Synergistic Anti-Friction Performance and Lubricating Film Mechanism of Erucamide and N-Phenyl-α-Naphthylamine in Polyurea Grease at Elevated Temperatures

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Lubricating film thicknesses calculation. Based on the experimental conditions—including temperature, reciprocating frequency, applied load, and the rheological properties of the grease—an elastohydrodynamic lubrication (EHL) calculation model was established [S1, S2, S3, S4]. The lubricating film thicknesses of the grease with and without ER and N-PAN additives were obtained through theoretical calculations, as shown in Fig. S1.

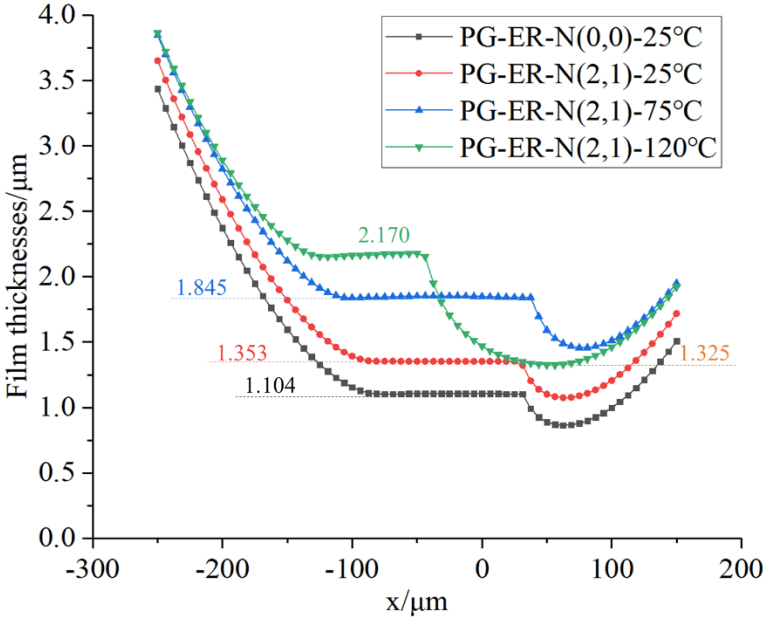

Fig. S1. Calculated results of lubricating film thicknesses

As shown in Fig. S1, the addition of 2 wt% ER and 1 wt% N-PAN enhances the film thickness compared with the base grease.

TGA of DSC test. The tests were conducted in an air atmosphere from room temperature to 125 °C at a heating rate of 5 °C min^{-1}, as shown in Fig. S2.

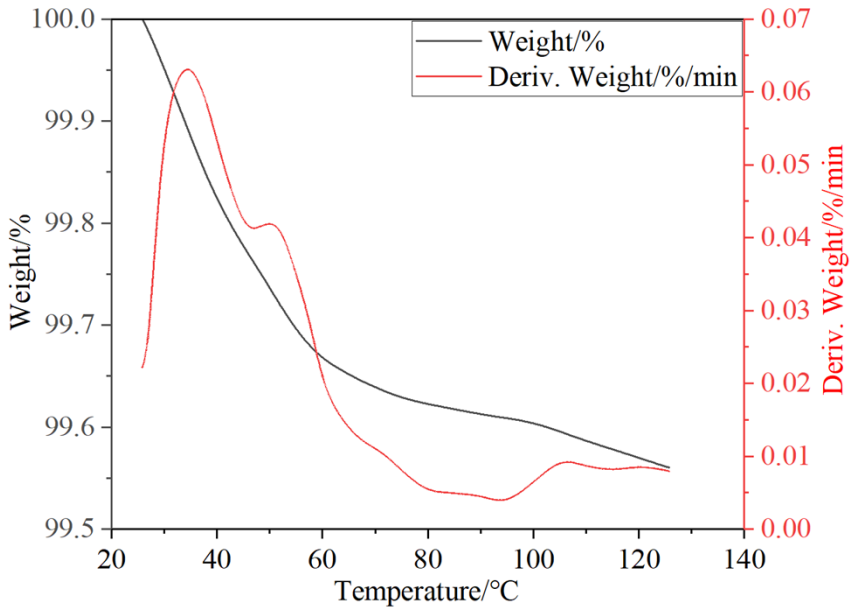

Fig. S2 Thermogravimetric analysis (TGA) curve of the PG-ER-N(2,1) grease

As presented in Fig. S2, a noticeable mass loss of the PG-ER-N(2,1) sample occurs below 34.49 °C, which is primarily attributed to the evaporation of moisture in the grease. The mass loss then stabilizes, with a total weight reduction of approximately 0.44% throughout the temperature range of room temperature to 125 °C. This result indicates that the grease exhibits excellent thermal stability without any significant decomposition or oxidation reactions within this temperature range.

Oxidation stability test of N-PAN. To verify the oxidation inhibition effect of N-PAN on the lubricant, the oxidation stability of the PAO base oil and PAO oils containing N-PAN was evaluated using a Rotating Oxygen Bomb apparatus, following the Chinese National Standard SH/T0193-92 “Lubricating oils—Determination of oxidation stability (Rotating bomb method)”. The tested samples included pure PAO base oil and PAO base oils containing 1 wt%, 2 wt%, and 3 wt% N-PAN. Each measurement was repeated three times, and the average value was recorded. The oxidation stability test

results of N-PAN are presented in the Supporting Information (Table S1)

Table S1. Oxidation stability test results of N-PAN

Sample	PAO base oil	PAO base oil + 1 wt% N-PAN	PAO base oil + 2 wt% N-PAN	PAO base oil + 3 wt% N-PAN
Average oxidation time /min	86	540	634	701

As shown in Table S1, the oxidation induction times of the samples containing 1 wt%, 2 wt%, and 3 wt% N-PAN increased by approximately 6.27, 7.37, and 8.15 times, respectively, compared with that of the pure PAO base oil. This demonstrates that the addition of N-PAN significantly prolongs the oxidation induction time and enhances the oxidation stability of the lubricant. (It should be noted that the sample containing 3 wt% N-PAN was not selected for further investigation, as excessive N-PAN content may lead to the formation of precipitates after oxidation, which is unfavorable for friction reduction.)

Friction coefficient.

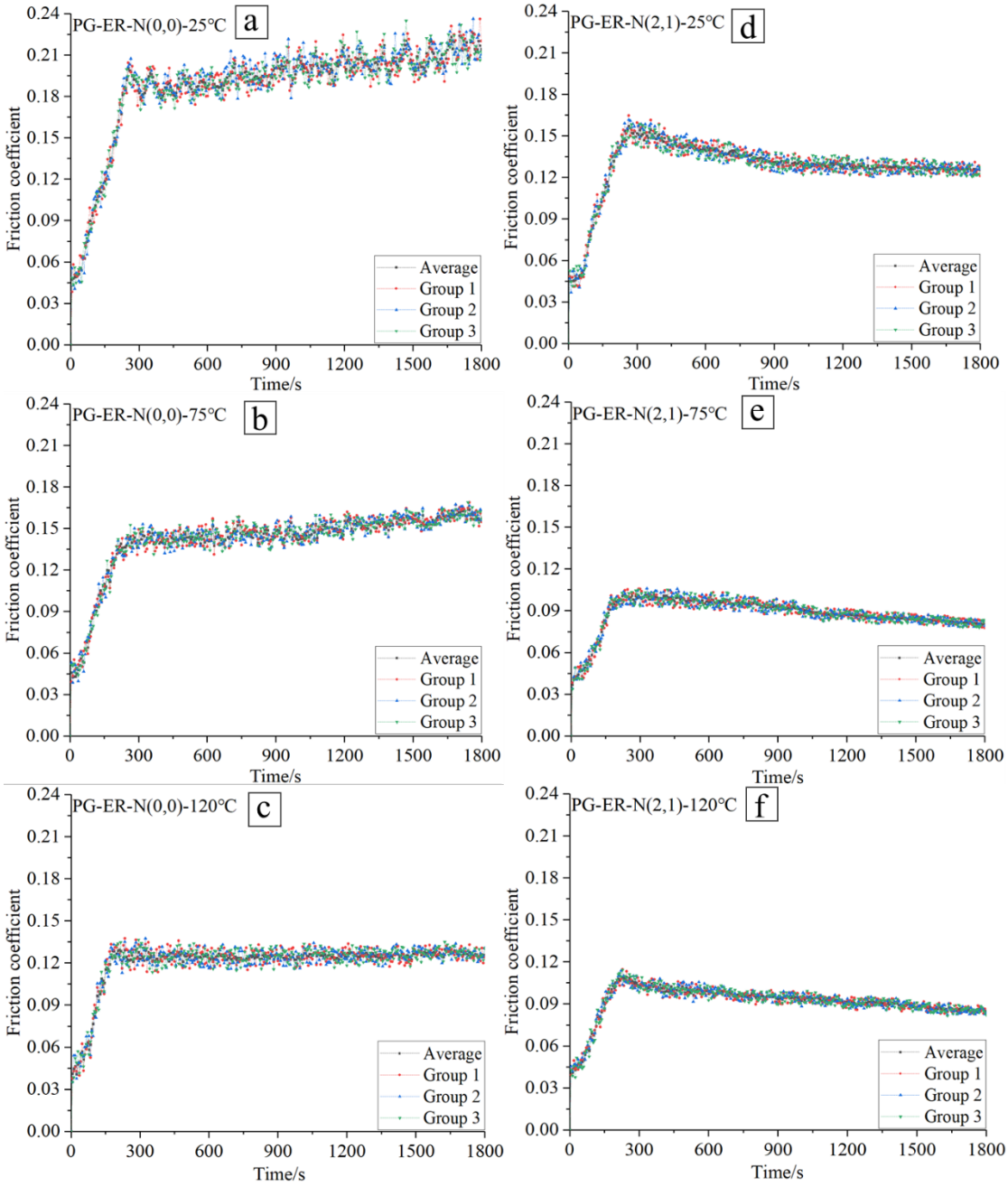

Fig. S3. Friction coefficients of PG-ER-N series greases at different temperatures for three repeated tests

Table S2. Average friction coefficients of PG-ER-N series greases at different temperatures for three repeated tests

Sample	PG-ER-N(0,0)-25℃	PG-ER-N(0,0)-75℃	PG-ER-N(0,0)-120℃	PG-ER-N(2,1)-25℃	PG-ER-N(2,1)-75℃	PG-ER-N(2,1)-120℃
Group1	0.1842	0.1450	0.1238	0.1292	0.0855	0.0904
Group2	0.1899	0.1417	0.1204	0.1244	0.0898	0.0915
Group3	0.1869	0.1400	0.1193	0.1279	0.0879	0.0946
Average	0.187	0.142	0.121	0.127	0.088	0.92

Wear rate analysis. Based on the cross-sectional profiles of the wear scars shown in Fig. 7, the cross-sectional area was obtained by integrating the contour curves. Combined with the reciprocating stroke of 8 mm and a test duration of 30 min, the wear rate was calculated, as shown in Table S3.

Table S3. Average wear rates of PG-ER-N series greases at different temperatures for three repeated tests

Sample	PG-ER-N(0,0)-25℃	PG-ER-N(0,0)-75℃	PG-ER-N(0,0)-120℃	PG-ER-N(2,1)-25℃	PG-ER-N(2,1)-75℃	PG-ER-N(2,1)-120℃
Group1/ $10^{-6}mm^3$	5.55	4.32	2.75	3.64	1.93	1.96
Group2/ $10^{-6}mm^3$	5.57	4.21	2.95	3.71	2.02	2.18
Group3/ $10^{-6}mm^3$	5.27	4.25	3.06	3.56	1.90	2.06
Average/ $10^{-6}mm^3$	5.46	4.26	2.92	3.64	1.95	2.07

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