IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

Development of microwave plasma method for measurement of wear particle parameters in lubricant oil samples from aircraft gas turbine engines

To cite this article: V G Drokov *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **560** 012059

Development of microwave plasma method for measurement of wear particle parameters in lubricant oil samples from aircraft gas turbine engines

V G Drokov[1], V V Drokov[1], N A Ivanov[2], V V Myrishenko[1], Y D Skudaev[1] and A Y Hodunaev[1]

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

E-mail: viktor.drokov@gmail.com

Abstract. The paper describes the new microwave plasma method for gaining information about wear particles in oil samples from aircraft gas turbine engines (GTE). The method allows one to measure the element concentration in the form of wear particles (the size is more than 2 micrometers), element concentration in the form of metal-organic admixture and sub-micrometer particles (less than 2 micrometers), quantity and elemental composition of particles simultaneously and in real time. The microwave plasma analyser has electrodeless microwave plasmatron of original design, which allows for the proportional ratio between size of particles and the output signal for particles less than 60 micrometers in size. For this analyser, the ratio of quantity of wear particles hitting axial (high-temperature) plasma regions to overall particle quantity is no less than 0,95. Compressor pumped air is used as a plasma-forming medium. For analysis of the oil sample from the oil filter, new diagnostic features are suggested and their relation to the technical state of the engine is suggested.

1. Introduction

Despite the great success in creation of high reliability GTEs, engine failures (up to 40% of the total number of failures) are still happening and result in aircraft incidents, reduced flight safety and engine operation efficacy [1]. Most often this is connected to extraneous particles in the engine lubrication system.

Currently, means for GTE technical state evaluation by parameters of wear particles consist of on-board instruments (such as magnetic plugs (MP), signaling filters (SF), various flow-through type detectors) and laboratory spectrometry equipment such as MFS, MOA, Spectroil, BARS, PRISM, SpectroSCAN and ferrography methods. The main assignment of tribodiagnostic methods is to detect an engine defect at the early stage and to accompany it to the pre-failure unit condition.

According to [2], magnetic plugs are not reliable enough in detection of ferromagnetic particles and do not react to paramagnetic metals of Mg, Al, Cu types. The defect can be detected just before catastrophic damage, during catastrophic damage, or not detected at all by the means of magnetic plugs. Engine maintenance cannot be planned by the results of parameters evaluation with magnetic plugs.

Engine maintenance by the means of signaling filters data is also difficult. The signalling filter can be triggered not only by particles, which are linked to the high wear level, but also by consolidates of singular metal particles, leftover particles from engine installation and assembly, carbon deposits, singular particles exceeding 100 micrometers, etc.

The notion of developers of tribodiagnostic systems works out real-time control sensors to allow continuous online assessment of engine units and assemblies to understand. Quite a few flow sensors for continuous control of lubrication systems are made, but they all share same flaws: analysis results are dependent on shape and trajectories of particles, sensors sensitivity is limited by size of the particles [2-4]. Determining of particles begins from sizes of more than 200 μm for ferromagnetic particles and 600 μm for paramagnetic particles. The detection of an engine defect at the early stage is impossible if particles of such sizes are detected, detection of a defect at an early stage of development is impossible. This is confirmed by the data obtained when testing the engine in JSC "ODK Aviadvigatel". The tests showed that the flow-through type detector installed in the engine oil system actuated almost simultaneously with the actuation of the standard signalling filter. Disassembly of the engine revealed a bearing defect according to the scheme of brittle chips. This means that the results of the flow-through type detector readings do not always allow detecting a defect at an early stage of development. Most likely, this is due to the fact that the detector did not feel the redistribution of the particle sizes from normal wear to catastrophic one.

Currently used ground instrument diagnostic techniques (atomic emission, X-ray, ferro-graphical) in most cases failed to detect a defect upon the appearance of the metal particles, separated from the damaged parts and to localize the damaged site. These JSC "Saturn" and of "AVIADVIGATEL" indicate that indications MFS equipment, MOA, Spectoil, BARS, prisms, SpectroScan, only 5% of engines with defects removed from operation by excess content of metal impurities in the oil sample. In the example mentioned above with a flow-through type detector of X-ray analysis of oil samples taken from the gearbox (GB) and the oil tank (MB) even confirmed the presence of bearing damage. This means that the problem of developing the tribodiagnostic methods capable of detecting defects at an early stage of development is relevant.

The aim of this work was the development of an express, informative microwave plasma method for measuring the parameters of wear particles in samples of lubricating oils that provide a highly reliable estimation of the technical condition of the GTE friction units lapped by the lubricating oil.

2. Principle of operation and constructive features of microwave plasma analyzer

A promising way to diagnose the mechanical systems washed by special fluids is the microwave plasma method of analysis. The method makes it possible to determine the shape of the presence of a metallic impurity (dissolved metal, wear particles), and other parameters of metallic particles (mass fraction, number, size, elemental composition of each particle). The principle of obtaining information on the parameters of a metallic impurity in the analysis of an oil sample is as follows.

A 1 ml sample of oil preliminarily prepared and prepared in an ultrasonic bath for analysis is taken to a disposable syringe dispenser 1, from which, with the help of a stepper motor drive, the oil is uniformly fed through the capillary to the ultrasonic nebulizer 2 at a rate of 100 μl/min. The oscillation frequency of the piezoceramic transducer of the ultrasonic nebulizer is about 22 kHz, and is adjusted to the resonance frequency of the directly spraying nozzle. Due to the lateral oscillations of the spray tube 4 made of stainless steel with an internal diameter of 0.75 mm, the oil flow entering the atomizer is converted into a fine aerosol consisting of liquid droplets with a size of no more than 10 μm and metal particles of micron sizes (wear products). The aerosol flows continuously into the excitation source of the spectra-the air plasma of a gas discharge of a microwave cyclotron-type microwave plasma torch – at a flow rate of 0.2 l/min for a flow of 0.2 l/min. The temperature of the air plasma is about 5200 K.

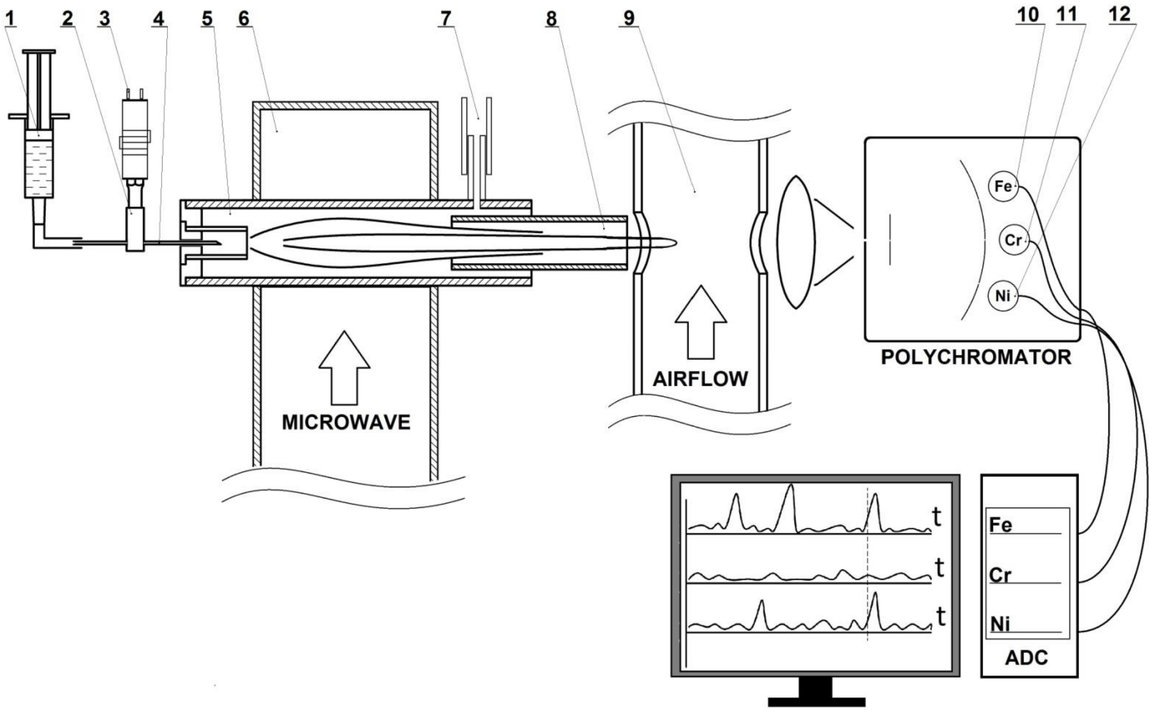

Figure 1. Schematic diagram of the microwave plasma spectrometer.

It is known that the analytical and information capabilities of spectral methods are determined by the parameters of the source of excitation of spectra (SES) and the method of separation and recording of the analytical signal. Therefore, let us dwell in more detail on the requirements for SES and its original design.

The microwave radiation supplied through the waveguide (6) maintains the microwave discharge of atmospheric pressure in the discharge chamber formed by a cylindrical quartz tube, the atomized oil supply unit, the swirler and the outlet nozzle (8). The plasma-forming gas is fed tangentially through the swirl nozzle (7) and exits through the exit nozzle, having heated in the microwave plasma. The combustion products of oil and metal vapor are ejected through the outlet nozzle and discharged to the outside with the aid of the device (9).

A distinctive feature of this design of the microwave plasma torch from all known is that due to the formation of a swirling flow having a radial component of the gas velocity directed toward the axis of the discharge chamber, the fine particles stabilize in the central zone of the plasma flame and do not reach the walls of the chamber. Due to this, the residence time of the particles in the plasma, the degree of their evaporation, the walls of the discharge chamber are not contaminated by the combustion products of the oil sample. Thus, the proportional relationship between the content and size of particles is kept to 60 μm, the coefficient of occurrence of metallic particles in the plasma is not less than 0.95.

The plasma torch is characterized by simple assembly and adjustment technology, high stability, comparable to the stability of gas flames, an extended plasma volume (the length of the jet is about 150 mm, the diameter of the high-temperature part is 5-6 mm).

The fail-safe operating time of the plasma torch greatly exceeds the guaranteed lifetime of the generator microwave lamp, which amounts to 2500 h.

In the microwave plasma complex, the original scheme for separating the analytical signal is also used.

Upon entering the plasma, the droplets of oil burn down, and the metal particles instantly heat up and evaporate. The resulting atomic vapor is excited, i.e. there is a burst of radiation (scintillation) from each evaporated particle. The rate of arrival of the analyzed sample is chosen such that the metallic particles of the microimpurity enter the plasma sequentially one at a time.

Radiation of atomic vapor with the help of a condenser is sent to a spectral device – a polychromator. The radiation spaced into the spectrum is registered by photomultipliers 10-12.

The duration of the radiation pulse of a particle is proportional to the time it is in the plasma and can range from 1 ms to 10 ms. Therefore, a sequence of pulses of different durations and amplitudes is formed at the output of the photomultipliers. Electric pulses from the photomultipliers are fed to the current-voltage converter and further processed by an analog-to-digital converter 13. The information for each analyzed sample is processed by a PC and recorded in a database.

Let us consider a method for introducing an analytic signal in a microwave plasma analyzer.

The analytical signal in the analysis of a sample including a dissolved metal (for example, an organometallic admixture) and a metal in the form of individual particles of micron size is generally a total signal consisting of a continuous equilibrium signal formed by the elements dissolved in the sample and a pulsed, evaporated metal particles, the signal from which exceeds significantly exceeds the value of the equilibrium signal. Such a signal, in fact, represents the sum of two random processes:

1. An equilibrium signal that is characterized by small noise amplitudes, a slow and smooth change in the mean value with time, and carrying information about the dissolved metal in the oil or (and) about the metal located in sub-micron particles smaller than 2 μm;

2. Pulse signal - individual non-overlapping pulses with a large amplitude (much greater amplitude of the background signal), carrying information about the elements contained in large wear particles.

The registration program provides separation of the analytical signal into two component signals, which are simultaneously processed by different programs.

By special calibration characteristics, the pulse signal is recalculated to the content of the elements that make up the wear particles, continuous - into the content of the element dissolved in the oil. The number of flashes (recorded pulses) is equal to the number of evaporated wear particles.

Figure 1 shows only three signal extraction channels, the number of them depends on the type of polychromator and can be increased. Each channel is configured to register flashes of the lines of the specified element.

When a particle enters the plasma, consisting, for example, only of iron, a sequence of radiation pulses will be present on channel 10.

In the case of complex metal particles consisting of several elements (for example, Fe-Ni steel) and simple ones, where each particle is represented by one element, then the PC sorts the radiation pulses by the simultaneity of their appearance.

The coincidence in time of two or more radiation pulses indicates the presence of a complex particle. In the diagram (Figure 1), coincident pulses along the Fe and Ni channels are presented as an example, which is identified as an alloy consisting of iron and nickel.

3. Parameters of particles of wearing in the analysis of the oil test and measured elements

The material presented above shows that when using an analytical sample in 1 ml, the analyzer outputs the following information in a time of 10 minutes:

1. content of the element in the oil sample in the form of wear particles (particle size more than 2 μm);

2. content of the element dissolved in oil and contained in the form of submicron particles (particle size less than 2 μm);

3. number of “simple” particles consisting of only one element;

4. number of “complex” particles consisting of two or more elements;

5. total number of wear particles;

6. average particle size of a given element;

7. the elemental composition of each wear particle.

It was noted above that the air supplied from the compressor is used as the plasma-forming gas. The use of air is a positive moment, as it does not require the delivery and use of more expensive gases - nitrogen and argon. On the other hand, the composition of the plasma-forming gas determines the plasma

IOP Conf. Series: Materials Science and Engineering **560** (2019) 012059 doi:10.1088/1757-899X/560/1/012059

temperature, which is of the order of 5200K. It is clear that such temperature imposes restrictions on the choice of the elements being analyzed.

However, to excite the atomic vapor of most elements used in the design of aviation gas turbine engines, such temperature is sufficient. This construction of the spectrometer allows simultaneously obtaining the parameters of particles of the following elements - Al, Cr, Ni, Mg, Fe, Ag, V, Cu, Mo, Ti, Mn.

4. Parameters of wear particles for sample wash from oil filter. Determination of ratings and wear indicators

The experience of using a microwave plasma analyzer for the diagnosis of friction points washed with lubricating oil showed, despite its high information content, it is not always possible to have reliable values of the technical state of the engine based on the analysis of the oil sample, drained from the gearbox. It is found that a significant increase in the reliability of diagnosis is achieved by measuring the parameters of the wear particles accumulated on the main oil filter. To this end, a technology was developed for obtaining a sample from an oil filter and the task was to determine the diagnostic features connecting the parameters of the wear particles with the technical state of the engine oil system components.

When assessing the technical condition of the engine lubrication system based on the analysis of the oil sample, there is no problem in the choice of diagnostic features. As such parameters, the absolute values of the mass fraction of the dissolved metal, the mass fraction of metals in the wear particles, the number of particles, etc. can be used.

The use of the same parameters for the sample wash from oil filter in practical practice is practically not applicable, since they depend on a greater number of factors that cannot be taken into account – filter life time, engine type, oil type, particle extraction from the filter, engine operating conditions, etc.

Therefore, we attempted to search for diagnostic features that would relate the technical state of the engine to the parameters of particles washed away from the main oil filter.

When measuring on a microwave plasma analyzer, attention was paid to the fact that in a working engine in an oil sample and a flushing sample, single-element, “simple” particles are present in fairly large quantities. With the appearance and development of damage, the number of “simple” particles decreased with simultaneous increase in particles consisting of two or more elements, “complex” particles.

This dependence was subsequently confirmed by the results of micro-X-ray spectral studies. Therefore, V_{gen}. is the ratio of the total number of “complex” wear particles (consisting of two or more elements) to the total number of “simple” wear particles (particles consisting of one element).

In addition, the parameter V_{elem} – the ratio of the number of “complex” wear particles to the number of “simple” wear particles for a particular element – was found.

The meaning of the selected parameters requires some clarification. The ratio of the number of complex particles to the number of simple wear particles V_{gen}. is an indicator of the overall technical state of the engine, since the regularity was noticed earlier: the lower this parameter, the better the state of the friction surfaces of engine parts and vice versa, an increase in this parameter indicated an increased wear of the engine parts.

Using the additional parameter V_{elem}, It is possible to define in more detail the type of the element responsible for increasing V_{gen}, And thus pay attention to the complex particles containing this element, which, in the final analysis, allows more accurate determination of the worn out engine assembly.

The following parameters were also found:

R_{gen} – the contribution of the total number of wear particles containing a certain element to the total number of wear particles (the rating of the wear particles by the elements);

R_{simple} – the contribution of the number of simple wear particles of a certain element to the total number of wear particles (the rating of simple wear particles by elements);

R_{comp}. – the contribution of a number of “compound” wear particles of a certain composition to the total number of wear particles (rating of complex particles of a certain composition, for example, Cu-Ag, Fe-Cr-Ni, etc.);

R_G – the number of different compositions of “complex” particles.

The rating of wear particles was calculated as the number of particles of a certain grade per 1,000 wear particles. This eliminates the effect of particle accumulation time on the filter, the degree of dilution of the sample, and so on.

Obviously, the rating error will be the lower, the more recorded wear particles. In oil samples, taken from the engines gearboxes, characterized by normal wear, the number of recorded particles in measurements on a microwave plasma spectrometer is not very large, on the order of several hundred, and the error in determining the rating is high. While in wash-offs from oil filters, the amount of wear particles is large enough that the error in determining the rating was minimal.

The maximum permissible errors in measuring ratings and wear indicators are given in Table 1.

Table 1. Limits of the permissible relative error in measuring ratings and wear indicators, $\pm D\%$, $P = 0.95$

Determined values	The number of determined particles, $n_{(det)}$, sm^{-3}						
	3-10	10-30	30-100	100-300	300-1000	1000-3000	3000-10000
R_{gen} R_{simple} R_G	60	40	30	20	15	10	10
V_{gen} V_{elem}	80	70	50	40	30	20	15

5. Conclusion

A microwave plasma method for obtaining information about a metallic impurity in oil samples of aviation gas turbine engines has been developed. The method makes it possible to simultaneously and expressly measure the mass fraction of the elements of the wear particles (larger than 2 μm in size), the mass fraction in the form of an organometallic impurity and submicron particles of less than 2 μm in size and the number and elemental composition of the particles.

In the analyzer, the original design of the electrodeless microwave plasma torch is used as a source of excitation of spectra, which differs from the known ones in that a swirling flow of a plasma gas having a radial velocity component directed toward the axis of the discharge chamber is formed in the plasma torch. Due to this, the metal particles stabilize in the central zone of the plasma flame (the zone of the highest temperature) and do not reach the walls of the chamber, which increases the residence time of the particles in the plasma, the degree of evaporation.

It was found that the proportional relationship between the content and particle size is kept up to 60 μm, the coefficient of occurrence of metallic particles in the plasma is not less than 0.95.

It has been revealed that when analyzing oil samples, single-element, “simple” particles and “complex” particles consisting of two or more elements are registered in fairly large quantities. At the same time, in a good engine, “simple” particles always prevail. With the appearance and development of damage, the number of “simple” particles decreases with a simultaneous increase in the number of “complex” particles. This effect was used as a diagnostic parameter for evaluating the technical state of the engine based on the analysis of flushing samples from the oil filter.

In addition, as a diagnostic feature in the analysis of flushing samples from the oil filter for engine diagnostics, a rating approach was used, which was calculated as the number of particles of a certain grade per 100 wear particles. This eliminated the effect of particle accumulation on the filter, the degree of dilution of the sample, and so on.

The limits of the permissible relative error in the measurement of ratings are estimated. So, with the number of registered particles for an exposure of more than 3000, the error does not exceed 15%.

IOP Conf. Series: Materials Science and Engineering **560** (2019) 012059 doi:10.1088/1757-899X/560/1/012059

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] Analysis of the impact of reliability on flight safety by aircraft type 2009 (Moscow: State Flight Safety Center) 148 p.
[2] Humphrey G, Rojas I, Churehill D, Cross D 2002 *JOAP Int. Condit. Monitor*. [Electron resource] available at: http://studylib.net/doc/8861620/the-secret-s---gastops-inc
[3] Toms A 2009 Using filter debris analysis to identify component wear in industrial applications [Electron resource] available at: http://www.testoil.com/downloads/Pdm_FDA_Paper.pdf
[4] Zaritsky S P, Stepanov V A Tupolev I F 1995 *1st Intern. Conf. “Energodiagnostika”* vol. 3 pp 293-306.
[5] Gastops website [Electron resource] available at: http://www.gastops.com/products/metalscan/.