{gen} > 1$ are excluded from statistical set. Probably, when $W_{gen} > 1$ wear processes become strong and such results should be excluded from statistical set when creating the non-defective engine model. The quantity of complex composites parameter varies in a very narrow range (10–100) and thusly has normal distribution.

4. Ratings
The development of the statistical model on results of analysis of the oil filter samples was made with the use of a different approach. That is because the absolute values of parameters, such as the mass concentration of the element, "simple" and "complex" particle counts cannot be directly linked to the engine's technical state. Such parameters depend on how long wear products were accumulated on the
filter, engine's peculiarities, wash method, sample uniformity and other factors, impossible to account for on practice.

Thus, rating approach was used. Instead of the wear particle count, normalized rating parameter was introduced, which is calculated as the quantity of particles of interest relative to 1000 wear particles:

\[
R = \frac{N}{N_{tot}} 1000.
\]

It is obvious that the less the rating determination error is, the more particles are detected in the sample. In the oil samples with the normal wear, particle count is in order of few hundreds and rating measurement error is great. But in the wash samples from oil filters, particle count can reach few thousand - value big enough for the rating determination error to be the minimal.

It's clear from the rating definition, that this parameter is varied in the (0,1000) range and the unlimited value statistics are unsuitable for its analysis.

The particle count rating distribution for elements Cu, Mg, Ni and V is shown on figure 3. It can be seen, that the mean value for Cu particle count is around 500 and distribution is close to normal. RMg has mean value around 150, the distribution is different from normal and positive asymmetry appeared. The same could be seen for RNi (mean is 50), RV (mean is 0.5). The decrease of mean value makes distribution more asymmetric and closer to the log-normal distribution.

The comparison of Cu, Mg, Ni, V particle count rating distribution to normal distribution using [5] allows to find the normalization function \( y = \frac{x}{\bar{x}} \), where \( \bar{x} \) is mean value. It does not affect the original distribution when rating mean value is 500, and allows removing the distribution asymmetry for lower rating values. In figure 4, comparison of normalized particle count ratings to normal distribution is shown.

![Figure 3. The distribution histogram of RCu, RMg, RNi, RV.](image-url)
Figure 4. The comparison of normalized particle count ratings RMg, RNi, RV distribution to normal distribution using Kolmogorov-Smirnov test. The closer the data points to line, the closer the empirical distribution to normal.

Log-normal distributions were transformed using $y = \ln x$ in creating of the statistical model for the oil filter wash sample. Further, for every resulting distribution, standard mean error and confidence intervals were found.

Potentiated values for these distributions were summed up in tables, separately for D30KP/KP-2 and D30KU-154 engines, with operation time in account. Definitions for table are: $\bar{x}$ is mean parameter value for result set, $\sigma$ - standard error, $\bar{x} + 2\sigma$, $\bar{x} + 3\sigma$ - threshold values. For every measured parameter, appearance probabilities were calculated.

The models were divided by these 5 operation time periods: between 0 and 500 h; 500, 1000 h; 1000, 2000 h; 2000, 3000 h; more than 3000 h.

For example, table 2 shows the reduced model for the non-defective D30KP engine by results of the measurement of the wear particle parameters in the oil sample at 500, 1000 operation time hours interval. Many complex-particle parameters were excluded from the model.

The sample set for each operation time was representative enough. For example, for the model D30KP/KP-2, minimal sample count was 176 for 3000+ hours operation time, and maximum was 777 samples for 1000 to 2000 hours operation time.

Despite ratings and wear coefficients being interrelated, each of them is calculated and discussed separately, the reason being that each of them contains its own independent information about distinct engine units.

Meaning of these parameters requires clarification. The general wear coefficient $W_{gen}$ is an indicator of the overall technical state of the engine. A pattern was recognized: the less the value of $W_{gen}$, the better the condition of friction surfaces of engine parts and vice versa.

The approach above, when the relative values are used as a diagnostic features, allows to negate the influences from the sample dilution, oil filter particle extraction uncertainty, engine operation time etc.
Table 2. Reduced statistical model for the non-defective D30KP engine in 500, 1000 operation time hours interval, using the oil sample parameters.

| Parameter                                      | Composition | \( \bar{x} \) | \( \bar{x} + 2\sigma \) | \( \bar{x} + 3\sigma \) |
|------------------------------------------------|-------------|----------------|--------------------------|--------------------------|
| Count of the wear particles, containing specific element | Mg-         | 35.37          | 121.34                   | 255.13                   |
|                                                  | Fe-         | 28.22          | 96.92                    | 203.91                   |
|                                                  | Cu-         | 247.3          | 837.1                    | 1765.17                  |
|                                                  | Ag-         | 42.96          | 182.3                    | 457.37                   |
|                                                  | V-          | 0.47           | 0.78                     | 1.02                     |
|                                                  | Al-         | 4.49           | 14.54                    | 29.76                    |
|                                                  | Cr-         | 1.54           | 3.39                     | 5.32                     |
|                                                  | Ni-         | 2.02           | 5.05                     | 8.73                     |
| "Simple" (one-element) particle count             | Mg-         | 31.26          | 109.32                   | 235.41                   |
|                                                   | Fe-         | 23.93          | 82.96                    | 177.83                   |
|                                                   | Cu-         | 243.15         | 834.9                    | 1778.5                   |
|                                                   | Ag-         | 41.57          | 181.05                   | 463.41                   |
|                                                   | V-          | 1.08           | 1.55                     | 1.88                     |
|                                                   | Cr-         | 0.01           | -                        | -                        |
| Mass concentration of the element in dissolved form | Mg-         | 0.08           | 0.39                     | 1.06                     |
|                                                   | Fe-         | 0.12           | 0.7                      | 2.19                     |
|                                                   | Cu-         | 0.1            | 0.48                     | 1.3                      |
|                                                   | Ag-         | 0.04           | 0.17                     | 0.43                     |
|                                                   | Al-         | 0.09           | 0.56                     | 2.13                     |
|                                                   | Cr-         | 0.01           | 0.05                     | 0.11                     |
| Mass concentration of the element in particle form | Ni-         | 0.02           | 0.06                     | 0.16                     |
|                                                   | Mg-         | 0.02           | 0.09                     | 0.22                     |
|                                                   | Fe-         | 0.11           | 0.68                     | 2.42                     |
|                                                   | Cu-         | 0.07           | 0.26                     | 0.61                     |
|                                                   | Ag-         | 0.03           | 0.14                     | 0.37                     |
|                                                   | Mg-Cu-      | 1.63           | 3.55                     | 5.51                     |
|                                                   | Cu-Ag-      | 1.68           | 3.82                     | 6.17                     |
|                                                   | Fe-Cu-      | 1.62           | 3.63                     | 5.82                     |
|                                                   | Mg-Fe-Cu-   | 1.24           | 2.18                     | 2.98                     |
| Count of the "complex" wear particles, containing two or more elements | Ni-Fe-      | 1.21           | 2.08                     | 2.79                     |
|                                                   | Al-Mg-Fe-   | 1.26           | 2.28                     | 3.17                     |
|                                                   | Al-Fe-      | 1.12           | 1.71                     | 2.14                     |
|                                                   | Mg-Fe-Cu-Ag-| 1.12           | 1.70                     | 2.13                     |
|                                                   | Al-Mg-Fe-Cu-| 1.04           | 1.28                     | 1.43                     |
|                                                   | Fe-Ag-      | 1.10           | 1.56                     | 1.88                     |
|                                                   | Fe-Cu-Ag-   | 1.13           | 1.75                     | 2.22                     |
|                                                   | Cr-Ni-      | 1.13           | 1.71                     | 2.12                     |
In total, using the microwave plasma analyser measurements, 83 defective engines were discovered that later were subjected to the factory disassembly study.

In 76 engines defect was confirmed. In 70 out of 76 engines the defect was localized up to the defective unit, and in 6 engines the defective unit was evaluated incorrectly.

The defect types, diagnosed using microwave plasma measurements:
- High pressure compressor bearing malfunction - 6 engines.
- Inter-shaft roller bearing malfunction - 7 engines.
- High pressure turbine roller bearing malfunction - 17 engines.
- Labyrinth sealing scallops teeth contact - 4 engines.
- Oil assembly malfunction - 2 engines.
- Central drive malfunction - 1 engine.
- Spline connections malfunction - 1 engine.
- Aft gearbox defects - 32 engines.

5. Conclusion
It has been established that in the non-defective engine, wear particle parameters in the oil sample have low values. The mass concentration of main alloy component (Cu, Fe) does not exceed tenths of ppm, and particle count - a few hundred per cc. It is shown that the microwave plasma measurements error does not affect accuracy of the diagnostic decision for these low thresholds. In the non-defective engine alloying elements (Cr, Ni, V) counts take single-digit values or do not appear at all. For “complex” particles, containing two or more elements, the total quantity also is in single digits and composition of particles does not fully reflect material, from which they are separated. The detection of Cu-Ag, Fe-cu, Fe-Ag, Fe-Cu-Ag is evident of the anomalous wear of separators, rolling bodies and bearing tracks. In addition, early defect stage is characterized by higher parameter values of Cu-Ag, Fe-Cu (wear of bronze and silvered separators). The defect development is accompanied by increasing counts of full composition particles, evident of rolling bodies and bearing tracks wear (Fe-Cr-Ni, Fe-Cr-Ni-V etc.).

To take a diagnostic decision relative to further engine operation, statistical models of non-defective engines by results of oil sample and oil filter wash sample parameters measurements are developed, which account for engine type and operation time. 2194 samples were used for the D30KP/KP-2 statistical model, and 1819 samples for the D30KU-154 model. Models account for more than for 100 parameters.

The study of wear particle parameters distribution during building of statistical models received special attention. That is because they affect the final threshold values, from which can be determined whether it is acceptable for the studied engine to stay in operation. Thus, for each parameter the best normalization function that transforms parameter value distribution to normal distribution was found.

For each wear particle parameter, these criteria were established:
- \( x < (\bar{x} + 2\sigma) \) - engine is non-defective, normal wear, can be operated further.
- \( (\bar{x} + 2\sigma) < x < (\bar{x} + 3\sigma) \) - strict check zone, probable anomalous wear;
- \( x > (\bar{x} + 3\sigma) \) - high probability of engine being faulty.

The engine technical state evaluation accuracy with localization of defect up to the defective unit by results of the microwave plasma measurements was about 85%.

6. Acknowledgments
This article was prepared using the results of work carried out in the framework of the federal target program “Research and development on priority directions of scientific-technological complex of Russia for 2014 - 2020 years”. Theme: “Development and creation of software and hardware microwave plasma system for monitoring, control and safe operation of the oil system of engines for ground and air purposes” The agreement with the Ministry of Education for a grant No. 14.577.21.0289, 075-02-2018-229. Unique identifier PNIER RFMEFI57718X0289.
References

[1] Keba I V 1980 Aircraft Gas-Turbine Engine Diagnostics (Moscow: Transport)

[2] Vlasov Yu A 2015 Methodology for diagnosing automobiles by electrophysical methods for monitoring parameters of operating oil. Abstract of the dissertation of the doctor of technical sciences (Tomsk: TGASU) p 43

[3] Paykin A G, Sirotin N N, Novikov A S 2007 Monitoring and diagnostics of the technical condition of GTE (Moskow: Nauka) p 472

[4] Drokov V G, Drokov V Vl, Myrishenko V V, Muhutdinov F I, Skudaev Y V and Haliullin V F 2018 Plant Laboratory 84(8) 39-43

[5] Drokov V G 2009 Increase of gas-turbine engines technical state evaluation using scintillation method to decrease emergency rates for aircraft operation. Degree aspiration thesis. Abstract of the dissertation of the doctor of technical sciences (Moskow: FSUE "State Research Institute of Civil Aviation") p 325

[6] Zil'bershteyn H I 1994 Spectral analysis of pure substances (St Petersbourg: Chemistry) p 336

[7] Wei Hong, Wenjian Cai, Shaoping Wang, Mileta M Tomovic 2018 Chinese Journal of Aeronautics 31(5) 867-882

[8] Stepanov V A 2002 Diagnostics of Friction Units of Gas Turbine Engine Transmission by Parameters of Wear Particles in Oil (Rybinsk: Saturn)

[9] Smagunova A N, Karpukova O M 2008 Methods of mathematical statistics in analytical chemistry (Irkutsk: Irkutsk State Universiti) p 339

[10] Borovikov V 2001 Statistics for Professionals (St Petersbourg: Peter Book)