Inhibiting Coking of Lubricating Oil and Thermal Insulation of Bearing Chamber Wall by TCA-2 Nitride Ceramic Coating

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ABSTRACT: High temperature around the rear bearing chamber of supersonic aero-engines often causes the coking of the lubricating oil on the shaft end cover. To figure out the problem, a method using the TCA-2 nitride ceramic coating with the thickness of several micrometers is proposed. A simulation experiment method of lubricating oil coking for high-temperature parts is developed, and the anticoking performance of the samples with the coating is studied. The results showed that the TCA-2 coating inhibits the coke of lubricating oil on the metal surface within a certain temperature range by about 40.7% under the 500 °C attributed to the decrease in the surface activity of high-temperature metal and increase in the heat resistance. The TCA-2 coating also shows good compatibility with the lubricating oil since the acid value change of lubricating oil decreases after the thermal oxidation experiment. The TCA-2 coating can effectively reduce the surface temperature of the oil side.

1. INTRODUCTION

As a part of the important systems to ensure the safe and reliable operation of aero-engines, the lubricating oil system can provide good lubrication and cooling to the engine bearings, gears, and accessory casings during engine operation. Its performance directly affects the operation, reliability, and life of aero-engines. With the improvement in the thrust—weight ratio of aero-engines, especially the need for higher speed, more stringent requirements are put forward for the high-temperature stability of lubricating oil. At the periphery of the rear bearing chamber of the engine, the environment temperature exceeds 450 °C. The turbine shaft temperature exceeds 600 °C (as shown in Figure 1), which far exceeds the maximum allowable temperature of the lubricating oil. After the engine shuts down, local high temperatures are caused by the effect of the thermal cocooning, while the lubricating oil circulation system is no longer working, which further increases the working temperature of the lubricating oil accumulated in the bearing chamber. When the temperature in the bearing chamber rapidly exceeds 350 °C, it is very easy to cause serious coking problems, which has become one of the important problems affecting the reliability of high-performance aero-engines.1

Aviation lubricating oil is prone to oxidation reaction under the conditions of high temperature, violent agitation, and full exposure to oxygen and metals, producing oxidation products such as organic acids, aldehydes, ketones, alcohols, esters, and gums. Acidic substances can corrode metals, while lacquer-like and char-like deposits can adhere to parts. Sediment is produced because colloids can be condensed into asphaltenes with less oxygen.2,3 Adding inhibitors is an important and effective way to solve the problem of coking; however, due to the rapid degeneration of additive performance at high temperatures, it is not suitable for engineering applications.
According to the results of related research, the temperature is an important factor in determining the coking of lubricating oil. When the temperature of lubricating oil increases, the dissolved oxygen in the lubricating oil induces some of its components to react to form hydroperoxides and other oxygen-containing coke deposits.\(^7\) As the temperature increases further, the lubricating oil begins to undergo thermal cracking, catalytic dehydrogenation, and other reactions on the surface of the high-temperature metal, forming thermal cracking and coking.\(^7\) Therefore, the use of inert coatings is expected to reduce the catalytic cracking coking activity of surface metal atoms, thereby effectively reducing high-temperature lubricating oil coking.

This paper proposes a method to restrain the high-temperature coking of lubricating oil with micron-level TCA-2 nitride coating and establishes a simulation method for high-temperature parts lubricating oil coking. The coking performance of specimens with and without coatings. A coating with high bonding strength, temperature resistance of 1200 °C and high temperature chemical inertness was prepared on the surface of the metal test piece. This coating can avoid direct contact between high-temperature lubricating oil and metal, and can inhibit catalytic oxidation and cracking to a certain extent. At the same time, the temperature of lubricating oil could be reduced due to the low thermal conductivity of the coating thus providing technical support for the highly reliable operation of aviation lubricating oil under more severe conditions.

2. TEST METHODS

2.1. Specimens. This paper focused on the coking test study of the ester aviation 4106 lubricating oil. The service temperature range of the 4106 lubricating oil is \(-40\) to \(200\) °C, and it can reach \(220\) °C in a short time. The main physical and chemical properties of the 4106 lubricating oil are shown in Table 1.

| item                        | test results |
|-----------------------------|--------------|
| kinematic viscosity, mm\(^2\)/s | \(-40\) °C 9974 |
|                             | 40 °C 25.2   |
|                             | 100 °C 5.11  |
|                             | 200 °C 1.36  |
| flash point (open), °C      | 260          |
| acid value, mgKOH/g         | 0.05         |

With reference to the corresponding structure of the engine, the metal test pieces were designed. The blank test piece is a high-temperature alloy metal sheet with a diameter of 34 mm and a thickness of 2 mm. TCA-2 coating has the advantages of high bonding strength, high-temperature oxidation resistance, low thermal conductivity, and chemical inertness. Therefore, the coating adopts TCA-2 nitride ceramic, and the coating thickness is 4 μm.\(^8,9\) The coating adopts TCA-2 nitride ceramic, and the coating thickness is 4 μm. The test pieces are shown in Figure 2.

2.2. Evaluation Method of the High-Temperature Coking Performance of Lubricating Oil. The researchers proposed many evaluation methods for high-temperature oxidation and coking of lubricating oil, such as oxidation stability and corrosiveness, pressure differential scanning calorimetry (PDSC), hot liquid process simulator (HLPS), inclined panel deposit test (IPDT), etc.\(^12-14\) PDSC is a technique that measures the exothermic or endothermic phenomenon of samples when heated under certain conditions. The deposition characteristics of oil under high temperatures are consistent with the test results.\(^15\) A HLPS can be used to evaluate the coking condition of ester lubricant oil under the condition of simulating gas turbine engine vent pipe flowing. The IPDT method uses lubricating oil to drip onto a slanted stainless steel plate that is constantly heated while maintaining air circulation. After a period of time, the characteristics or weight of the deposits formed on the steel plate are evaluated.\(^16\)

Considering the actual usage scenarios, Palekar et al.\(^17\) used the Penn-State micro-oxidation (PSMO) test method to evaluate the deposition tendency and thermal oxidation stability of diesel engine lubricants under conditions of high temperatures. The evaluation results show a good correlation with the engine test. Ku et al.\(^18\) developed a thin-film oxidation test (TFOT) method, which simulates the film oxidation test of automotive crankcase lubricants and evaluates the thermal oxidation stability of the oil under conditions of high temperatures.

These methods mainly assess the oxidative coking performance of the lubricating oil itself under conditions of high temperatures, or the evaluation of the coking performance under the working conditions of vehicle engines. For specific working conditions in aero-engines, the above methods cannot simulate the high-temperature working environment of a gas–oil mixture inside the bearing chamber.

To more realistically simulate the oil and air working conditions of the bearing chamber of aero-engines and estimate the thermal insulation and coking inhibiting performances of the TCA-2 nitride ceramic coating under extreme conditions, a new evaluation method for the high-temperature coking performance of lubricating oil was proposed by referring to HLPS and IPDT methods. To simulate the oil and gas environment of the engine, an experimental device for the high-temperature coking test of lubricating oil was designed. The thermal insulation and coking inhibiting performances of the TCA-2 nitride ceramic coating under different conditions were studied through performance tests.

2.3. Experimental Principle and Method. 2.3.1. Lubricating Oil Coking Simulation Experiment. To truly simulate the oxidation and coking of lubricating oil inside the bearing chamber at high temperatures, the oil coking experimental device was designed. The surface of the metal sheet is heated by high-temperature gas, while the lubricating oil and air are sprayed on the opposite sides of the metal sheet to simulate the process of oxidation and coking of the lubricating oil on the high-temperature wall.

The schematic diagram of a lubricating coking simulation test device at high temperatures is shown in Figure 3. The red
pipeline is the heating area of the purge gas. It is heated by applying a high-power direct current to both ends of the metal gas circuit with multiple turns. By adjusting the current value of the direct current, the temperature of the gas pipeline is controlled. When the gas flows through the pipeline, it is heated to the desired temperature. The orange pipeline is the lubricating oil preheating area. It sets the heating temperature of the high-temperature heating zone by winding a high-temperature heating tape outside the lubricating oil delivery pipeline, and the lubricating oil is heated to the required temperature when it flows through the pipeline. The green dotted line is the control instrument circuit. The preheating temperature, heating gas flow rate, lubricating oil flow rate, and test metal sheet temperature are all controlled by instruments and meters, and unified data is collected and stored in the computer.

The test process uses high-temperature air heating, and the schematic diagram of the test device is shown in Figure 4. The main device adopts a vertical spray heating device, and the metal sheet of the coking test piece is a round metal sheet (yellow area in Figure 4). The lubricating oil comes into contact with the metal sheet in the form of oil mist and then flows out from the outlet when it falls. The test was carried out by changing the heating temperature conditions. The heating temperatures were 500, 550, and 600 °C, and the test duration was 10 h.

The thermocouples were spot welded on both sides of the metal sheet. One side of the test piece was heated to a predetermined temperature, and then some lubricating oil was delivered to the heating zone at a constant flow rate by a lubricating oil supply pump. After adjusting the relevant parameters to the experimental predetermined values at the oil flow rate of 20 mL/min, the gas flow rate of 400 mL/min, and the oil temperature of 100 °C, the collector continued to collect the metal sheet wall temperature. After the experiment, the surfaces of the metal sheet were removed, cleaned, and dried naturally at room temperature. The appearance changes were compared in the morphology photograph, and the differences in the weight before and after the test were measured. Meanwhile, the acid value, density, and viscosity changes of the lubricating oil were measured.

2.3.2. Thermal Oxidation Experiment. The thermal oxidation experiment process referred to the test method GJB563 of aviation lubricating oil oxidation stability.19 The metal test pieces were tied together for the test and then put in a test tube filled with the lubricating oil. By heating to the oil temperature and injecting air continuously during a period, the performance changes of the lubricating oil (including appearance, acid value, density, viscosity, etc.) were obtained.

The test oil sample quantity is 165 mL, and the experimental conditions are shown in Table 2.

| Experiment | Temperature (°C) | Time (h) | Airflow Rate (mL/min) |
|------------|------------------|----------|----------------------|
| Experiment 1 | 175              | 72       | 83                   |
| Experiment 2 | 218              | 72       | 83                   |

2.4. Coking Quantity Analysis Method. Lubricating oil forms coking products on the surface of high-temperature metals, which are essentially macromolecular coking precursors formed by secondary reactions such as dehydrogenation and polymerization between the free radicals of the hydrocarbon components of the lubricating oil and other liquid compounds before the formation of the coking products. Coking or carbon deposits were formed under the catalytic action of the hot surface.20,21

This paper used the carbon burning method to analyze the amount of coking on the heat exchange wall. The principle is
to fully burn the coking deposits so that the carbon elements in
the carbon deposits are completely converted into carbon
dioxide, and the carbon dioxide quantity is measured by an
infrared analyzer to calculate the mass of the carbon deposits
(as shown in Figure 5).

3. RESULTS AND DISCUSSION

3.1. Coking Inhibition Experiment Analysis. In the
experiments, one side of the test piece was heated to 500, 550,
and 600 °C, respectively, and the test time was 10 h. The
comparisons of the coking quantities and appearance of the
test piece are shown in Figure 6. It is shown that the surface of
the metal blank sheet and the coating sheet showed differ-
ent degrees of coking.

The results show that when the gas heating temperature is
500 °C, the carbon deposition of the coated sheet is about
40.7% lower than that of the blank sheet. At the heating
condition of 550 °C, the carbon deposition of the coated sheet
is reduced by about 14% compared with the blank sheet. When
heated to 600 °C, the coating sheet is invalid for inhibiting
coking.

The reason for the above phenomenon is that the
deoxidization coking is greater than the oxidation coking at
high temperatures, and the reverse applies at low temperatures.
Therefore, the coating showed an obvious inhibition effect on
metal surface oxidation at temperatures lower than 550 °C.
However, the cracking coking reaction was dominant when the
heating temperature exceeded 550 °C. The results further
showed that the quantity of coking at the coating piece was
higher at 600 °C because coking is more likely to occur on the
rough surface coated by TCA-2 nitride ceramic.

3.2. Thermal Oxidation Experiment Analysis. The
lubricating oil attached to test pieces was cleaned with a
petroleum slit and dried at room temperature after the
experiment. Table 3 shows the comparison of appearance and
mass difference of the pieces between before and after the
experiments. It can be seen that the surface of the blank pieces
showed obvious discoloration and oxidation phenomenon,
while the color change is not distinct at the coating pieces.
After the experiments, mass differences were not detected for
all pieces, and no coating disbonding was found.

To obtain the change in the lubricating oil after the thermal
oxidation experiment, the mass difference, acid value, density,
and viscosity were measured and are listed in Table 4. As can
be seen from the table, the loss of mass of the lubricating oil
was less after experiments. It showed that some oil evaporated
in the conditions of high temperature and air injection.
Whether there is a coating on the surface of the metal has little
impact on the evaporation of the oil. It is can be seen that the
acid value of the oil was increased after the experiment because
of high-temperature oxidation. The metal can catalyze the
oxidation of petroleum-based lubricating oil, while the coating
can inhibit the thermal oxidation of the lubricating oil.
Therefore, the changes in the acid value of the oil are smaller
when the metal surface is coated. It can be seen from the
results that the density and viscosity of lubricating oil did not
change. Above all, we consider the TCA-2 coating has good
compatibility with the petroleum-based lubricating oil.

3.3. Product Analysis. Figure 7 shows the gas chromato-
gram of the lubricating oil after the 500 °C test on the blank
and coating samples. It can be seen that there is a cracking
component (~7%) on the blank sample but a relatively small
cracking component (~3%) on the TCA-2 coating sample. The
result indicates that the coating can effectively inhibit the
catalytic cracking reaction of oil at high temperatures, thus
reducing the formation of cracking coking products. The passivation feature of TCA-2 coating avoids the catalytic decomposition reaction of lubricating oil by high-temperature metals. It had a protective effect on the high-temperature coking of lubricating oil.

### 3.4. Coating Thermal Insulation Performance Analysis

In this research, the lubrication coking simulation experiment device was used to test the thermal insulation performance of the TCA-2 coating. In the tests, the lubricating oil passed through the surface of the test metal sample at the rate of 20 mL/min, while the other side of the sample was heated by a high-temperature (maximum 600 °C) gas at the rate of 400 mL/min. The test results are shown in Figure 8a. It can be seen that the temperature difference of the surface is small during low temperatures. As the temperature gradually increased, the whole trend of surface temperature in the blank sample increased more rapidly.

To further compare the thermal insulation performance of two different samples, the temperature differences between two sides of samples are shown in Figure 8b. It can be clearly seen from the figure that coating has little effect on the temperature differences in the low temperature. When the heating...
temperature exceeds 450 °C, the temperature differences reached more than 100 °C. Under the 600 °C heating condition, the temperature difference between the two sides of the coating sample is about 150 °C, which is over 25 °C higher than the difference of the blank sample. Combined with Figure 8a, the temperature of the coating oil side is more than 60 °C lower than that of the blank oil side. The results show that the coating can reduce the surface temperature of the oil side under the same lubricating oil test conditions. Thus, we consider that the TCA-2 coating exhibits good thermal insulation performance.

4. CONCLUSIONS

In this study, the lubricating oil coking simulation experiment was designed and completed by simulating the aero-engine oil and gas mixture environment. Accordingly, the inhibition of coking and thermal insulation performance of TCA-2 coating were obtained. The TCA-2 coating can reduce the coking quantities of lubricating oil on metal surfaces in a certain temperature range, which mainly inhibits the thermal oxidation and cracking of lubricating oil. The coating coking suppression effect is about 40.7% under the 500 °C heating condition. The TCA-2 coating shows good compatibility with a petroleum-based lubricating oil. The change in the acid value of lubricating oil decreased obviously after the thermal oxidation experiment. Under the 600 °C heating condition, the temperature of the oil side decreased by more than 60 °C compared with that of the uncoated sample. The coating can effectively reduce the surface temperature of the oil side and exhibit good thermal insulation performance.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The work is supported by the National Science and Technology Major Project of China.

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