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INFLUENCE OF FILLERS ON THE RHEOLOGICAL PROPERTIES OF THEIR COMPOSITIONS WITH LUBRICATING GREASES

WPŁYW WYPEŁNIACZY NA WŁAŚCIWOŚCI REOLOGICZNE ICH KOMPOZYCJI ZE SMARAMI PLASTYCZNYMI

Key words: lubricating greases, fillers, rheological properties, machinery lubrication systems.

Abstract The paper presents the results of studies on the influence of fillers, introduced into lubricating greases, on the rheological properties of resultant grease compositions. These fillers were graphite and PTFE powders. They are added to greases in order to improve their tribological properties. They also affect their rheological properties, and they mainly change the value of the shear stress in grease during its flow in a lubrication system. Knowledge of this value is important in designing automated central lubrication systems in which these compositions may be used. Measurements during experimental tests were performed by means of a rotary rheometer Rheotest 2.1. Tests were performed on pure lithium and bentonite greases, with the addition of oxidation and corrosion inhibitors as well as compositions of these greases with different shares of the above mentioned fillers. These tests were performed by changing the gradient of shearing rate. Test results have shown that both the kind of grease and the kind of filler introduced into this grease affect the rheological properties of produced grease compositions.

Słowa kluczowe: smary plastyczne, wypełniacze, właściwości reologiczne, układy smarowania maszyn.

Streszczenie W pracy przedstawiono wyniki badań nad wpływem wypełniaczy wprowadzanych do smarów plastycznych na właściwości reologiczne powstałych kompozycji smarowych. Wypełniaczami tymi były proszki grafitu i PTFE. Dodawane są one do smarów w celu poprawy ich właściwości tribologicznych. Wpływają też na ich właściwości reologiczne, a głównie na zmianę wartości naprężenia stycznego w smarze podczas jego przepływu w układzie smarowniczym. Znajomość tej wartości jest ważna podczas budowy zautomatyzowanych układów centralnego smarowania, w których mogą być wykorzystane te kompozycje. Pomiary podczas badań doświadczalnych przeprowadzono na reometrze rotacyjnym Rheotest 2.1. Badaniom poddano smary litowy i bentonitowy czyste, z dodatkami inhibitorów utleniania i korozji oraz kompozycji tych smarów z udziałami wymienionych powyżej wypełniaczy. Badania te prowadzono, zmieniając gradient prędkości ścinania. Wyniki badań wykazały, że zarówno rodzaj smaru, jak też rodzaj wypełniacza wprowadzonego do tego smaru mają wpływ na własności reologiczne wytworzonych kompozycji smarowych.

INTRODUCTION

The diversity of lubricating equipment, lubrication methods, and a wide range of commercially offered lubricants are often reasons for doubts about the correct choice of a lubricant and lubrication method. The rich assortment of available lubricants and lubricating equipment allow users to make a more optimal choice for a specific application; however, at the same time, the multiplicity of these products and devices often lead to misuses, causing breakdowns. Another problem is improper use of lubricants, consisting in feeding too

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large amounts of lubricants to tribological nodes, which, apart from higher operating costs of friction nodes, is a threat to the environment. However, recently there have been improvements in this area. According to statistical data quoted by the literature **[L. 1]**, in highly developed countries, despite an increase in the number of machines and devices, the demand for lubricants declines. This decline results from the fact that they are supplied to lubricated nodes in a strictly defined time and in optimal doses.

Lubrication methods are different and, depending on the needs, besides manual lubrication (being used less and less often), they can be semi-automatic or fully automatic lubrication.

Both in semi-automatic and at fully automated lubrication, central lubrication systems are used. The main feature of these systems is that many friction nodes are lubricated by means of one pressure device. Lubricants used in these systems are oils and lubricating greases. So far, lubrication using lubricating grease is, besides air-oil lubrication, the simplest and least expensive method of minimal lubrication. Grease portions used here can be fed to a tribological node in optimum, usually very small amounts; therefore, this method is increasingly being used. Therefore, a lot of attention is dedicated to the quality of these greases by introducing into their structure various additives, which significantly improve their lubricating efficiency.

DISCUSSION ON RESEARCH ISSUES

Besides tribological properties of lubricating greases that ensure the best possible lubricating properties in a tribological node, lubricating efficiency is also affected by their rheological properties. Rheological properties of grease determine whether it will be fed to lubricated surfaces, and if so, whether in the required amount. Rheological properties of grease are affected both by the kind of thickening agent and base oil, and largely also by additives introduced to obtain additional properties required by operating conditions of a given node. These additives significantly affect the structure of grease in which the fundamental role is played by, besides the base oil, the kind, properties, and geometric form of the thickener. The geometric form of individual types of a thickener is very diverse, and ensembles of its particles take on shapes of oval bodies, plates, threads, or various forms of streaks.

Both the geometric form and the surface energy of these ensembles have a significant influence on the resulting structure of grease, including its rheological properties. Among rheological properties, the structural viscosity and a yield stress (flow limit) has essential significance for transporting grease in a lubrication system (from a grease tank to a lubricated node). In order to modify the structure of grease and make it more resistant to, often very high, external loads, additives are used, which, by altering interactions between the base oil and ensembles of particles of the thickener "improve" the quality of the grease. Solid lubricants, such as graphite or molybdenum disulphide, as well as powdered PTFE or some non-ferrous metals are often introduced into this structure. The purpose of this modification of the grease structure is to improve its lubricity under heavy-duty conditions and low rubbing speed, i.e. under conditions of mixed friction. In areas where the grease separating two contacting surfaces is missing, these fillers provide conditions for boundary (semi-dry) friction. It is important, however, to ensure that these fillers added to the grease do not cause a significant increase in structural viscosity and the yield stress, i.e. parameters which determine the so-called "pumpability"" of greases. An increase in these parameters impedes the flow of grease in the lubrication system and may block its inflow to a lubricated assembly. The above-mentioned fillers added to lubricating grease should have, due to their volume fraction, an adverse influence on the "pumpability" of the resultant grease composition by raising its viscosity. However, at the same time, it should be borne in mind that this viscosity is significantly influenced by physicochemical interaction between ensembles of particles of the thickener and of the filler introduced in form of a powder into the grease. This interaction depends on the "initial" structure of grease and the current state of this structure after the introduction of filler. Shapes of ensembles of filler particles (oval, thread-, streak-like, or flake-like forms), their energy potential and surface energy of introduced filler particles may change values of both the structural viscosity and the yield stress of the resultant grease composition. **Figure 1** schematically illustrates the effect of both these interactions **[L. 2, 4]**. As shown in **Fig. 1a**, the addition of powdered filler has caused a decrease in the value of shear stress despite the thickening of the resultant grease composition with a few percentage shares of filler being a solid substance. As shown in this figure, the introduction of active filler particles leads to such a modification of bonds between the ensembles of thickener particles that consequently, decrease the values of structural viscosity and yield stress.

If, however, the introduced filler particles are not very active or are inactive, then the geometric factor causing the thickening of the resultant grease composition is of major significance, and the physicochemical interaction between these particles is of no essential importance. In consequence, both the value of structural viscosity and the yield stress increase **(Fig. 1b)**.

In an earlier publication with the author's participation, results of previous research were given on the influence of fillers in the form of powdered graphite, PTFE, and MoS_2 on values of shear stresses occurring in resultant grease compositions at different gradients of shearing rate at a fixed temperature and shearing time.

This publication presents extended and more detailed research on the influence of some of these fillers, i.e. PTFE and graphite powders, on the value of shear stresses both in the "grease mass" and in the boundary (near-wall) layer. Particular attention was paid to the boundary layer. The results of the research on properties of grease in the boundary layer are particularly useful when designing central lubrication systems. Therefore, the research is a reference to previously published results and is their extension.

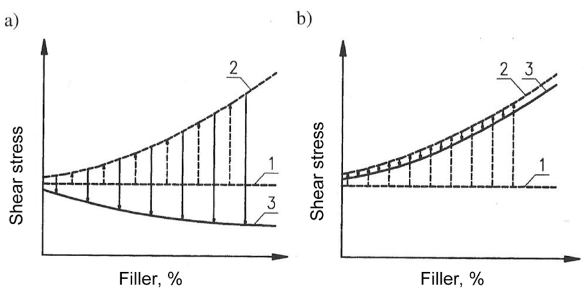


Fig. 1. The dominant influence of physicochemical (a) and geometric interaction (b) on the value of shear stress in a composition of lubricating grease with filler. 1 – the course of shear stress in a grease without a filler, 2 – influence of geometric factor on the value of shear stress in a grease composition, 3 – combined influence of geometric and physicochemical factors on the value of this stress [L. 2, 4]

Rys. 1. Dominujący wpływ oddziaływania fizykochemicznego (a) i geometrycznego (b) na wartość naprężenia stycznego w kompozycji smaru plastycznego z wypełniaczem. 1 – przebieg naprężenia stycznego w smarze bez wypełniacza, 2 – wpływ czynnika geometrycznego na wartość naprężenia stycznego w kompozycji smarowej, 3 – sumaryczny wpływ czynnika geometrycznego i fizykochemicznego na wartość tego naprężenia **[L. 2, 4]**

SUBJECT MATTER, METHODOLOGY, AND COURSE OF TESTS

Tests were carried out on greases classified in the 1st consistency class, produced on the basis of deeply refined mineral oil thickened with lithium soap of 12-hydroxystearic acid and modified with bentonite. Samples of these greases (both lithium and bentonite ones) were made with the following compositions: pure (without additives), with oxidation and corrosion inhibitors, as well as with oxidation and corrosion inhibitors and filler additives in the form of graphite and PTFE. Oxidation and corrosion additives were of the same quality and quantity as in commercial greases of the "Litomos" group (in case of lithium grease) and the "Bentomos" group (in case of bentonite grease). Initially measurements of grease compositions with concentrations from 1 to 15% were carried out; however, experimental tests and analyses were performed only on 5, 10, and 15% concentrations of fillers, because at these concentrations the influence of fillers on rheological properties of these compositions was most noticeable.

The main research was carried out on lithium grease, and test results of bentonite grease **(Figs. 7** and **8)** are presented for comparison.

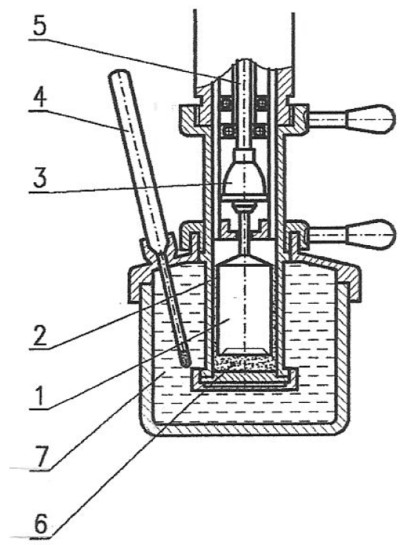


Fig. 2. Measuring head of the rheometer Rheotest 2.1: 1 – internal cylinder, 2 – external cylinder, 3 – clutch, 4 – thermometer, 5 – drive shaft, 6 – grease being tested , 7 – thermostatic medium

Rys. 2. Głowica pomiarowa reometru Rheotest 2.1: 1 – cylinder wewnętrzny, 2 – cylinder zewnętrzny, 3 – sprzęgło, 4 – termometr, 5 – wałek napędowy, 6 – badany smar, 7 – czynnik termostatujący

Measurements were carried out in the rotary rheometer Rheotest 2.1, equipped with a measuring head shown in **Fig. 2**. In order to study the influence of fillers on the rheological properties of the composition both in the grease mass and in the boundary layer, tests were carried out at gradients of shearing rate from 0.05 s^{-1} to 48.6 s^{-1}. Test results presented in this paper were obtained at a temperature of 25^{o}C.

Results of the research concerning the dependence of the shear stress on the gradient of shearing rate for lithium grease "without additives," for the same grease with oxidation and corrosion inhibitors, as well as compositions of this grease with graphite and PTFE powders are presented in **Figs. 3, 4, 5**, and **6**. For comparison, **Figures 7** and **8** show the results of the research into the dependence of the yield stress on the gradient of shearing rate of bentonite grease with additions of oxidation and corrosion inhibitors and filler in the form of 15% of graphite. The summary of test results for individual "compositions" of greases is presented in **Table 1**, which, besides results shown in these drawings, shows the data of tested greases containing 5% and 10%

a) b)

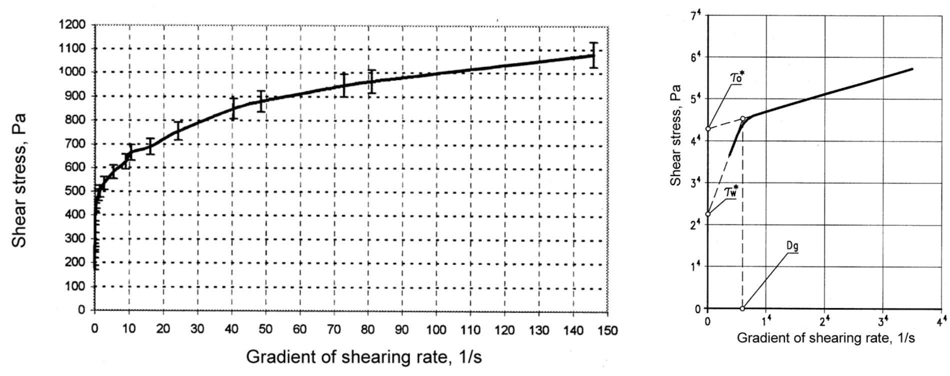


Fig. 3. The dependence of the shear stress on the gradient of shearing rate in lithium grease "without additives": a) the curve determined on the basis of mean values with marked confidence intervals, b) the above dependence presented graphically in coordinates in the power system τ^*_o = 337 Pa, τ_{Dg} = 178 Pa, τ^*_w = 26 Pa

Rys. 3. Zależność naprężenia stycznego od gradientu prędkości ścinania smaru litowego „bez dodatków": a) krzywa wyznaczona na podstawie wartości średnich z zaznaczonymi przedziałami ufności, b) powyższa zależność przedstawiona graficznie we współrzędnych w układzie potęgowym τ^*_o = 337 Pa, τ_{Dg} = 178 Pa, τ^*_w = 26 Pa

of above mentioned fillers, as well as "pure" bentonite grease. In **Fig. 3b**, the parameter "n" (here n = 4) from the generalized Casson's rheological model is adopted as an exponent. A similar solution is applied in other cases, i.e. in **Figs. 4b, 5b, 6b, 7b**, and **8b**. By using coordinates in the power system, the curve showing the relationship between the shear stress and the gradient of shearing rate of this grease (with different degrees of curvature determined by the value of the parameter "n") can be replaced with two half-lines. This allows us to read the value of the yield stress in the grease mass τ^*_o and on the wall τ^*_w.

As it was demonstrated in previous publications of the author **[L. 3, 5, 6]**, this is a very simple and fairly accurate method for determining yield stresses τ^*_o and τ^*_w. A certain inaccuracy is the assumption that the value of the fall in the yield stress in the boundary layer decreases as far as to the wall according to the same curve. More likely is the hypothesis that the course of this stress right at the wall (in the area of the surface layer) marked in **Fig. 3** by a dashed line is undetermined, and its value in this layer may increase.

Figure 4 shows the results of research on the dependence of shear stress on the gradient of shearing rate of the same lithium grease with additions of oxidation and corrosion inhibitors.

a) b)

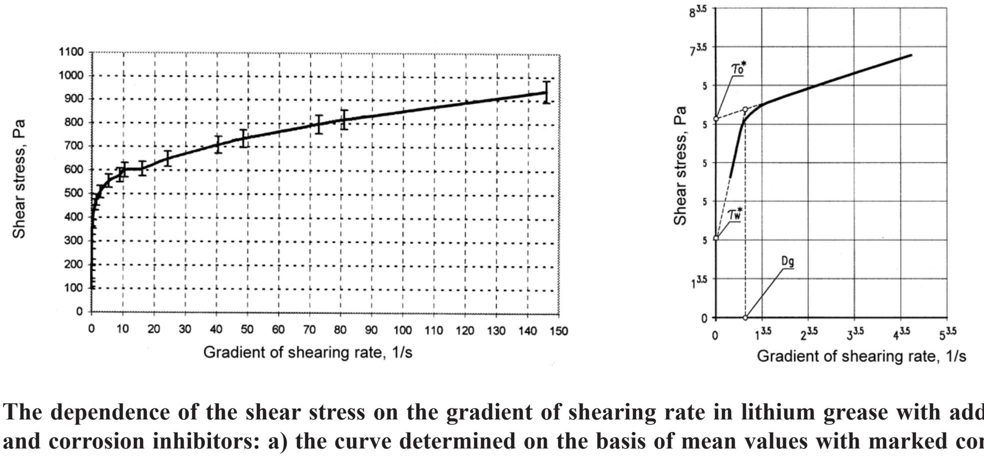


Fig. 4. The dependence of the shear stress on the gradient of shearing rate in lithium grease with addition of oxidation and corrosion inhibitors: a) the curve determined on the basis of mean values with marked confidence intervals, b) the above dependence presented graphically in coordinates in the power system τ^*_o = 320 Pa, τ_{Dg} = 103 Pa, τ^*_w = 12 Pa

Rys. 4. Zależność naprężenia stycznego od gradientu prędkości ścinania smaru litowego z dodatkiem inhibitorów utlenienia i korozji: a) krzywa wyznaczona na podstawie wartości średnich z zaznaczonymi przedziałami ufności, b) powyższa zależność przedstawiona graficznie we współrzędnych w układzie potęgowym τ^*_o = 320 Pa, τ_{Dg} = 103 Pa, τ^*_w = 12 Pa

When analysing the course of curves in **Figures 3** and **4** and also **Figures 5, 6, 7** and **8** on the following pages, one can notice that certain characteristic areas appear when, at very small values of the gradient of shearing rate, a distinct downward inflexion (bend) of the curve is noticeable, indicating certain disturbances in its course. This "bend" of the curve indicates the presence of phenomena occurring during the shearing of greases or their compositions in the gap between two cylinders of the rotary rheometer. These are boundary (near-wall) phenomena **[L. 5, 6]**, which are observed during rotation of the internal cylinder at very small value of the gradient of shearing rate. This research shows that, after exceeding a certain value of the yield stress, this shearing occurs at a very short distance from the wall of this cylinder, and the remaining mass of the grease remains intact. In the area right next to the wall in the grease, occur a surface layer and a thinned layer, together called a boundary layer. The occurrence of the thinned zone results in a decrease in value of structural viscosity in this zone; therefore, the value of the shear stress also significantly falls here. This is visible in diagrams presented in **Figures 3, 4, 5, 6, 7** and **8** in the form of a downward inflexion of the curve in the area of very small gradients of shearing rate. This fall depends on the type of grease, the properties of the wall material, and the temperature at which this shearing occurs.

As it appears from the analysis of discussed drawings, by plotting graphs in power coordinates, we can read values of both the yield stress in the grease mass τ^*_o, and the yield stress at the wall τ^*_w. Reading out the stress τ^*_w is hindered, because the minimum value of the gradient of shearing rate which could be obtained by means of the rheometer used for the tests was the value $D = 0.0167\ s^{-1}$.

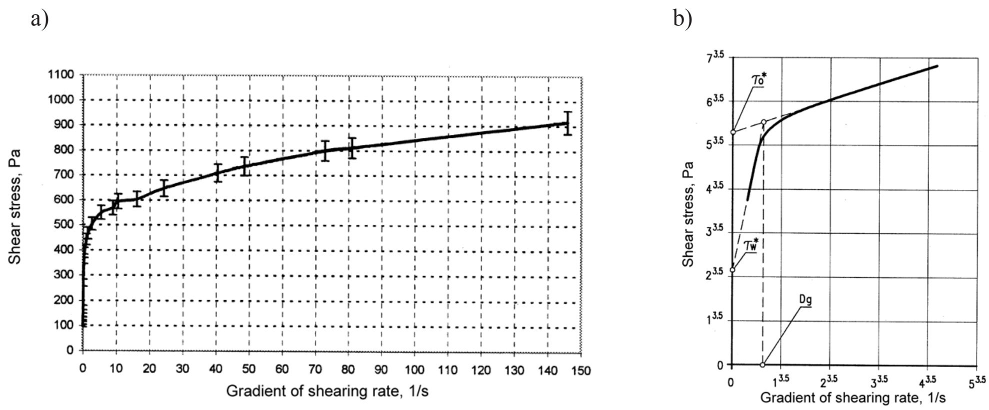


Fig. 5. The dependence of the shear stress on the gradient of shearing rate in lithium grease with oxidation and corrosion inhibitors and 15% of graphite filler: a) the curve determined on the basis of mean values with marked confidence intervals, b) the above dependence presented graphically in coordinates in the power system $\tau^*_o = 338$ Pa, $\tau_{Dg} = 104$ Pa, $\tau^*_w = 15$ Pa, $D_g = 0.3\ s^{-1}$

Rys. 5. Zależność naprężenia stycznego od gradientu prędkości ścinania smaru litowego z inhibitorami utleniania i korozji oraz 15% wypełniaczem grafitu: a) krzywa wyznaczona na podstawie wartości średnich z zaznaczonymi przedziałami ufności, b) powyższa zależność przedstawiona graficznie we współrzędnych w układzie potęgowym $\tau^*_o = 338$ Pa, $\tau_{Dg} = 104$ Pa, $\tau^*_w = 15$ Pa, $D_g = 0{,}3\ s^{-1}$

It is unknown whether, at lower values of this gradient, values of the shear stress would fall in a similar degree as at the gradient values higher than $D = 0.0167\ s^{-1}$. It is likely that, along with approaching the wall, which is to the area where the shearing occurs at lower gradient of shearing rate, the thinning of the grease thickener decreases, and at the very wall, the amount of thickener in the grease increases. Also, the structural viscosity increases, and therefore the yield stress on the wall increases. This requires further research involving more accurate equipment.

Changes in values of shear stresses, both in the boundary layer as well as in grease layers more distant from the wall, depend on the type of grease and fillers introduced into this grease. In case of the boundary layer, the material of the wall also plays an essential role. As demonstrated by the research, the introduction of active particles of oxidation and corrosion inhibitors into the structure of lithium soap, as well as fillers in the form of graphite powders, has caused the weakening of the interaction between the ensembles of particles in this soap to such a degree that the value of shear stress (and thus the structural viscosity) declined during the shearing of the resultant grease composition. These changes occurred both in the boundary layer and in the remaining layers of this grease with additives. This is shown, as an example, in **Fig. 4**, where the distinct influence of oxidation and corrosion inhibitors on the decrease in stresses is visible both in the "grease mass" and in the boundary layer (in the boundary layer the fall was almost twofold). The addition of 15% of graphite had lesser effect **(Fig. 5)**. As demonstrated by the experimental research, the addition of the MoS_2 filler had a greater influence on the change in values of these stresses. This was presented in previous publications **[L. 2, 4]**.

In the case of the composition of lithium grease with PTFE powder, this influence in the “grease mass” was almost not found. This (small) effect occurred only in the boundary layer and in the “grease mass” with at least 15% share of PTFE powder.

In summary, differences demonstrated by individual grease compositions, already reported in previous publications **[L. 2, 4]**, where the influence of MoS_2, PTFE and graphite fillers on the rheological properties of compositions was compared, have been confirmed especially in the case of graphite filler. The filler in the form of graphite powder caused a fall in the value of the yield stress in the grease composition, where (in the “grease mass”) it was about 15%. In the boundary layer, when the grease was sheared at a very low value of the gradient of shearing rate (D = 0.0167 s^{-1}), no significant changes were found in value of the yield stress. On the wall even a slight increase in value of this stress occurred.

A smaller influence on the change in value of the shear stress, and also the yield stress, was found with the PTFE powder, where changes in values of this stress occurring along with the increase in PTFE fraction were very insignificant and slightly decreased only at the 15% share of this filler in the grease composition. These differences result from different interactions between particles of lithium soap and particles of fillers, base oil, and other additives in the grease.

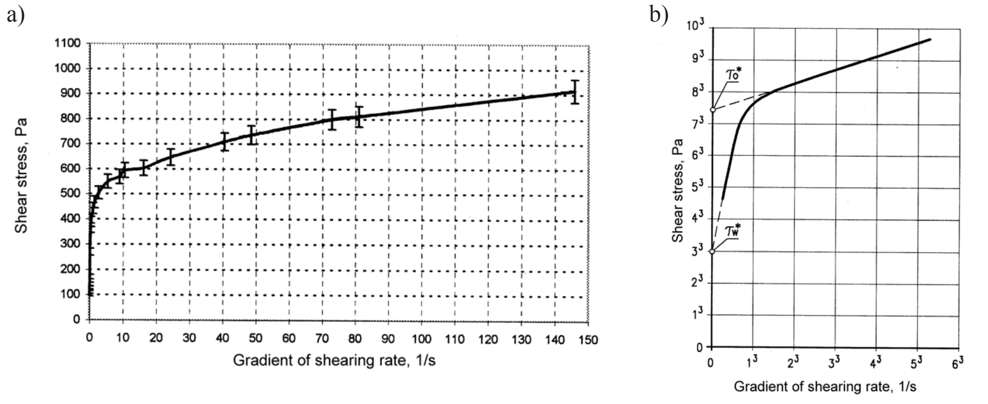


Fig. 6. The dependence of the shear stress on the gradient of shearing rate in lithium grease with oxidation and corrosion inhibitors and 15% of PTFE filler: a) the curve determined on the basis of mean values with marked confidence intervals, b) the above dependence presented graphically in coordinates in the power system τ^*_o = 412 Pa, τ_{Dg} = 100 Pa, τ^*_w = 24 Pa

Rys. 6. Zależność naprężenia stycznego od gradientu prędkości ścinania smaru litowego z inhibitorami utlenienia i korozji oraz 15% wypełniacza PTFE: a) krzywa wyznaczona na podstawie wartości średnich z zaznaczonymi przedziałami ufności, b) powyższa zależność przedstawiona graficznie we współrzędnych w układzie potęgowym τ^*_o = 412 Pa, τ_{Dg} = 100 Pa, τ^*_w = 24 Pa

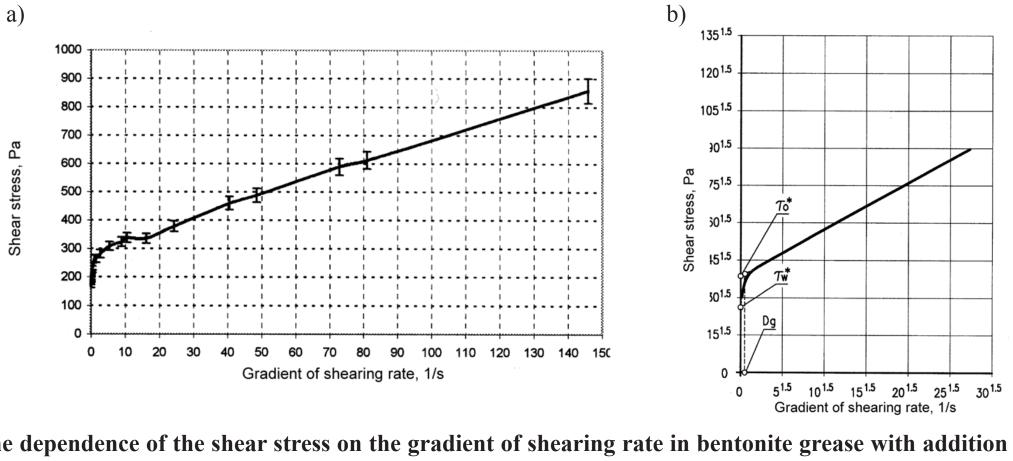
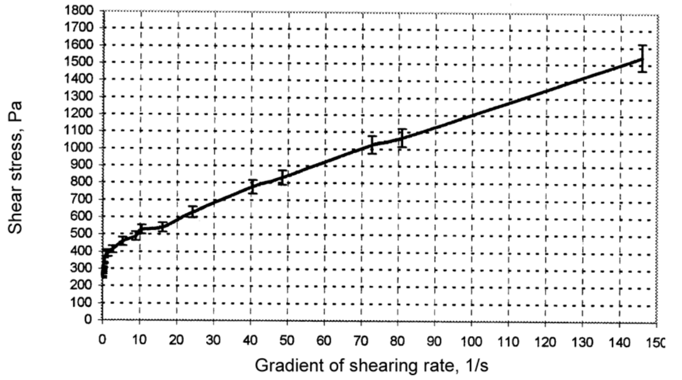


Fig. 7. The dependence of the shear stress on the gradient of shearing rate in bentonite grease with addition of oxidation and corrosion inhibitors: a) – the curve determined on the basis of mean values with marked confidence intervals, b) – the above dependence presented graphically in coordinates in the power system τ^*_o = 243,5 Pa, τ_D = 171 Pa, τ^*_w = 134.5 Pa

Rys. 7. Zależność naprężenia stycznego od gradientu prędkości ścinania smaru bentonitowego z dodatkiem inhibitorów utlenienia i korozji: a) krzywa wyznaczona na podstawie wartości średnich z zaznaczonymi przedziałami ufności, b) powyższa zależność przedstawiona graficznie we współrzędnych w układzie potęgowym τ^*_o = 243,5 Pa, τ_D = 171 Pa, τ^*_w = 134,5 Pa

Lithium soap, due to the form it takes on in the grease (long streaks and threads with very active fibrils at the ends), has a high "thickening ability"; therefore, even at a few percentage of its concentration, this grease has a relatively high consistency class. This means that, in the case of lithium grease, physicochemical properties of soap fibres play a fundamental role in the thickening of its structure, and the geometric factor plays a minor role here. The addition of active particles of oxidation and corrosion inhibitors to this grease, similarly as addition of active particles of graphite powder, causes disturbances in the structure of lithium soap, which is manifested by the weakening of bonds between the lithium soap fibres and, consequently, a lower value of the structural viscosity of the resultant grease composition. In the case of PTFE powder, its incorporation into the structure of lithium grease has a smaller influence on bonds in this structure, due to the low surface energy of PTFE and hence the weak impact of this powder on fibres of lithium soap. This is shown in **Figure 6**, where values of parameters: τ^*_o (412 Pa), τ_D (100 Pa) and τ^*_w (24 Pa) were (on average) higher than the corresponding values for the grease with added oxidation and corrosion inhibitors. This means that the physicochemical factor had a minimal impact, and the geometric factor was decisive here, i.e. the thickening of the structure by adding 15% of PTFE powder.

a)



b)

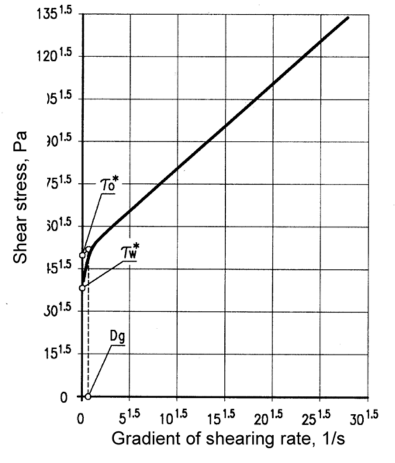


Fig. 8. The dependence of the shear stress on the gradient of shearing rate in bentonite grease with oxidation and corrosion inhibitors and 15% of graphite filler: a) a curve determined on the basis of mean values with indicated confidence intervals, b) the above dependence presented graphically in coordinates in the power system $\tau^*_o = 354$ Pa, $\tau_{Dg} = 259$ Pa, $\tau^*_w = 234$ Pa

Rys. 8. Zależność naprężenia stycznego od gradientu prędkości ścinania smaru bentonitowego z inhibitorami utlenienia i korozji oraz 15% wypełniaczem grafitu: a) krzywa wyznaczona na podstawie wartości średnich z zaznaczonymi przedziałami ufności, b) powyższa zależność przedstawiona graficznie we współrzędnych w układzie potęgowym $\tau^*_o = 354$ Pa, $\tau_{Dg} = 259$ Pa, $\tau^*_w = 234$ Pa

The dependence of the yield stress on the amount of filler in the case of bentonite grease looks differently **(Figs. 7, 8)**. Here, similarly as in lithium grease, the addition of oxidation and corrosion inhibitors has caused the fall in value of this stress compared with corresponding values of shear stress in the case of "pure" grease (without these additives). This fall was significant, because it was over twofold (about 2.5 times). The addition of fillers (both graphite and PTFE) caused an increase in these values; however, no differences in these values have been observed after introducing individual fillers. A certain increase occurred in values of the yield stress in the "grease mass," i.e. far from the wall, and a slightly greater increase in this stress occurred on the surface of the wall. This is shown in **Table 1**. The surface energy of bentonite clay being the thickener in this grease demonstrates a much lower value than the surface energy of lithium soap. Therefore, in order to obtain grease with the same consistency class, in the production of bentonite grease, the percentage of this clay is much greater than of soap in production of lithium grease.

Therefore, after the introduction of graphite or PTFE powder filler, due to the low reactivity of bentonite clay, further thickening of solid substances in grease occurs, and consequently there is a thickening of the resulting grease composition. Here, after introducing these fillers, the physicochemical factor affecting the weakening of bonds between plates of bentonite clay was considerably of less significance, and the increase in consistency of grease was determined by the geometric factor. Therefore, the increase in structural viscosity and the yield stress occurred correspondingly with the increase in the filler share. This increase was the highest in the "grease mass," i.e. where the concentration of both the thickener and the filler was the highest. It was also relatively high on the surface of the wall, which proves that the thinning of grease by the impact of the surface is much lower here than in the case of lithium grease. This means that, in the case of bentonite grease, the geometric factor has the decisive influence on the increase in structural viscosity and shear stress, i.e. these quantities increase along with the rise in the volume fraction of the filler.

Table 1. Summary of test results for individual compositions of lithium and bentonite greases
Tabela 1. Zestawienie wyników badań poszczególnych kompozycji smarów litowego i bentonitowego

Type of grease composition	Value of yield stress in grease mass τ_o^*, Pa	Value of yield stress in boundary layer τ_{Dg}, Pa	Value of shear stress on the wall τ_w^*, Pa
"Pure" lithium grease	337	178	26
Lithium grease with additions of oxidation and corrosion inhibitors	320	103	12
Lithium grease with addition of oxidation and corrosion inhibitors and 5% of graphite	370	101	7
Lithium grease with addition of oxidation and corrosion inhibitors and 10% of graphite	380	98	12
Lithium grease with addition of oxidation and corrosion inhibitors and 15% of graphite	338	104	15
Lithium grease with addition of oxidation and corrosion inhibitors and 5% of PTFE	402	96	17
Lithium grease with addition of oxidation and corrosion inhibitors and 10% of PTFE	367	83	19
Lithium grease with addition of oxidation and corrosion inhibitors and 15% of PTFE	412	100	24
„Pure" bentonite grease	630	436	361
Bentonite grease with addition of oxidation and corrosion inhibitors	243	171	134
Bentonite grease with addition of oxidation and corrosion inhibitors and 5% of graphite	234	158	118
Bentonite grease with addition of oxidation and corrosion inhibitors and 10% of graphite	302	210	125
Bentonite grease with addition of oxidation and corrosion inhibitors and 15% of graphite	354	259	234
Bentonite grease with addition of oxidation and corrosion inhibitors and 5% of PTFE	262	203	181
Bentonite grease with addition of oxidation and corrosion inhibitors and 10% of PTFE	291	210	198
Bentonite grease with addition of oxidation and corrosion inhibitors and 15% of PTFE	290	197	190

CONCLUSIONS

Test results presented in the paper show that the type of thickener of grease, as well as the type of filler introduced into this grease, have a significant influence on rheological properties of resultant grease compositions. Grease which has been thickened with polar lithium soap demonstrates, without additives, fairly high values of structural viscosity and shear stresses. These values significantly decrease after adding oxidation and corrosion inhibitors to this grease, and after additional introduction of graphite powder filler, a further reduction in value of these parameters occurs. The introduction of this filler caused a fall in the value of the yield stress of the resultant grease composition; however, as the tests showed, these values were decreasing with the growth of percentage share of this filler in the grease. Due to the limited space of this article, the presentation of greater number of graphs is not possible; therefore, only graphs with 15% share of the filler have been included. Data concerning other concentrations of fillers in tested greases is shown in **Table 1**. The drop in the yield stress in case of graphite filler with a volume fraction of 15% amounted to about 15% in the “grease mass”, and in the boundary layer the drop, in principle, did not occur. The addition of PTFE powder had a very small influence on the change in values of these parameters, due to the low surface energy of this material.

The above-mentioned fillers differently affect the rheological properties of grease thickened with non-polar bentonite clay, where the addition of these fillers to grease containing oxidation and corrosion inhibitors has caused an increase in the yield stress both in the “mass” of the composition (the highest) and in the boundary layer. The greatest increase (of about 60%) was found in the “mass” of the composition of bentonite grease with graphite powder (15%). According to test results presented in previous publications **[L. 2, 4]**, a smaller growth was observed in the boundary layer of the composition of bentonite grease both with MoS_2 and with PTFE powders. In the case of graphite, the rise in the yield stress also in the boundary layer was significant (this requires further tests).

In summary one may conclude, that the results of presented research indicate that changes in rheological properties of lubricating greases after the introduction of fillers are influenced by various factors. This may be the “geometric” factor when the introduction of a new solid substance thickens the previous grease structure. Then both the structural viscosity and the yield stress increase. This may also be the “physicochemical” factor, when the introduction of such a substance affects the internal state of this structure, thus reducing the mutual interaction between the particles of the grease thickener manifesting itself by the decrease in the structural viscosity and the shear stress.

The influence of these factors is essential for selecting structural parameters when designing an automated central lubrication system using compositions of lubricating greases with the said fillers. The adverse influence of fairly large particles of fillers on the operation of components (e.g., manifolds) of lubrication systems can be reduced by using powders with smaller particles. It would be interesting here to examine the use of fillers with particles of nanometric dimensions.

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