Research Article
Effect of Temperature on the Chemical Composition and Physicochemical Properties of Diester Aviation Lubrication Oil

Ting Yao,1 Na Zhang,2 Jianqiang Hu,3 Xiaoxiao Liao,4 Yongli Shen,4 and Zhuoting Gan5

1Analysis and Test Center, Huangshan University, Huangshan 245041, China
2School of Chemistry and Chemical Engineering, Huangshan University, Huangshan 245041, China
3Department of Aviation Oil, Air Force Logistics College, Xuzhou 221006, China
4Unit 94923 of People’s Liberation Army of China, Wuyishan 354301, China
5School of Tourism, Huangshan University, Huangshan 245041, China

Correspondence should be addressed to Zhuoting Gan; ztgan73@126.com

Received 12 June 2020; Revised 26 July 2020; Accepted 26 August 2020; Published 4 September 2020

Academic Editor: Rui Wu

Copyright © 2020 Ting Yao et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

High temperature is the main factor responsible for degrading the lubrication and antiwear properties of aero-lubricating oils. Accordingly, this study assessed the effects of thermal treatment of diester aviation lubricating oil and the associated mechanism. Fourier-transform infrared spectroscopy and gas chromatography/mass spectrometry analyses showed that low-molecular-weight compounds, such as monoesters, diesters, alcohols, and olefins, were the primary degradation products. An assessment of the degradation mechanism of bis(2-ethylhexyl)decanedioate showed that pyrolysis, resulting in the cleavage of β-C–H and C–C bonds, was the main process involved. Additional investigation using advanced polymer chromatography showed that the molecular weights of oil samples changed slightly at high temperatures, while the viscosity and viscosity-temperature index values were relatively stable. High-pressure differential scanning calorimetry established that the thermal oxidation stability of these oils decreased above 250°C. Finally, variations in the chemical compositions of the oil samples were found to be highly correlated with changes in physicochemical properties during thermal processing, with the formation of low-molecular-weight polar compounds greatly increasing the acid numbers of the oils.

1. Introduction

The lubricating oils employed in engines have various important functions, such as cooling the engine, reducing abrasion by friction, and eliminating corrosive agents [1, 2]. Furthermore, just as human blood analysis can be used to assess the presence of disease, oil analysis can provide important information to facilitate early detection of machine failure [3]. With continued development in the aeronautical industry, the operating temperature of modern aeroengines has increased above 160°C, while turbine bearings can be heated as high as 280°C. When the cooling air flow is stopped, the bearing temperature can even exceed 400°C [4]. The performance of aero-lubricating oils (ALOs) inevitably deteriorates at such high service temperatures, with this process receiving increasing attention as an important risk factor in the field of aviation [5].

In contrast to mineral-based oils, synthetic lubricating oils (SLOs) are synthesized to perfectly match various working environments, based on modifying the molecular structure and function for the actual intended application [6]. Several different SLOs have been developed, including polyethers, esters, and synthetic hydrocarbons. However, SLOs based on synthetic hydrocarbons with sufficiently low viscosity and low acid number (AN) values at high temperatures can be difficult to obtain [7]. Ester oils prepared by dehydration and esterification reactions of acids and alcohols are relatively homogeneous [8], and ester lubricating oils (ELOs) show excellent resistance to thermal oxidation and wear, as well as low temperature fluidity, low volatility and toxicity, superior lubricating characteristics, and biodegradability [9–11]. Therefore, these oils can play important roles, such as lubricating, cooling, antirusting, and
sealing, under the harsh operating conditions found in aerospace applications and other industrial environments [12, 13]. The performance of ELOs is closely correlated with their molecular structure and chemical composition, while the viscosity and viscosity index of ELOs are largely determined by molecular conformation. Specifically, longer main carbon chains result in higher viscosity, viscosity index, and pour point values. However, both the viscosity and viscosity index increase, while the pour point decreases, when side chains are introduced [14]. The thermal decomposition and antioxidiant characteristics of ester oils are also affected by their molecular structure, although thermal decomposition and oxidation mechanisms are different for different oils [15].

High temperature is the primary factor responsible for reducing the lubricating effect of an ALO. Thermal stress not only induces cracking, oxidation, and polymerization [16] but also affects the physical adsorption of oil films on various surfaces. Specifically, high temperature can cause desorption, leading to the loss of oriented adsorption or melting of the oil film [17]. Furthermore, ELOs bearing various molecular structures exhibit different forms of degradation at high temperatures. Bian et al. [18] found that high temperatures, particularly hot spots, are among the main factors responsible for oil degradation. Meanwhile, Jiang reported that seven different ester-based lubricating oils subjected to high temperatures showed visible differences in degradation and stability [19]. Zong et al. [20] also reported that the viscosity of some ALOs was less affected by heating at 300°C, while Fan et al. [21] evaluated the physicochemical and tribological properties of synthetic ester lubricating oils isooyctyl furan dicarboxyrate (isooyctyl-FD), isooyctyl adipate (isooyctyl-A), and isooyctyl sebacate (isooyctyl-S). Isooyctyl-FD was determined to have thermal and oxidation stabilities comparable to those of isooyctyl-A and isooyctyl-S. The friction-reduction and antiwear properties of isooyctyl-FD were observed to be superior, while its viscosity changes with temperature and low-temperature properties were inferior. Wu et al. [16] investigated the oxidative degradation products of di-2-ethylhexyl sebacate (DEHS) by Fourier-transform infrared spectroscopy (FTIR) and gas chromatography-mass spectrometry (GC-MS). The results showed that oxidation and pyrolysis were the primary degradation processes of DEHS and that 2-ethyl-1-hexanol and mono(2-ethylhexyl) sebacate were the major degradation products. Additionally, some highly polar products were formed that had the potential to significantly improve the antiwear and friction-reducing properties of DEHS. Therefore, the performance of ALOs is largely dependent on their molecular structures and chemical compositions.

Although high-pressure differential scanning calorimetry (PDSC) can be used to assess the resistance of oils to oxidation at high temperatures, using this technique to explore the mechanism of high-temperature oxidative degradation at the molecular level is difficult [22–24]. Therefore, a number of modern analytical techniques have been proposed as alternatives. Kohler et al. [25] studied changes in ester-based ALOs employed in civil aviation aircraft after long-term usage. The Kohler group examined molecular-level degradation using electrospray ionization (ESI)-MS, liquid chromatography (LC)-ESI-MS, and LC-tandem MS. Frauscher et al. [26] investigated the decomposition of bis(2-ethylhexyl) adipate containing 4,4’-methylene-bis(2,6-di-tert-butylphenol) using 18O2 labelling with GC coupled with electron ionization MS, determining that the C–O ester bond was the primary site for oxidative attack. Qian et al. [27] examined the thermal oxidation mechanism of dioctyl adipate (DOA) using GC-MS and visual reactive force field molecular dynamics (ReaxFF MD). The results indicated that the AN increased significantly and the tribological properties were improved owing to the formation of highly polar carboxylic acids and low-molecular-weight monoesters. Jin et al. [28] compared the decomposition of DOA to that of trisdecyl trimellitate (TDTM) using both PDSC and ReaxFF MD and proposed atomic-level oxidation mechanisms for both compounds. TDTM was found to have superior resistance to oxidation owing to dissociation of the C–O bond in the alcohol chain being initiated for TDTM, while the C–O bonds in alcohol and ester groups in DOA were susceptible to oxidation. A greater number of DOA degradation fragments were identified, along with the formation of a polymerized product, while TDTM evidently did not generate any larger molecules.

The compositions of diester aero-lubricating oils (DEALOs) are complex (comprising base oils and various additives), and these materials have useful physical properties, including oxidative stability, good lubrication properties, and wear resistance, stability under extreme pressures, and high flash points. The properties of these substances are affected by temperature, load, and engine speed, resulting in uncertain and random degradation of physicochemical properties during service. Therefore, the degradation processes and products of DEALOs vary significantly based on their specific molecular structures. The effects of these structures on the stability of diesters have been investigated [16, 29, 30], although there have been few reports concerning changes in the structure and composition of DEALOs at elevated temperatures. Therefore, in-depth investigations of the structure-performance relationship associated with DEALOs during thermal treatment (TT) will provide a better understanding of the effects of TT on tribological performance. Additionally, information concerning changes in chemical composition will assist in evaluating the application limitations of DEALOs.

In this study, DEALOs were subjected to TT at 180, 200, 230, 250, 270, and 300°C. The treated specimens and a fresh oil sample were then fully characterized using a number of different analytical techniques, and the effects of TT on the physicochemical properties of the materials were investigated. Furthermore, correlations between the oil molecular structures and physicochemical properties (kinematic viscosity, viscosity index, AN, oxidation value, and degradation products) were also examined.

2. Materials and Methods

2.1. Materials. The DEALO sample was supplied by Unit 94923 of the People’s Liberation Army of China. This material comprised bis(2-ethylhexyl) decanedioate (BEHDD) as a base
oil together with additives including antioxidants, anti-
foaming agents, and preservatives. The kinematic viscosity
(KV) of the sample at 100°C was ≥3.2 mm² s⁻¹, the acid
number was ≤0.2 mg KOH g⁻¹, and the specified operating
temperature range was 60 to 200°C. All solvents used in
the experiments were commercially purchased analytical-grade
reagents that were purified by distillation prior to use.

2.2. Sample Preparation. In each trial, a DEALO (150 mL)
was heated for 2 h at 180, 200, 230, 250, 270, or 300°C in a 500-
ml stainless steel autoclave with stirring at 1,000 rpm under
the ambient air atmosphere with no pressurization. Each
sample was subsequently cooled and filtered to obtain
specimens referred to herein as DE₁₈₀, DE₂₀₀, DE₂₃₀, DE₂₅₀,
DE₂₇₀, and DE₃₀₀ respectively. An untreated oil sample stored
at room temperature (DE₉) was used as a reference sample.

2.3. Chemical Characterization. The DE₁₈₀, DE₂₀₀, DE₂₃₀,
DE₂₅₀, DE₂₇₀, DE₃₀₀, and DE₉ specimens were characterized by
FTIR spectroscopy ( Nicolet 380, Thermo Fisher, USA), GC-MS
(Hewlett-Packard 7890A/5975C, Agilent, USA), and APC
(AcQUITY APC, Waters, USA). Prior to FTIR analysis, each
sample was mixed with KBr and pressed into a pellet, from
which spectra were recorded over the wavenumber range of
400–4000 cm⁻¹. All samples were analyzed using an Agilent
7890A-5975C GC/MS system equipped with an HP-5 MS
capillary column (crosslinked 0.5% phenylmethyl siloxane;
30 m × 0.25 mm inner diameter; film thickness, 0.25 µm). The
electron impact mode ion source temperature was set at 230°C
with the electron energy set at 70 eV, and a quadrupole analyzer
was employed with an m/z range of 35–500. Data processing
was performed using MSD ChemStation software, and com-
pounds were identified by comparing mass spectra with
NIST08 library data. The relative content (RC) of each com-
pound was obtained using the peak area normalization method
N–H deformation vibration at 1591 cm⁻¹, –CH₂– (1355 cm⁻¹),
and C–N stretching vibration at 1670 cm⁻¹ were examined
with the mobile phase at a flow rate of 0.5 mL min⁻¹. Prior
to analysis, samples (5 mg) were dissolved in THF (1.5 mL) and
the injection volume was set at 10 µL. These analysis conditions
were based on a previously reported procedure [31].

2.4. Physicochemical Properties. The KV values of the spec-
imens were determined at 40 and 100°C based on the method
GB/T 265/1998 (2004), and the AN of each sample was obtained
using the method GB/T 265/1998 (2004). Each measurement
was repeated three times to ensure the accuracy of the data.
Degradation and oxidation of each of the seven oil samples
were evaluated using synthetic turbine module from the In-
Service Lubricants Analysis Pack in the FTIR software. Spectral
ranges of 3595–3500 cm⁻¹ and 1800–1670 cm⁻¹ were examined
to assess degradation and oxidation, respectively. In each trial,
approximately 2.5 mL of the oil sample was forced through a
flow cell using a syringe (taking care to exclude air bubbles) after
which spectra were acquired.

2.5. Thermal Stability. The thermal stabilities of the seven oil
samples were assessed using a DSC 8000 instrument (Per-
kinElmer, USA). The initial oxidation temperature (IOT) of
each specimen was obtained based on the method QJ/DSH
275-1998. In each trial, an oil sample (0.6 mL) was transferred
into an open aluminum pan that was subsequently sealed. The
specimen was then heated from 50 to 300°C at 20°C min⁻¹
under an oxygen flow rate of 20 mL min⁻¹ and oxygen
pressure of 3.5 MPa. The oxidation induction time (OIT) was
determined using the method SH/T 0719-2002. In each ex-
periment, an oil sample (1.0 mL) was first held at 50°C, then
heated to 220°C at 160°C min⁻¹ under nitrogen. Subsequently,
high-purity oxygen was rapidly passed into the heating
chamber until the oxygen pressure reached 3.5 MPa, after
which oxygen flow was kept constant at 20 mL min⁻¹.

3. Results and Discussion

3.1. Chemical Characterization of Oil Samples

3.1.1. FTIR Analysis. In complex molecules, functional groups
are typically the most important structural components [32].
FTIR spectroscopy is helpful in this regard, having been used for
many years to determine the distribution of functional groups in
lubricating oils [33]. The FTIR spectra of the seven oil samples
following various TT processes were found to be similar, with
few changes after heating. Therefore, only the spectra of DE₉,
DE₂₂₀, and DE₃₀₀ are provided in Figure 1. These spectra
exhibited peaks attributed to –CH₃ and –CH₂– (2959, 2930, and
2859 cm⁻¹), –CH₂– (1464 cm⁻¹), –CH₃ (1372 cm⁻¹), and –(CH₃)₃
(727 cm⁻¹) groups, indicating that these samples contained long-chain
alkanes. Peaks attributed to C=O (1737 cm⁻¹) and C–O–C
(1174 cm⁻¹) groups were also present, confirming the presence
of fatty acid esters. The N–H stretching vibration at 3463 cm⁻¹,
N–H deformation vibration at 1591 cm⁻¹, and C–N stretching
vibration at 1355 cm⁻¹ all confirmed that the samples contained
amine antioxidants, while the peak at 1241 cm⁻¹ further indi-
cated that these were aromatic secondary amines. The peaks
present at 3544, 1097, and 1013 cm⁻¹ suggested the presence
of alcohols, and the peak at 1420 cm⁻¹ was attributed to phenyl-P
moieties. As increasing the temperature did not significantly
affect these functional groups, the ester, amine, and alcohol
functional groups were evidently unaffected by heating.

3.1.2. GC-MS Analysis. As shown in Figures 2(a)–2(c)
and Table 1, a total of 53 organic compounds were detected in
the seven oil samples. These included six hydrocarbons (HCs),
one alcohol, 20 esters (10 monoesters, eight diesters, one
triester, and one carbonate), 17 additives and additive
derivatives (ADs), and nine other compounds (OCs). A
total of 32, 35, 35, 36, and 36 compounds were found in the
series of samples from DE₉ to DE₂₅₀, respectively, with
minimal variation in the types and amounts of these
compounds below 250°C. In contrast, at 270 and 300°C, 42
and 48 compounds were detected in DE₂₇₀, respectively.
Total ion chromatograms (Figure 2(b)) showed significant
variation in compounds prior to heating for 12 min, with
hydrocarbons and monoesters comprising the majority of
Figure 1: FTIR spectra of DE₀, DE₂₃₀, and DE₃₀₀ samples.
Figure 2: (a) Total ion chromatograms of oil samples after heating at different temperatures. (b) Total ion chromatograms of various oil samples over a retention time range of 1.4–12.4 min. (c) Total ion chromatograms of oil samples over a retention time range of 12.6–24.0 min.
| Peak | RT (min) | Compounds                               | CAS number | Chemical formula | Molecular weight | Structural formula | Relative content (%) |
|------|---------|-----------------------------------------|------------|-----------------|------------------|-------------------|----------------------|
| 1    | 1.571   | (1R,2R)-1,2-dimethylcyclopentane        | DEr        | C_{7}H_{14}     | 98               | ![Hydrocarbon](image) | 0.013                |
| 2    | 1.656   | 2-Methyl-4-methylene hexane             | DE180      | C_{8}H_{16}     | 112              | ![Hydrocarbon](image) | 0.093 0.144 1.344    |
| 8    | 4.687   | Hexadec-1-ene                           | DE200      | C_{16}H_{32}    | 224              | ![Hydrocarbon](image) | 0.009                |
| 9    | 4.755   | (Z)-hexadec-3-ene                       | DE230      | C_{16}H_{32}    | 224              | ![Hydrocarbon](image) | 0.014                |
| 10   | 4.865   | (Z)-hexadec-8-ene                       | DE250      | C_{16}H_{32}    | 224              | ![Hydrocarbon](image) | 0.006                |
| 11   | 5.171   | 5,6-Dipropyldecane                      | DE270      | C_{16}H_{34}    | 226              | ![Hydrocarbon](image) | 0.011 0.012 0.010 0.011 0.009 0.008 0.019 |
| 3    | 2.161   | 2-Ethylhexan-1-ol                       | Alcohols   | C_{8}H_{14}O    | 130              | ![Alcohols](image)   | 0.043 0.064 0.136 0.610 0.552 0.704 0.643 |
| 4    | 2.640   | 2-Ethylhexyl acetate                    | Esters     | C_{10}H_{20}O_{2} | 172            | ![Esters](image)     | 0.086                |
| 5    | 3.160   | 2-ethylhexyl isobutyrate                |            | C_{12}H_{24}O_{2} | 200           | ![Esters](image)     | 0.019                |
| 6    | 3.742   | 2-Ethylhexyl butyrate                   |            | C_{12}H_{24}O_{2} | 200           | ![Esters](image)     | 0.014 0.028          |
| 7    | 4.474   | 2-Ethylhexyl pentanoate                 |            | C_{13}H_{26}O_{2} | 214           | ![Esters](image)     | 0.019 0.054          |
| 12   | 5.260   | 2-Ethylhexyl hexanoate                  |            | C_{14}H_{28}O_{2} | 228           | ![Esters](image)     | 0.020 0.009 0.014 0.036 |
| 14   | 5.990   | 2-Ethylhexyl 2-ethylhexanoate           |            | C_{16}H_{32}O_{2} | 256           | ![Esters](image)     | 0.018 0.015 0.015 0.022 0.018 0.018 0.025 |
| 16   | 6.824   | 2-Ethylhexyl 2-methoxyacetate           |            | C_{14}H_{22}O_{3} | 202           | ![Esters](image)     | 0.018 0.168          |
| 17   | 6.881   | 2-Ethylhexyl octanoate                  |            | C_{16}H_{32}O_{2} | 256           | ![Esters](image)     | 0.012 0.023 0.068    |
| 18   | 7.702   | 2-Ethylhexyl isobutyl carbonate         |            | C_{15}H_{26}O_{3} | 230           | ![Esters](image)     | 0.025 0.045 0.029 0.207 0.470 0.785 3.123 |
| 19   | 7.916   | 2-Ethylhexyl decanoate                  |            | C_{16}H_{36}O_{2} | 284           | ![Esters](image)     | 0.073                |
### Table 1: Continued.

| Peak | RT (min) | Compounds | CAS number | Chemical formula | Molecular weight | Structural formula | RELATIVE CONTENT (%) |
|------|---------|-----------|------------|------------------|------------------|-------------------|----------------------|
| 21   | 9.358   | Isopentyl undec-10-enoate | 10214-27-4 | C_{16}H_{30}O_{2} | 256              | ![Structure](structure1.png) | 0.022 0.033 0.036 0.024 0.036 0.018 |
| 24   | 11.189  | Ester     | 370        |                  |                  |                   | 0.466                |
| 27   | 11.893  | Bis(2-ethylhexyl) adipate | 103-23-1 | C_{22}H_{42}O_{4} | 370              | ![Structure](structure2.png) | 1.752 1.692 1.628 1.651 1.644 1.665 1.743 |
| 30   | 12.572  | 1-butyl 10-(2-ethylhexyl) decanedioate | 1000354-19-9 | C_{22}H_{42}O_{4} | 370              | ![Structure](structure3.png) | 0.085 0.780 0.115 0.138 0.143 0.213 |
| 34   | 12.998  | 1-(2-Ethylhexyl) 10-isobutyl decanedioate | 1000354-19-8 | C_{22}H_{42}O_{4} | 370              | ![Structure](structure4.png) | 1.752 1.692 1.628 1.651 1.644 1.665 1.743 |
| 46   | 14.913  | Isomer of 47 | 122-62-3 | C_{26}H_{50}O_{4} | 426              | ![Structure](structure5.png) | 0.360 0.468 0.383 0.516 0.344 0.467 0.210 |
| 47   | 15.658  | Bis(2-ethylhexyl) decanedioate | 122-62-3 | C_{26}H_{50}O_{4} | 426              | ![Structure](structure6.png) | 85.712 84.436 85.89 84.443 85.367 83.533 78.412 |
| 49   | 16.899  | 1,2,3-Propanetri-carboxylic acid | 070289-34-8 | C_{18}H_{38}O_{7} | 402              | ![Structure](structure7.png) | 0.145 0.163 0.182 0.175 0.208 0.307 0.210 |
| 51   | 18.491  | Bis(2-ethylhexyl) dodecanedioate | 19074-24-9 | C_{26}H_{50}O_{4} | 454              | ![Structure](structure8.png) | 2.122 2.113 1.959 2.186 2.036 1.899 2.335 |
| 53   | 23.722  | 2-Ethylhexyl octadecyl oxalate | 1000357-85-7 | C_{26}H_{50}O_{4} | 454              | ![Structure](structure9.png) | 0.065 0.380 |

| Additives | |
|-----------|-------------|
| 20        | 9.074 (E)-4,4’-(ethene-1,2-diyl)dianiline | 7314-06-9 | C_{16}H_{14}N_{2} | 210 | ![Structure](structure10.png) | 0.086 0.088 0.075 0.068 0.089 0.080 0.057 |
| 22        | 10.513 N-Phenyl-1-naphthylamine | 90-30-2 | C_{16}H_{13}N | 219 | ![Structure](structure11.png) | 1.044 1.232 0.981 0.884 0.858 0.787 0.865 |
| 25        | 11.338 N-(2-methylheptan-2-yl)-N-phenylaniline | 1000370-31-3 | C_{20}H_{27}N | 281 | ![Structure](structure12.png) | 0.173 0.168 0.168 0.163 0.149 0.169 0.123 |
| 26        | 11.465 Bis(4-(tert-butyl)phenyl)amine | 1000370-31-1 | C_{20}H_{27}N | 281 | ![Structure](structure13.png) | 0.075 0.063 0.074 0.057 0.069 0.066 0.041 |
| 28        | 12.085 Triphenyl phosphate | 115-86-6 | C_{18}H_{15}O_{4}P | 326 | ![Structure](structure14.png) | 0.729 0.708 0.653 0.699 0.711 0.752 0.886 |
| 29        | 12.471 Isomer of 31 | | C_{19}H_{17}O_{4}P | 340 | ![Structure](structure15.png) | 0.096 0.15 0.096 0.087 0.099 0.103 |
| 31        | 12.668 Diphenyl o-tolyl phosphate | 5254-12-6 | C_{19}H_{17}O_{4}P | 340 | ![Structure](structure16.png) | 1.399 1.381 1.294 1.340 1.305 1.275 1.615 |
| Peak | RT (min) | Compounds | CAS number | Chemical formula | Molecular weight | Structural formula | Relative content (%) |
|------|---------|-----------|------------|------------------|-----------------|-------------------|---------------------|
| 32   | 12.891  | Diphenyl p-tolyl phosphate | 78-31-9 | C₁₉H₁₇O₄P | 340 | ![Structural formula](image) | 0.895 0.872 0.832 0.874 0.796 0.806 0.912 |
| 36   | 13.292  | Phenyl di-p-tolyl phosphate | 034909-69-8 | C₂₀H₁₉O₄P | 354 | ![Structural formula](image) | 1.47 1.423 1.281 1.449 1.342 1.366 1.571 |
| 38   | 13.556  | Isomer of 36 | | C₂₀H₁₉O₄P | 354 | ![Structural formula](image) | 0.935 1.146 1.035 0.941 0.898 0.881 1.23 |
| 40   | 13.831  | Isomer of 36 | | C₂₀H₁₉O₄P | 354 | ![Structural formula](image) | 0.532 0.528 0.437 0.427 0.394 0.537 0.343 |
| 41   | 13.931  | Isomer of 43 | | C₂₂H₂₁O₄P | 368 | ![Structural formula](image) | 0.231 0.335 0.276 0.253 0.248 0.321 0.292 |
| 42   | 13.980  | Isomer of 43 | | C₂₂H₂₁O₄P | 368 | ![Structural formula](image) | 0.396 0.388 0.322 0.329 0.265 0.379 0.328 |
| 43   | 14.289  | Tri-m-tolyl phosphate | 563-04-2 | C₂₃H₂₁O₄P | 368 | ![Structural formula](image) | 0.891 0.897 0.786 0.806 0.784 0.851 0.904 |
| 44   | 14.619  | Tri-p-tolyl phosphate | 78-32-0 | C₂₃H₂₁O₄P | 368 | ![Structural formula](image) | 0.206 0.217 0.215 0.246 0.272 |
| 50   | 17.893  | Dioctyl diphenylamine | 101-67-7 | C₂₈H₄₃N | 393 | ![Structural formula](image) | 0.147 0.163 0.162 0.151 0.124 0.187 0.154 |
| 52   | 19.038  | Bis(4-(2,4,4-trimethylpentan-2-yl)phenyl)amine | 15721-78-5 | C₂₈H₄₃N | 393 | ![Structural formula](image) | 0.034 |

| Others | |
|--------|--|
| 13     | 5.444 | Unknown | 240 | 0.018 | 0.008 |
| 15     | 6.068 | Unknown | 240 | 0.039 | 0.029 | 0.04 | 0.044 | 0.047 | 0.051 | 0.109 |
| 23     | 10.811| Unknown | 0.041 |
| 33     | 12.956| Isomer of 33 | 354 | 0.182 | 0.177 | 0.177 | 0.207 | 0.149 | 0.138 | 0.101 |
| 35     | 13.06 | 1-((7-Methoxybenzo[d][1,3]dioxol-5-yl)methyl)-4-(3-methylbenzyl)piperazine | 100294-50-4 | C₂₁H₂₆N₂O₃ | 354 | ![Structural formula](image) | 0.159 | 0.170 | 0.137 | 0.154 | 0.128 | 0.151 | 0.122 |
| 37     | 13.479| Unknown | 368 | 0.135 | 0.154 | 0.119 | 0.130 | 0.103 | 0.127 | 0.101 |
| 39     | 13.598| Unknown | 368 | 0.281 | 0.192 | 0.204 | 0.198 | 0.240 | 0.189 |
| 45     | 14.692| (E)-1-benzyl-2-((2,6-dimethyltetrahydro-[1,3]dioxino[5,4-d][1,3]dioxin-4-yl)methylene)-1-phenylhydrazine | 1000129-05-9 | C₂₂H₂₆N₂O₄ | 382 | ![Structural formula](image) | 0.331 | 0.257 | 0.34 | 0.32 | 0.310 |
| 48     | 16.664| Unknown | | | | | 0.128 | 0.085 | 0.078 | 0.1 |

RT: retention time.
these species. Overall, the data showed that these DEALO samples were highly resistant to thermal oxidation and exhibited minimal evaporation.

Table 1 indicates that hydrocarbons in the oils ranged from C7 to C16, including one cycloalkane, four olefins, and one isoparaffin. Dimethyl cyclopentane (1) and three hexadecene isomers (8–10) were detected only in DE300, while 2-methyl-4 methylene hexane (2) was found in samples DE230–DE300 after heating above 230°C. As the temperature was increased, compound variation and RC values also increased. A total of six different species were eventually identified and the RCs of the hydrocarbons increased to 1.40% for DE300. A total of 20 different esters, ranging from C10 to C28, were found in the seven samples, including ten monoesters, eight diesters, one carbonate, and one triesters. The number of different esters found in DEr, DE180, DE200, DE230, DE250, DE270, and DE300 was 8, 10, 9, 10, 15, and 19, respectively. Few changes in these esters were observed below 270°C, but further variation occurred above this temperature, suggesting fragmentation of the long-chain base oils. The variety of monoesters also increased above 270°C. C10–C13 (4–7) and C14 monoesters (19), as well as 2-ethylhexyl 2-methoxyacetate (16), were only detected following heating above 270°C. The monoester/diester ratios were 2:5, 4:5, 4:5, 3:5, 4:5, 7:6, and 9:8 in DEr, DE180, DE200, DE230, DE250, DE270, and DE300, respectively.

The same esters showed varying RCs for different oil specimens. Specifically, the RC of 2-ethylhexyl isobutyl carbonate (18) increased across the DEr–DE300 series, and the RC values for 1-butyl 10-(2-ethylhexyl)decanedioate (30) also increased with increasing temperature above 230°C. However, the RC for base oil BEHDD (47) varied only slightly below 270°C, with values of 85.712, 84.436, 85.890, 84.443, 85.367, and 85.533%, respectively. Increasing the temperature to 300°C reduced the RC for base oil BEHDD (47) to 78.412%. Therefore, polymerization reactions were likely promoted with increasing temperature, with the rate of polymerization exceeding the rate of bond cleavage. GC-MS analysis identified 2-ethylhexyloctadecylxolalate (53) following heating at 270 and 300°C, with a molecular weight of 454. The present GC-MS analysis was only able to detect volatile nonpolar or weakly polar compounds with molecular weights of less than 500 Da, such that the majority of polymers could not be detected. However, the APC results confirmed that polymerization occurred in these oil samples as the temperature increased. As these polymers were able to almost completely dissolve in the oil, there was almost no change in the molecular weight, even at 300°C.

3.2. Physicochemical Properties of Oil Samples

3.2.1. Viscosity and Acid Number. Viscosity is among the most basic physical properties of a lubricating oil. This property is related to the internal friction coefficient of the fluid and directly affects the lubricating characteristics of the oil [36]. As shown in Figure 4, the KV values of the DEALO specimens at 40 and 100°C (\(\nu_{40}\) and \(\nu_{100}\)) were 11.17 and 3.24 mm²/s, respectively, and no obvious changes were observed after heating. The viscosity index (VI) represents the degree of change in viscosity with temperature for a fluid [37, 38]. The VI for the fresh oil sample was determined to be 168.53, which is typical for a very high grade material. With increasing temperature, the VI initially decreased, then increased, and finally decreased again. Small molecular compounds (SMCs) were concluded to be present at higher concentrations than high-molecular-weight compounds (HMWCS) below 200°C owing to some pyrolysis. Therefore, the VI values of DE180 and DE200 were lower than that of DEr.

As the temperature was continually increased, WMCs were generated as a result of thermal oxidation processes [39, 40], although the oil viscosity did not significantly increase [39, 41, 42]. The GC-MS data indicated that various SMCs, including HCs, alcohols, monoesters, and other compounds, also appeared at high temperatures. Simultaneously, the antioxidants and antiwear agents were decomposed into these SMCs, which negatively affected the viscosity-temperature characteristics of the oils [16]. The VI values of the oil samples exhibited less variation at relatively high temperatures, with
values ranging from 168.93 to 162.13. Overall, these data show that this DEALO was close to being an ideal lubricating oil [43, 44] suitable for use in aeroengines.

In contrast to the viscosity values, the AN of each oil sample changed dramatically with heating at different temperatures. As shown in Figure 5, no large variations in AN were observed below 230°C, with values of 0.14, 0.19, and 0.24 mg KOH g⁻¹ for samples DEr–DE200, respectively. However, the AN value was increased to 0.77 mg KOH g⁻¹ in DE230, which exceeded the typical useable upper limit of 0.5 mg KOH g⁻¹. As the temperature was further increased, the AN values also increased, at 1.07, 2.15, and 10.62 mg KOH g⁻¹ for DE250, DE270, and DE300, respectively, all of which greatly exceeded the normal useable range. Acidic compounds in such oils are primarily generated from decomposition of the base oils and additives [45]. Specifically, acidic colloids are produced by oxidation of the base oils, and extreme pressure antitrust agents and rust inhibitors that contain phosphorus or sulfur can readily form acids. The present DEALOs were primarily composed of BEHDD, amine antioxidants (n-phenyl-1-naphthylamine and dioctyldiphenylamine), and an antiwear agent (tri-o-tolylphosphate). The terminal alcohol group in diisoxide sebacate has an active hydrogen because hydrogens bonded to β-carbons are prone to thermal decomposition to produce six-membered cyclic intermediates that decompose to acids and alkenes [46]. Olefins in the oils were identified during GC/MS analysis [8–10], and the formation of these compounds was attributed to cracking, which also generated alcohols, aldehydes, and carboxylic acids by reactions with oxygen. An alcohol (3), a carbonate (16), low-molecular-weight monoesters, and some unknown compounds containing carboxyl groups (13,15) were also identified. Decomposition of the antioxidants and antiwear agent to form acidic derivatives at high temperatures would be expected to greatly increase the AN of the oil samples. When this value is increased sufficiently, the oil will begin to corrode metal parts and shorten the service life of the machine in which it is used. Furthermore, high-molecular-weight polymers will form a sludge, while cracking will generate low-molecular-weight acids that are highly soluble in the oil owing to the excellent solubility of esters. Consequently, the AN can increase by several orders of magnitude [47, 48]. The formation of these acidic compounds will also increase the polarity of the oil [49]. Polar compounds can improve the strength of oil films and, therefore, enhance the lubrication ability of the oil [16, 50], although such films can also be disrupted at elevated temperatures and high engine loads. For these reasons, DEALOs provide superior lubrication in the operational temperature range of ~60 to 200°C.

3.2.2. Oxidation Value and Degradation Products. As shown in Figure 6, higher temperatures promoted both degradation and oxidation. The degradation values determined for the DEr–DE300 series from FTIR analysis were 4.78, 5.46, 7.39, 9.87, 12.91, 16.19, and 20.22, respectively. Therefore, the extent of degradation was concluded to be limited below 230°C but sharply increase above this temperature. This trend was similar to that exhibited by the AN data. The oxidation values increased relatively slowly below 270°C but increased more steeply from DE270 to DE300. These data confirmed that oxidation reactions occurred to a significant extent at high temperatures. Both the oxidation and
pyrolysis reactions of ester-based oils can occur at such temperatures, and the main products (carbonyl-containing compounds such as acids, monoesters, and aldehydes) can further increase the acidity of the oil and promote the degradation of additives.

3.3. Thermal Stability of Oil Samples. The high-temperature oxidation stability (HTOS) of an ALO refers to its ability to resist oxidation and degradation at elevated temperatures. HTOS is not only an important indicator of performance but also a key parameter that determines the maximum operating temperature of the oil. Therefore, a detailed investigation of the HTOS is crucial to improve the oil quality and select the optimal oil for a given application. PDSC assesses the oxidation of a thin film of oil, simulating the oxidation of lubricating oils under working conditions [51]. This technique can evaluate the oxidative stability of lubricating base oils and performance of antioxidants and has the advantages of being fast, accurate, and reproducible. In PDSC, IOT and OIT are determined using temperature-programmed and constant-temperature methods. Higher IOT and OIT values reflect better oxidation resistance in an oil. In the present work, a constant temperature of 210°C was applied during OIT analysis. Assessing the TOS of aviation oils is important, but challenging [52]. As shown in Figure 7, the IOT for DEr was found to be 254.69°C, with an inflection point at this temperature followed by a significant decline. The IOT for DE300 was much lower, at 243.37°C. An OIT was observed at 210°C with an inflection point at 250°C, such that the OIT of DE300 was only 17.11°C. Overall, the TOS values for the DEALOs were better below 250°C, although these oils continue to be used as the main lubricating oils for aeroengines at present.

3.4. Possible Degradation Mechanism. The TOS values of DEALO samples were evidently affected by the molecular structure of the ester. The activation energy will also be different for different compounds, and the deterioration mechanism will vary at high temperatures [53, 54]. The TOS of BEHDD is largely determined by the reactivity of the hydrogen atom on the β-carbon of the alcohol group. This hydrogen can combine with a carbonyl oxygen atom in the ester to form an intramolecular hydrogen bond and generate a six-membered ring structure. When heated, the C–H bond at the β-position breaks, producing olefins and carboxylic acids that are corrosive to metals (Figure 8).

The thermal oxidation of esters is believed to typically proceed via a free radical chain reaction initiated by light or heat and catalyzed by metals, involving initiation, propagation, and termination. As shown in Figure 9, the oxidation of lubricating oils eventually generates ketones and aldehydes, which form sludge and other deposits that limit the service life of the oil and reduce its high-temperature performance [55]. Adding antioxidants to lubricating oils can be beneficial, and the two antioxidants used in this study were arylamine antioxidants (AAAXs) with excellent high temperature antioxidation properties. AAAXs act as free radical scavengers [56] by combining with free radicals to eliminate them. The present experiments were performed with some exposure to air, but few thermal oxidation products were detected by GC-MS. Pyrolysis is suggested to be the main thermal degradation mechanism of BEHDD, such that pyrolysis and cleavage of β-C–H and C–C bonds primarily occur (Figure 10) [16, 26, 57].

As shown in Figure 10(a), BEHDD can be hydrolyzed at high temperatures. The C–O ester bond is preferentially cleaved to generate products such as 2-ethylhexan-1-ol (3) and 2-ethylhexyl-10-oxodecanoate, which can be further oxidized to the more stable 10-((2-ethylhexyl)oxy)-10-oxodecanoic acid. Thermal cleavage can also occur at the C2–C3 bond in the alcohol chain, generating 1-butyl-10-(2-ethylhexyl)
**Figure 9**: Oxidation process scheme for lubricating oils.

**Figure 10**: Continued.
decanedioate (30) (Figure 10(b)). As shown in Figure 10(c), cleavage of the \( \beta \)-C–H bond can proceed via a six-membered cyclic intermediate at high temperatures to produce free radicals I and II. The latter can form 10-((2-ethylhexyl)oxy)-10-oxodecanoic acid. In contrast, the former is an unstable eight carbon alkene that undergoes a number of chemical reactions, such as free radical rearrangement and chain propagation at high temperatures, to give 2-methyl-4-methylenehexane (2), hexadec-1-ene (8), (Z)-hexadec-3-ene (9), (Z)-hexadec-8-ene (10), and 5,6-dipropyldecane (11). Cleavage of the ester C–C bond can also occur, providing 2-ethylhexyl acetate (4), 2-ethylhexyl butyrate (6), 2-ethylhexyl pentanoate (7), 2-ethylhexyl octanoate (17), 3-methylheptan-2-yl nonanoate (18), and 2-ethylhexyl octadecyl oxalate (53). Finally, free radicals I and III can combine to form 2-ethylhexyl 2-ethylhexanoate (14).

**4. Conclusions**

This work investigated the effects of heating on the properties of DEALOs. The main conclusions are as follows.

During the initial heating process, pyrolysis was the primary result, along with polycondensation. Antioxidants and antiwear agents were degraded to some extent to generate chromophores or auxochromes that darkened the oils. Degradation of the oils was relatively limited below 250°C, with no obvious changes in the chemical constituents. The RC values for BEHDD at 270 and 300°C were significantly lower than that of the fresh oil, and analysis of the degradation mechanism showed that pyrolysis and cleavage of \( \beta \)-C–H and C–C bonds were the main contributors to decomposition. Lower molecular weight compounds, such as monoesters, diesters, alcohols, and olefins, were all generated at high temperatures. Polymerization produced a sludge while low-molecular-weight compounds generated by cracking dissolved almost completely in the oil sample, such that the viscosity and VI were relatively stable. The appearance of SMCs, including monoesters, alcohols, and olefins, as well as acidic derivatives of additives, greatly increased the NA values of the oil samples. These compounds can improve the strength of oil films and enhance the lubrication ability of the oil to some extent.

**Data Availability**

All data generated or analyzed during this study are included in this article.

**Conflicts of Interest**

The authors declare no conflicts of interest.

**Acknowledgments**

This research was funded by the Anhui Provincial Natural Science Foundation of China (grant no. 1908085ME162), the Open Research Project of Anhui Simulation Design and Modern Manufacture Engineering Technology Research Center (Huangshan University; grant no. SGCZXZD1902), and the Jiangsu Provincial Natural Science Foundation of China (grant no. BK20191155).

**References**

[1] Q. A. Ricardo, M. S. Roseli, C. C. Reinaldo, M. Norbert, and L. P. Carmem, “The determination of trace metals in lubricating oils by atomic spectrometry,” Spectrochimica Acta Part B: Atomic Spectroscopy, vol. 62, pp. 952–961, 2007.
[2] S. Pehan, M. S. Jerman, M. Kegl, and B. Kegl, "Biodiesel influence on tribology characteristics of a diesel engine," Fuel, vol. 88, no. 6, pp. 970–979, 2009.

[3] J. Wakiur, L. Ponton, P. Chemweno, and P. Muchiri, "Analysis of lubrication oil contamination by fuel dilution with application of cluster analysis," in Proceedings of the XVII International Scientific Conference on Industrial Systems (IS'17), University of Novi Sad, Novi Sad, Serbia, October 2017.

[4] Z. H. Ye, Research on dynamic behavior of high-speed rolling bearings in aero-engines, Ph.D. thesis, Harbin Institute of Technology, Harbin, China, 2013, in Chinese.

[5] A. R. Lansdown and S. Lee, "Aviation lubricants," in Chemistry and Technology of Lubricants, R. M. Mortier, M. F. Fox, and S. T. Orszulik, Eds., pp. 345–351, Springer, Berlin, Germany, 3rd edition, 2010.

[6] W. M. Liu, J. Xu, D. P. Feng, and X. B. Wang, "The research status and prospect of synthetic lubricating oils," Tribology, vol. 33, pp. 91–104, 2013.

[7] S. J. Ruan, Y. W. Fei, J. Ma, J. T. Hao, X. C. Peng, and F. Guo, "Analysis on the correlation of physical and chemical Indexes of high temperature oxidation products of hydrocarbon aviation oil," Lubrication Engineers, vol. 43, pp. 111–115, 2018.

[8] L. L. Ge, Y. X. Liang, and J. J. He, "Study on thermal oxidation mechanism of ester base oil," China Petroleum Processing and Petrochemical Technology, vol. 47, pp. 88–93, 2016.

[9] P. Nagendramma and S. Kaul, "Development of ecofriendly/biodegradable lubricants: an overview," Renewable and Sustainable Energy Reviews, vol. 16, no. 1, p. 764, 2012.

[10] G. F. Simmons and S. B. Glavatskih, "Synthetic Lubricants," in The American Petroleum Institute, vol. 27, pp. 24–26, 1999, in Chinese.

[11] J. J. Tang, "Lecture on basic knowledge of synthetic lubricating engines," in Synthetic Lubricants Research on dynamic behavior of high-speed rolling bearings in aero-engines, no. 4, pp. 65–69, 2016, in Chinese.

[12] G. F. Simmons and S. B. Glavatskih, "Synthetic lubricants in high-speed ball bearings," in Tribology and Wear, vol. 8, no. 1, pp. 164–181, 2020.

[13] Z. Gan, T. Yao, M. Zhang, J. Hu, X. Liao, and Y. Shen, "Effect of temperature on the composition of a synthetic hydrocarbon aviation lubricating oil," Tribology International, vol. 140, p. 105852, 2019.

[14] D. Kealey and P. J. Haines, Instant Notes in Analytical Chemistry, pp. 233–241, Taylor & Francis, London, UK, 1st edition, 2002.

[15] S. Zeymani, M. Mikou, J. Naja, and A. Elachhab, "Spectroscopic analysis of synthetic lubricating oil," Tribology International, vol. 114, pp. 27–32, 2017.

[16] J. J. Jiang, K. J. Jiang, and Y. S. Zhai, "Oxidation stability of aircraft lubricating oils," Journal of Materials Engineering, vol. 27, pp. 24–26, 1999, in Chinese.

[17] Y. Zong, X. F. Jiang, C. W. Yue, and Y. P. Xiao, "Study on thermal oxidation stability of aviation lubricatingoil under high temperature," Lube Oil, vol. 30, pp. 19–21, 2015, in Chinese.

[18] Y. Fan, J. Ai, S. Zhang et al., "Lubricating properties of ester oil prepared from bio-based 2,5-furandicarboxylic acid," Friction, vol. 8, no. 2, pp. 360–369, 2020.

[19] B. K. Sharma and A. J. Stupanovic, "Development of a new oxidation stability test method for lubricating oils using high-pressure differential scanning calorimetry," Thermochimica Acta, vol. 402, no. 1-2, pp. 1–18, 2003.

[20] C. D. Gamilin, N. K. Dutta, N. Roy Choudhury, D. Kehoe, and J. Matsins, "Evaluation of kinetic parameters of thermal and oxidative decomposition of base oils by conventional, iso-thermal and modulated TGA, and pressure DSC," Thermochimica Acta, vol. 392–393, pp. 357–369, 2002.

[21] Z. G. Zhang, L. B. Chen, L. Q. Song, and H. W. Wang, "Study on degradation of antioxidant additive in an aviation lubricating oil," Lubrication Engineering, vol. 39, pp. 112–114, 2014, in Chinese.

[22] M. Kohler and N. V. Heeb, "Characterization of ageing products of ester-based synthetic lubricants by liquid chromatography with electrospray ionization mass spectrometry and by electrospray ionization (tandem) mass spectrometry," Journal of Chromatography A, vol. 926, no. 1, pp. 161–165, 2001.

[23] M. Frauscher, C. Besser, G. Allmaier, and N. Dör, "Oxidation products of ester-based oils with and without antioxidants identified by stable isotope labelling and mass spectrometry," Applied Sciences, vol. 7, no. 4, p. 396, 2017.

[24] M. Frauscher, C. Besser, G. Allmaier, and N. Dör, "Oxidation products of ester-based oils with and without antioxidants identified by stable isotope labelling and mass spectrometry," Applied Sciences, vol. 7, no. 4, p. 396, 2017.

[25] M. Frauscher, C. Besser, G. Allmaier, and N. Dör, "Oxidation products of ester-based oils with and without antioxidants identified by stable isotope labelling and mass spectrometry," Applied Sciences, vol. 7, no. 4, p. 396, 2017.

[26] M. Frauscher, C. Besser, G. Allmaier, and N. Dör, "Oxidation products of ester-based oils with and without antioxidants identified by stable isotope labelling and mass spectrometry," Applied Sciences, vol. 7, no. 4, p. 396, 2017.
I. Stanciu, "Viscosity index for oil used as biodegradable lubricant," *Indian Journal of Science and Technology*, vol. 13, no. 3, pp. 352–359, 2020.

P. Mousavi, D. Wang, C. S. Grant, W. Oxenham, and P. J. Hauser, "Effects of antioxidants on the thermal degradation of a polyol ester lubricant using GPC," *Industrial & Engineering Chemistry Research*, vol. 45, no. 1, pp. 15–22, 2006.

P. Mousavi, D. Wang, C. S. Grant, W. Oxenham, and P. J. Hauser, "Measuring thermal degradation of a polyol ester lubricant in liquid phase," *Industrial & Engineering Chemistry Research*, vol. 44, no. 15, pp. 5455–5464, 2005.

S. Siouris and C. W. Wilson, "Thermodynamic properties of pentaerythritol-based species involved in degradation of aviation gas turbine lubricants," *Industrial & Engineering Chemistry Research*, vol. 49, no. 23, pp. 12294–12301, 2010.

R. Kreivaitis, J. Padgurskas, M. Gumbytė, V. Makarevičienė, and B. Spruogis, "The influence of oxidation on tribological properties of rapeseed oil/oksidacijos itaka rapsu ˛ aliejaus tribologiniams savybas/Влияние Окисления Рапсового Масла На ЕГо Трибологические Свойства," *Transport*, vol. 26, no. 2, pp. 121–127, 2011.

S. Q. A. Rizvi, *A Comprehensive Review of Lubricant Chemistry, Technology, Selection, and Design*, ASTM International, Conshohocken, PA, USA, pp. 47–97, 2009.

M. A. Maleque, H. H. Masjuki, and A. S. M. A. Haseeb, "Effect of mechanical factors on tribological properties of palm oil methyl ester blended lubricant," *Wear*, vol. 239, no. 1, pp. 117–125, 2000.

X. M. Chen, S. Y. Li, G. Y. Li, X. S. Ni, Z. C. Cheng, and Z. J. Zhao, "Discussion of sample pretreatment methods for determination of acid number in lubricants," *Instrumentation Analysis Monitoring*, vol. 42, pp. 1297–1300, 2013, in Chinese.

B. R. Moser, B. K. Sharma, K. M. Doll, and S. Z. Erhan, "Diesters from oleic acid: synthesis, low temperature properties, and oxidation stability," *Journal of the American Oil Chemists’ Society*, vol. 84, no. 7, pp. 675–680, 2007.

W. T. Zhang, J. L. Li, P. X. Xiao, H. J. Wu, and S. Yang, "The relationship between acid value and lubricating oil performance," *Petroleum Products Application Research*, vol. 32, pp. 65–69, 2014, in Chinese.

Y. W. Fei, Z. S. Cheng, H. W. Yang, and T. Yao, "Property analysis of aviation lubricant base oil synthesized from ester," *Contemporary Chemical Industry*, vol. 42, pp. 1297–1300, 2013, in Chinese.

Q. Zhang and W. W. Shi, "Progress of the synthesis and friction reducing properties study of oiliness agent," *Lubrication Engineering*, vol. 39, pp. 114–118, 2014, in Chinese.

H. Cen, A. Morina, and A. Neville, "Effect of lubricant ageing on lubricants’ physical and chemical properties and tribological performance; Part I: effect of lubricant chemistry," *Industrial Lubrication and Tribology*, vol. 70, no. 2, pp. 385–392, 2018.

L. S. Pamela, H. P. Gerald, and T. R. Alan, "The development of a standard method for determining oxidation induction times of hydrocarbon liquids by PDSC," *Thermochimica Acta*, vol. 243, pp. 201–208, 1994.

F. M. T. Luna, B. S. Rocha, E. M. Rola Jr. et al., "Assessment of biodegradability and oxidation stability of mineral, vegetable and synthetic oil samples," *Industrial Crops and Products*, vol. 33, no. 3, pp. 579–583, 2011.

H. Zhang, X. L. Gao, Z. Cheng, and L. Wu, "The study on tribological behaviors of the synthetic ester as lubricant base oil," *Journal of Central China Normal University*, vol. 46, pp. 440–443, 2012, in Chinese.

J. Lahijani, F. E. Lockwood, and E. E. Klaus, "The influence of metals on sludge formation," *A S L E Transactions*, vol. 25, no. 1, pp. 25–32, 1982.

L. B. Chen and S. H. Guo, "The development of research on thermal oxidation and condition monitoring of ester lubricants," *Synthetic Lubricant*, vol. 28, pp. 19–24, 2001.

W. G. Xue, X. G. Zhou, and J. M. Li, "Research on current status and progress of lubricants antioxidants," *Synthetic Lubricant*, vol. 40, pp. 7–13, 2013.

T. Yao, H. W. Yang, L. Guo et al., "The deterioration mechanism of diester aero lubricating oil at high temperature," *Journal of Spectroscopy*, vol. 2017, Article ID 5392864, 8 pages, 2017.