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Determination of low-temperature properties of lubricating greases

The article presents the results of laboratory tests of low-temperature properties of lithium complex greases produced on base oils, characterized by a different chemical structure. Low-temperature properties of lubricating greases were determined according to the following test methods:
- low-temperature cone penetration – PN-ISO 13737,
- flow pressure – DIN 51805-2,
- apparent viscosity – PN-C-04146.

It was found that the low-temperature properties of lubricating greases can be modified by introducing oils with a different chemical structure into the oil base. The lowest temperature of application of the tested lithium complex greases was determined.

Key words: lubricating greases, low-temperature properties, base oils.

Badanie właściwości niskotemperaturowych smarów plastycznych

W artykule przedstawiono wyniki badań laboratoryjnych właściwości niskotemperaturowych smarów litowych kompleksowych, wytworzonych na wytypowanych olejach bazowych o różnym charakterze chemicznym. Właściwości niskotemperaturowe smarów plastycznych oznaczano według następujących metod badawczych:
- penetracja w niskiej temperaturze – PN-ISO 13737,
- ciśnienie płynięcia – DIN 51805-2,
- lepkość strukturalna – PN-C-04146.

Stwierdzono, że właściwości niskotemperaturowe smarów plastycznych można modyfikować, poprzez wprowadzenie do bazy olejowej olejów o odmiennym charakterze chemicznym. Ustalono najniższą temperaturę stosowania badanych próbek smarów kompleksowych litowych.

Słowa kluczowe: smary plastyczne, właściwości niskotemperaturowe, oleje bazowe.

Introduction

Lubricating greases are solid to semifluid substances forming by dispersing a solid phase (thickener) in a liquid phase (base oil). The liquid phase constitutes 70÷90% (*m*/*m*) and it is a basic component of the grease. The character of this phase determines, among others, the low-temperature properties, lubricating properties, oxidation stability, and changes in the properties depending on temperature [3, 7, 9÷14].

A suitability of the oil for production of greases is evaluated based on the oil's properties such as: viscosity and viscosity index, rheological properties at low temperatures, flash point, lubricating properties and the ability to protect from corrosion [15, 16].

Selection of a proper base oil depends on the oil's kinematic viscosity at the working temperature of the bearing being lubricated. Most favourably, as the base oil for grease production, the oil characterised by a viscosity close to that of the oil, with which a given friction pair should be lubricated if it had to be lubricated with an oil [7, 8].

While selecting the base oil for production of a grease with a required range of the low-temperature limit of the grease application, the pour point of the base oil should be determined, value of which decides to the highest degree on the low-temperature properties of greases [2]. An adequately low pour point of the base oil ensures a good operation of the bearing at low-temperature limit of the grease application [16].

Lithium greases prepared on paraffinic base oils do not exhibit good low-temperature properties because of the level of the base oil's pour point. Slightly better low-temperature properties are exhibited by greases prepared on naphthenic base oils. Use of a synthetic oil (e.g., polyalphaolefin oil, PAO) in the oil base ensures better low-temperature properties. Introduction of a diester oil, characterised by an extremely low pour point and a good thermal oxidation stability, into the PAO, leads to a synergy of both oil bases and an improvement of the low-temperature properties [20].

Selection of the base oil used for the grease production, has a significant impact on the behaviour of the grease during flow, particularly at low temperatures. Paraffinic base oils contain significant amounts of saturated hydrocarbons, which obstruct the grease's flow while crystallising. Depressants added to the base oil during the production of the grease, prevent aggregation of paraffin crystals and thus improve the grease's flow at low temperatures. Unlike the paraffinic oils, naphthenic oils typically do not contain large amounts of molecules which may crystallise at low temperature [4].

Greases based on synthetic oils are used under circumstances, in which mineral oils cannot be used because of the conditions (e.g., extremely high or low temperatures, high pressure) [20].

Technological progress requires that greases meet increasingly high operational requirements, among others, more and more broad range of the operating temperature, and a more perfect thermal oxidation stability. Using non-conventional base oils, complex high-temperature greases may be obtained, which meet these requirements, with good low-temperature properties, ensuring start-up and failure-free operation of machines and installations [1, 7, 10, 12÷14, 20].

Lithium complex greases, currently constituting approx. 20% of all greases produced globally, allow for increasing the operational temperature of the grease in relation to ordinary lithium greases, while maintaining other favourable properties, such as: thermal and mechanical stability, and high resistance to water. Dropping point of greases of such a type is approx. 280°C, while that of ordinary lithium greases is approx. 190°C. Lithium complex greases found wide application for lubrication of friction pairs in automotive vehicles and in various industrial equipment [3, 5, 6, 8, 11].

Operation of machines and installations at a low temperature (below 0°C) requires use of lubricating greases with good low-temperature properties, ensuring start-up and failure-free operation [1, 20]. Specialist lubricating greases are a group of lubricants, which include greases with a lower application limit below –35°C, resistant to temperatures higher than 230°C, resistant to water and high loads (400÷600 kG, with a frequency of rotation 1200–1500 rpm) [2].

To determine operating conditions of lubricating greases, it is necessary to carry out tests included in the PN-ISO 6743-9 standard [24]. The test results allow also for determining the classification symbol of the grease, for instance **ISO-L-XCDFB 2**, including:

- the **ISO** initials,
- letter "**L**," defining the class of the lubricants,
- letter "**X**," defining the family grease,

and four symbols characterising the properties of the grease:

- 1st symbol – the lower operating temperature **C** (–30°C),
- 2nd symbol – the upper operating temperature **D** (140°C),
- 3rd symbol – level of the water resistance and protection against corrosion **F** (water contamination and anti-rust protection),
- 4th symbol – the ability to lubricate under high loads **B** (extreme pressure (EP) properties),

and NLGI consistency number **2** (based on worked penetration range).

The PN-ISO 12924 standard *Środki smarowe, oleje przemysłowe i produkty podobne (Klasa L) – Grupa X (Smary) – Wymagania* [*Lubricants, industrial oils and related products (Class L) – Family X (Greases) – Specification*] recommends carrying out the following tests to determine the low-temperature properties of greases or the lower operating temperature (1st symbol in the classification symbol of the grease acc. to PN-ISO 6743-9) [24, 26]:

- starting torque and running torque – ASTM D 1478 or NFT 60-629 [17, 21],
- flow pressure – DIN 51805-2 [18],
- low-temperature penetrability – PN-ISO 13737 [25].

Depending on the test type which has been the base for determination of the lower operating temperature of the grease, Symbol 1 is completed by a suffix letter between brackets:

- (L) – starting/running torque,
- (F) – flow pressure,
- (P) – low-temperature penetrability.

The PN-C-96014 standard *Środki smarowe – Smary plastyczne klasy K – Klasyfikacja i wymagania*, introducing the DIN 51825 standard *Lubricants – Lubricating greases K – Classification and requirements*, to define the low-temperature properties necessary to determine the lower operating temperature, recommends carrying out the following test [23]:

- flow pressure, according to the DIN 51805-2 standard [18], required lower than or equal to 1400 hPa,
- torque, according to the IP186 standard [19], required static torque lower than or equal to 1000 mNm and required dynamic torque lower than or equal to 100 mNm [23].

Table 1. Tests for determination of the lower operating temperature [26]

The lowest application temperature [°C]	Starting torque [mN · m]			Flow pressure [hPa]		Penetrability [1/10 mm]	
	value	running torque [mN · m]					
		1st symbol	value	value	1st symbol	value	1st symbol
0		A (L)			A (F)	≥ 140	A (P)
–20		B (L)			B (F)	≥ 120	B (P)
–30	≤ 1000	C (L)	≤ 100	≤ 1400	C (F)	≥ 120	C (P)
–40		D (L)			D (F)	≥ 100	D (P)
< –40		E (L)			E (F)	≥ 100	E (P)
–	Test methods: ASTM D 1478 or NFT 60-629			Test method: DIN 51805-2		Test method: ISO 13737	

Aim of the paper

The aim of the paper was to determine the influence of a base oil used in lithium complex greases on the properties of these greases at a low temperature, namely their consistency, flow pressure and apparent viscosity.

Methodology of the studies

Studies on the low-temperature properties of prepared samples of lithium complex greases were carried out according to the following test methods:

- PN-ISO 13737:2011 *Przetwory naftowe i środki smarowe – Pomiar penetracji smarów plastycznych w niskich temperaturach penetrometrem ze stożkiem* [*Petroleum products and lubricants – Determination of low-temperature cone penetration of lubricating greases*],
- DIN 51805-2:2016 *Prüfung von Schmierstoffen – Bestimmung des Fließdruckes von Schmierfetten mit dem Verfahren nach Kesternich – Teil 2: Automatisches Verfahren* [*Testing of lubricants – Determination of flow pressure of lubricating greases according to Kesternich method – Part 2: Automatic method*],
- PN-C-04146:1963 *Przetwory naftowe – Pomiar lepkości strukturalnej smarów stałych* [*Petroleum products – Measurement of apparent viscosity of lubricating greases*].

Determination of low-temperature cone penetration acc. to PN-ISO 13737

The method for determination of low-temperature cone penetration acc. to the PN-ISO 13737 standard [25] consists in a measurement of grease penetration of a cooled sample under specific conditions as per the test temperature, using a cone cooled to the same temperature. To carry out the test, two grease samples were prepared in full-scale grease cups, one for temperature control, the other for the penetration measurement. The grease sample for the penetration measurement was worked by 60 full double strokes of the plunger, and then, the surface of the grease was evened. Both cups with the grease and the penetrometer cone were placed in a cooling chamber, at the test temperature. After cooling for 4 hours, the cooled cone was installed in the penetrometer (Figure 1), and then, the unworked penetration measurement of the grease was carried out.

Fig. 1. Penetrometer for determination of grease penetration (photo: INiG – PIB)

Determination of flow pressure of lubricating greases acc. to DIN 51805-2

Acc. to the DIN 51805-2 standard [18], flow pressure is the pressure required to push a grease stream through a standardized nozzle, under conditions defined in the standard (Figure 2). A standardized steel nozzle was filled with the grease, sealed with a silicone o-ring then planed in an apparatus (Figure 3) equipped with a thermostatic block. After reaching the given temperature, the pressure is increased automatically by a defined increment (depending on the flow pressure of the grease) with

30-second intervals, until the grease stream is pushed through the nozzle – this pressure constitutes the measurement result and is called flow pressure of lubricating greases.

Fig. 2. Nozzle with the grease for the flow pressure of lubricating greases test (photo: INiG – PIB)

Fig. 3. Apparatus for the flow pressure of lubricating greases test (photo: INiG – PIB)

Determination of apparent viscosity of the greases acc. to PN-C-04146

The method for determination of apparent viscosity of solid greases according to the PN-C-04146 standard [22] consists in forcing the grease through a capillary tube under a decreasing pressure, obtained using a plunger with a known characteristics. The apparatus allows for carrying out the measurement in a wide temperature range due to the fact that the medium is supplied from the thermostatic chamber. The apparatus consists of three glass capillary tubes fixed into metal sockets with glue (Figure 4), having lengths of approx. 11.5 cm and diameters of approx. 0.02, 0.05, and 0.1 mm. A proper capillary tube is selected depending on the test temperature, the type and NLGI consistency number of the grease. The AKW-2 automatic capillary viscometer is shown in Figure 5. The capillary tube was filled with the grease and installed in the apparatus. The given measurement temperature was obtained supplying coolant from a cryostat to the chamber with the capillary tube. After the test temperature was reached, the apparatus was started. During the measurement, the apparatus plotted curves representing pressure change in the chamber – the grease flowed through the capillary tube driven by the expanding spring (Figure 6). Based on the obtained curves and characteristic data of the apparatus, shear stress and deformation rate gradient of the grease were calculated. After the calculation of these quantities, a graph was plotted being a basis for the determination of the apparent viscosity for any deformation rate gradient of the grease (Figure 7).

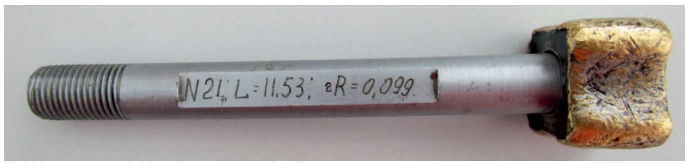

Fig. 5. AKW-2 automatic capillary viscometer (photo: INiG – PIB)

Fig. 4. Capillary tube for determination of apparent viscosity of the greases (photo: INiG – PIB)

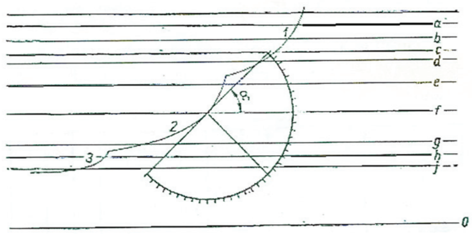

Fig. 6. Curves representing the pressure changes in the chamber during the measurement [23]

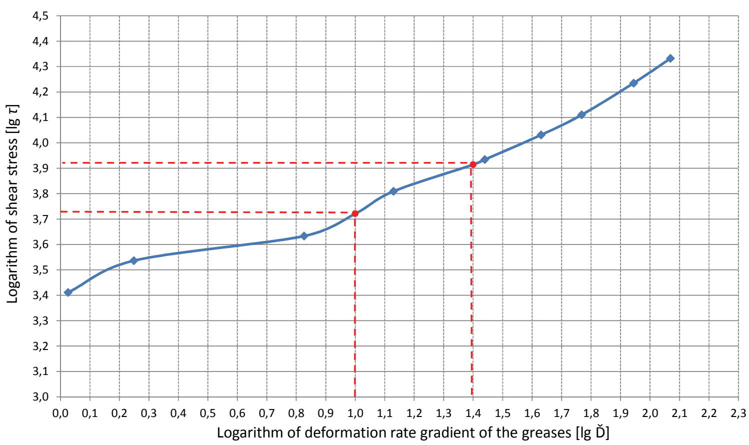

Fig. 7. Graph for the determination of apparent viscosity at any deformation rate gradient of the grease (e.g.: 10 s^{-1}, then lg D = 1)

Samples for the tests

Base oils commonly used by lubricants manufacturers for production of lithium complex greases were selected:

- a paraffinic oil (denoted with **P**), of group I acc. to API,
- a naphthenic oil (denoted with **N**), of group V acc. to API,
- synthetic polyalphaolefin oil (denoted with **S**), of group IV acc. to API.

The determined properties of the base oils and their compositions are shown in Table 2.

Table 2: The determined properties of the base oils and their compositions

Sample No.	1	2	3	4	5	6	7	8	9
Oil base composition [% (*m*/*m*)]	**P**	**P:N**			**N**	**P:S**			**S**
	100	70:30	50:50	30:70	100	70:30	50:50	30:70	100
Properties									
Kinematic viscosity: – at 40°C [mm^2/s] – at 100°C [mm^2/s]	100.700 10.960	101.200 10.230	103.100 9.904	105.600 9.535	75.400 9.661	107.200 8.927	64.400 9.049	56.930 8.608	46.930 7.891
Viscosity index	92	77	66	52	106	28	117	125	138
Pour point [°C]	–12	–15	–21	–30	–18	–30	–24	–33	–57
Flash point (COC) [°C]	220	216	214	214	227	214	234	240	260

Method for preparation of the grease samples for the tests

Lithium complex greases were obtained by a standard production procedure, including the following operations:

- preparation of a soap concentrate in a base oil – approx. 50% of the base oil was heated to a temperature of 80÷90°C; both acids, 12-hydroxystearic acid and sebacic acid, were dosed; after the dissolution of the acids, lithium hydroxide in a water suspension (1:1) was added in 4 portions during approx. 2 hours; the saponification process was carried out in a reactor at a temperature of 90±5°C for 1 hour,
- dewatering of the soaps – the water was evaporated at 100÷120°C,
- dispersing of the soaps in the base oil – the remaining amount of the oil was added and the reaction mixture was heated gradually to a temperature of 170±5°C, which was maintained for approx. 0.5 hour,
- grease cooling – the grease was cooled dynamically,
- final treatment of the grease – the grease was cooled to a temperature of 60°C, and homogenised in a corundum Fryma-type mill, using a slit of 0.2 mm.

Greases NLGI consistency number 2 worked penetration range – 60 double strokes – 265 to 295 [mm/10] and drop point of approx. 280°C were obtained.

Studies on low-temperature properties

Penetration of the greases at low temperature acc. to PN-ISO 13737

Samples of lithium complex greases, prepared using the base oils from selected API groups on compositions of these oils were subjected to penetration tests at low temperature, in the temperature range of 0°C to –30°C. The test results are shown in Tables 3–4 and in Figs. 8–9.

Based on the obtained results, it was found that among the greases produced on **P**, **N** and **S** oils, the grease on the **S** oil is characterised by the smallest consistency change with a decrease in temperature, and it exhibits the highest penetration value at a temperature of –30°C.

Among the greases produced on the **P:N** and **P:S**, oil compositions, the samples with a ratio of 70:30 exhibit the largest penetration change with a decrease in the test temperature, and the samples with a ratio of 30:70 exhibit the smallest penetration change.

The greases produced on the **P:N** and **P:S** oil compositions are characterised by the following dependence: an increase in the share of the **N** and **S** oil is accompanied by a decrease in the dependence of the greases' consistency on the temperature.

While comparing the greases produced on the **P:N** oil compositions with analogous greases produced on the **P:S** oil compositions, it was found that higher penetration values (a softer grease) at negative temperatures are obtained for the compositions with the **S** oil, which is connected with its lower flow temperature.

Table 3. Low-temperature cone penetration of grease samples – depending on the share of the naphthenic oil in the oil base

Sample No.	1	2	3	4	5
P:N oils share [% (*m/m*)]	100	70:30	50:50	30:70	100
Property					
Worked penetration at 25°C [mm/10]	280	277	279	273	273
Penetration [mm/10]:					
– at 0°C	207	238	223	201	201
– at –10°C	186	209	205	179	189
– at –20°C	152	179	151	161	173
– at –30°C	107	119	129	133	145

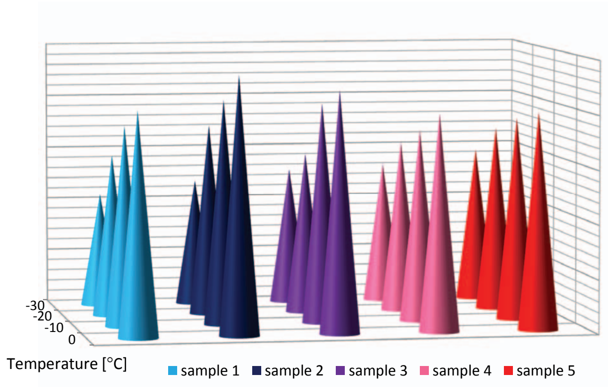

Fig. 8: Low-temperature cone penetration of grease samples – depending on the share of the naphthenic oil in the oil base

Table 4. Low-temperature cone penetration of grease samples – depending on the share of a synthetic oil in the oil base

Sample No.	1	6	7	8	9
P:S oils share [% (*m/m*)]	100	70:30	50:50	30:70	100
Properties					
Worked penetration at 25°C [mm/10]	280	255	278	285	273
Penetration [mm/10]:					
– at 0°C	207	217	231	229	219
– at –10°C	186	205	199	211	213
– at –20°C	152	175	177	195	173
– at –30°C	107	145	165	175	169
– at –40°C	–	–	–	143	161

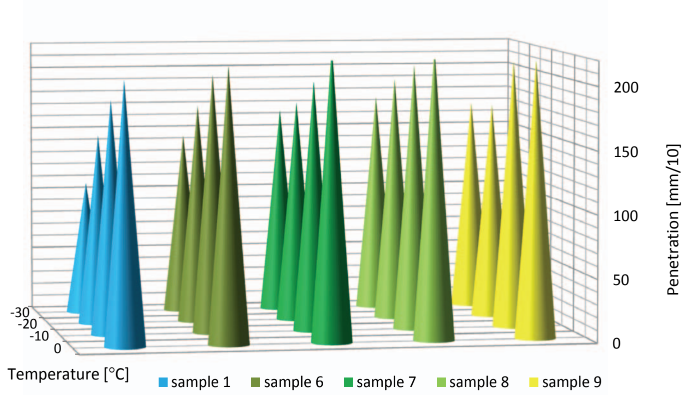

Fig. 9: Low-temperature cone penetration of grease samples – depending on the share of a synthetic oil in the oil base

Flow pressure of the greases acc. to DIN 51805-2

For the obtained samples of lithium complex greases, flow pressure was determined in the temperature range of 30°C to –40°C. The test results are shown in Tables 5–6 and in Figs. 10–11.

At a temperature of –30°C, the greases on the **P** oil and on the **P:N** composition with a ratio of 70:30 were characterised by a flow pressure exceeding the detection limit of the apparatus. The lowest flow pressure was exhibited by the grease on the **N** oil and it amounted to approx. 1400 mbar.

At a temperature of –40°C, the greases on the **P** and **N** oils, and on the **P:S** composition with a ratio of 70:30 exhibited a flow pressure exceeding the detection limit of the apparatus. The lowest flow pressure was exhibited by the grease on the **S** oil and it amounted to approx. 700 mbar.

Table 5. Flow pressure of grease samples – depending on the share of the naphthenic oil in the oil base

Sample No.	1	2	3	4	5
P:N oils share [% (*m/m*)]	100	70:30	50:50	30:70	100
Properties					
Flow pressure [mbar]:					
– at 30°C	102	80	103	111	102
– at 20°C	120	90	111	128	122
– at 10°C	153	128	134	161	161
– at 0°C	203	164	166	297	312
– at –10°C	415	319	302	408	453
– at –20°C	851	550	424	614	750
– at –30°C	–*	–*	1541	1488	1400
– at –40°C	–*	–*	–*	–*	–*

* Flow pressure exceeds the detection limit of the apparatus.

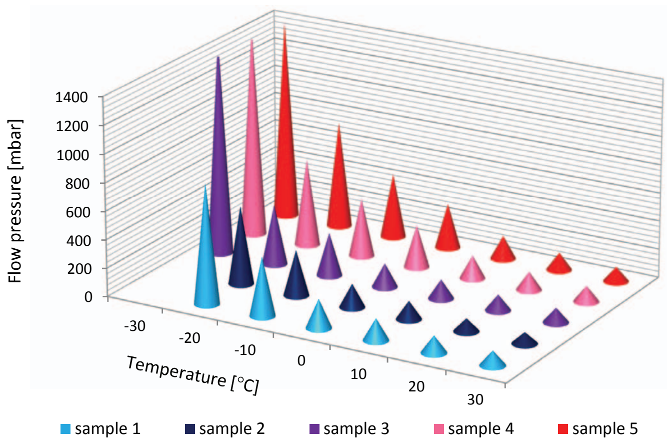

Fig. 10: Flow pressure of grease samples – depending on the share of the naphthenic oil in the oil base composition

Table 6. Flow pressure of grease samples – depending on the share of a synthetic oil in the oil base

Sample No.	1	6	7	8	9
P:S oils share [% (*m*/*m*)]	100	70:30	50:50	30:70	100
Properties					
Flow pressure [mbar]:					
– at 30°C	102	104	130	124	148
– at 20°C	120	144	134	144	160
– at 10°C	153	146	142	147	170
– at 0°C	203	170	181	160	237
– at –10°C	415	309	287	281	282
– at –20°C	851	536	491	485	338
– at –30°C	–*	1152	1149	716	482
– at –40°C	–*	–*	1878	1512	718

* *Flow pressure exceeds the detection limit of the apparatus.*

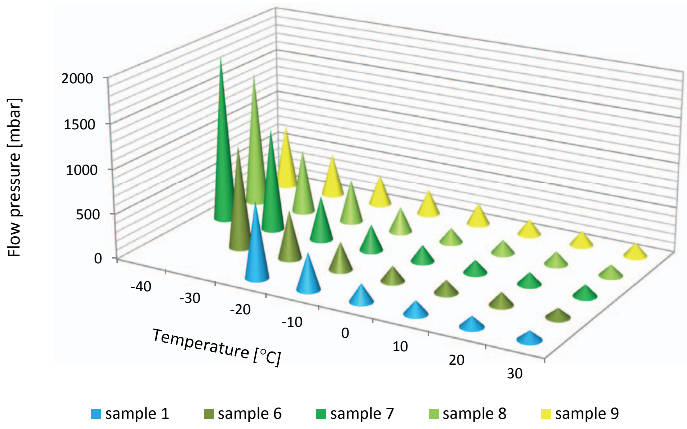

Fig. 11. Flow pressure of grease samples – depending on the share of a synthetic oil in the oil base

Based on the obtained results, it was found that the lower the test temperature, the higher the flow pressure. At a temperature above 0°C, the flow pressure values for all tested grease samples are similar, they do not depend on the character of the base oil.

While comparing the greases produced on the **P:N** oil compositions with analogous greases produced on the **P:S** oil compositions, it was found that a lower flow pressure is obtained for the compositions with the **S** oil, which is connected with its flow temperature.

Apparent viscosity of the greases acc. to PN-C-04146

For the obtained samples of lithium complex greases, apparent viscosity was determined in the temperature range of 0°C to –30°C. For each temperature, apparent viscosity was read at following deformation rate gradients of the grease: 10 s^{-1}, 25 s^{-1}, and 100 s^{-1}. The test results are shown in Tables 7–8.

The greases produced on the **N** oil are characterised by the highest values of apparent viscosity (at a defined value of the deformation rate gradient of the grease) in the temperature range of

Table 7. Apparent viscosity of grease samples – depending on the share of the naphthenic oil in the oil base

Sample No.	1	2	3	4	5
P:N oils share [% (*m*/*m*)]	100	70:30	50:50	30:70	100
Properties					
Apparent viscosity, Pa · s, at a deformation rate gradient of the grease of 10 s^{-1}					
– at 0°C	263	270	309	363	437
– at –10°C	476	550	663	750	871
– at –20°C	1585	1600	1620	1638	1660
– at –30°C	3617	3329	3137	2944	2656
Apparent viscosity, Pa · s, at a deformation rate gradient of the grease of 25 s^{-1}					
– at 0°C	144	174	199	224	240
– at –10°C	251	265	392	441	501
– at –20°C	549	620	660	746	799
– at –30°C	3837	3065	2550	2035	1264
Apparent viscosity, Pa · s, at a deformation rate gradient of the grease of 100 s^{-1}					
– at 0°C	57	62	85	93	155
– at –10°C	114	121	175	180	229
– at –20°C	218	230	245	260	288
– at –30°C	7675	5497	4045	2593	415

Table 8. Apparent viscosity of grease samples – depending on the share of a synthetic oil in the oil base

Sample No.	1	6	7	8	9
P:S oils share [% (*m*/*m*)]	100	70:30	50:50	30:70	100
Properties					
Apparent viscosity, Pa · s, at a deformation rate gradient of the grease of 10 s^{-1}					
– at –0°C	263	210	200	182	186
– at –10°C	476	377	331	281	251
– at –20°C	1585	730	663	517	380
– at –30°C	3617	1254	1047	832	562
Apparent viscosity, Pa · s, at a deformation rate gradient of the grease of 25 s^{-1}					
– at 0°C	144	124	111	105	100
– at –10°C	251	211	174	159	138
– at –20°C	549	417	363	289	219
– at –30°C	3837	822	550	479	332
Apparent viscosity, Pa · s, at a deformation rate gradient of the grease of 100 s^{-1}					
– at 0°C	57	49	46	43	41
– at –10°C	114	89	82	76	57
– at –20°C	218	172	151	144	97
– at –30°C	7675	229	182	177	186

0°C to –20°C, while at a temperature of –30°C, highest values of apparent viscosity characterises the greases produced on the oil **P**.

The greases produced on the **S** oil are characterised by the lowest values of apparent viscosity (at a defined value of the deformation rate gradient of the grease). In the temperature range of 0°C to –20°C, an increase in the amount of the **N** oil in the greases produced on the **P:N** oil composition (at a defined value of the deformation rate gradient of the grease) is accompanied by an increase in the apparent viscosity at the given test temperature. At a temperature of –30°C, a reverse dependence is observed, an increase in the amount of the **N** oil is accompanied by a decrease in the apparent viscosity. In the temperature range of 0°C to –20°C, an increase in the amount of the **S** oil in the greases produced on the **P:S** oil composition (at a defined value of the deformation rate gradient of the grease) is accompanied by a decrease in the apparent viscosity at the given test temperature.

It was found that a decrease in the test temperature is accompanied by an increase in apparent viscosity of the greases. At the given temperature, an increase in the deformation rate gradient of the grease is accompanied by a decrease in its apparent viscosity.

Summary

Studies on low-temperature properties of lithium complex greases were carried out, prepared on the following oils: a paraffinic oil (group I), a naphthenic oil (group V), a synthetic oil (group IV), and on their compositions.

Studies on the low-temperature properties of prepared samples of lithium complex greases were carried out according to the following test methods:

- PN-ISO 13737:2011 – cone penetration of the greases at low temperature,
- DIN 51805-2:2016 – flow pressure,
- PN-C-04146:1963 – apparent viscosity.

It was found that the low-temperature properties of lubricating greases can be modified by introducing oils with a different chemical structure into the oil base.

The lower operating temperature of the tested lithium complex greases was determined:

- based on the results of the cone penetration at low temperature, amounting to:
  - –20°C for the grease prepared on the paraffinic oil and for the greases prepared on compositions of the paraffinic and naphthenic oils,
  - –30°C for the grease prepared on the naphthenic oil and for the greases prepared on compositions of the paraffinic and polyalphaolefin oils,
  - –40°C for the grease prepared on compositions of the paraffinic oil with the polyalphaolefin oil share of at least 70% (*m*/*m*);
- based on the flow pressure, amounting to:
  - –20°C for the grease prepared on the paraffinic oil and on compositions of the paraffinic oil and the polyalphaolefin oil,
  - –30°C for the grease prepared on the naphthenic oil,
  - –30°C for the grease prepared on compositions of the paraffinic oil with the polyalphaolefin oil share of at least 30% (*m*/*m*),
  - –40°C for the grease prepared on the polyalphaolefin oil.

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