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THE EFFECT OF THE TYPE OF WALL MATERIAL AND GREASE COMPOSITION PAIRING ON SHEAR STRESSES IN BOUNDARY LAYER

WPŁYW SKOJARZENIA RODZAJ MATERIAŁU ŚCIANKI ORAZ SKŁADU KOMPOZYCJI SMAROWEJ NA NAPRĘŻENIA STYCZNE W WARSTWIE PRZYŚCIENNEJ

Key words: lubricating greases, fillers, rheological properties, boundary layer, machine lubrication systems.

Abstract The paper presents the results of research on the influence of fillers introduced into plastic greases on the rheological properties of the boundary layer of the resultant lubricant compositions. The fillers were PTFE and MoS_2 powders. They are added to lubricants to improve their tribological properties; however, these fillers also affect the rheological properties of the composition. This affects the change of the shear stress value in the lubricant during its flow in the lubrication system. Knowledge of this value, especially during the flow of the lubricant composition in the boundary layer, has a significant impact on the operation of automated central lubrication systems in which these compositions can be used. Measurements were carried out by means of a rotary rheometer (Rheotest 2.1). Tests were performed on lithium and bentonite greases (without additives) as well as compositions of these greases containing various percentage of the fillers mentioned above. Test results showed that both the type of grease and the type of filler introduced into this grease affect the rheological properties in the boundary layer of the produced lubricating compositions.

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

Streszczenie W pracy przedstawiono wyniki badań nad wpływem wypełniaczy, wprowadzanych do smarów plastycznych, na właściwości reologiczne warstwy przyściennej powstałych kompozycji smarowych. Wypełniaczami tymi były proszki PTFE i MoS_2. Dodawane są one do smarów w celu poprawy ich właściwości tribologicznych, ale wypełniacze te wpływają też na właściwości reologiczne kompozycji. Wpływa to na zmianę wartości naprężenia stycznego w smarze podczas jego przepływu w układzie smarowniczym. Znajomość tej wartości, a szczególnie podczas przepływu kompozycji smarowej w warstwie przyściennej ma istotny wpływ na działanie zautomatyzowanych układów centralnego smarowania, w których mogą być wykorzystane te kompozycje. Pomiary przeprowadzono na reometrze rotacyjnym Rheotest 2.1. Badaniom poddano smary litowy i bentonitowy (bez dodatków) oraz kompozycje tych smarów z udziałami wymienionych powyżej wypełniaczy. Wyniki badań wykazały, że zarówno rodzaj smaru, jak też rodzaj wypełniacza wprowadzonego do tego smaru mają wpływ na własności reologiczne w warstwie przyściennej wytworzonych kompozycji smarowych.

INTRODUCTION

A wide variety of tribological nodes, lubrication methods, and lubricants offered are often the reason for difficulties in choosing the right agent or lubrication method. The currently available great diversity of these measures **[L. 10]** and lubrication devices enables users to make a more optimal selection for a particular tribological node. At the same time, the variety of these means and devices, as well as the lack of sufficient knowledge, may lead to erroneous applications causing failures and breakdowns.

An important problem is also providing tribological nodes with an excessive amount of lubricating agents that increases nodes operating costs and poses a threat to the natural environment as well.

Various lubrication methods are used, but, recently, semiautomatic or fully automated lubrication systems have become predominant, because these methods significantly improve the quality of lubrication. Both

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semi-automatic and fully automated lubrication use central lubrication systems, the essence of which is that many friction nodes are lubricated by means of one pressure device. Lubricants used in these systems are oils and greases. Lubrication with grease is one of the simplest and cheapest methods of minimum lubrication (same as air-oil lubrication). Grease portions used here can be fed to the tribological node in the most favourable, sometimes very small amounts, and therefore this method is now widely used. Therefore, much attention is paid to the quality of lubricating greases by introducing into their structure various additives, which significantly improve the efficiency of lubrication. The additives are also solid lubricants. When introduced into the grease structure, they form lubricating compositions which improve lubrication conditions in the tribological nodes.

DISCUSSION ON RESEARCH ISSUES

The effectiveness of lubrication with lubricating greases is influenced by their tribological properties as well as rheological properties. Rheological properties determine whether the grease will be supplied to the lubricated surfaces and whether the amount of grease is suitable.

Rheological properties of lubricating grease are influenced by both the type of base oil, the thickener, and the various additives introduced into this grease. These additives affect the structure of the lubricant, where, besides the base oil, the type, properties, and geometrical form of the thickener play a fundamental role. Both the geometric form and the surface energy of thickener particle clusters have a significant impact on the resultant lubricant structure, including its rheological properties. From among the rheological properties, the structural viscosity and yield stress are of great importance when transporting this lubricant in the lubrication system. To make the grease structure more resistant to external loads, additives that "improve" the quality of the grease are used. Moreover, solid lubricants, such as graphite, molybdenum disulphide, or PTFE powders, as well as non-ferrous metals, are often introduced into this structure.

The aim is to improve the lubricity of the resultant lubricant composition at heavy loads and low slippage speeds, i.e. under mixed friction conditions. When there is no lubricant separating two contacting surfaces, these fillers provide boundary (semi-dry) friction conditions. The question here is what percentage of the filler by its volume fraction will not cause an increase in structural viscosity, which could worsen the pumpability of the resultant composition and limit its applicability in automated lubrication systems. Test carried out earlier by the author **[L. 4]** showed that, after the fillers were introduced, the structural viscosity and shear stress did not increase; even quite opposite, in some combinations of the grease with the filler, these values decrease. In the studies presented in the author's earlier publication **[L. 5]**, it was shown that the structural viscosity, and hence the shear stress of the lubricant composition resulting from the introduction of filler particles into the grease, are greatly influenced by the physicochemical interaction between the clusters of these particles and the thickener particles. This interaction depends on the "initial" structure of the lubricant and the activity of the introduced filler particles in the direction of "remodelling" this structure into a new system taking into account the influence of these "new" particles. Some fillers may increase and others may reduce the structural viscosity of the resulting composition (and also shear stress). **Figure 1** presents a diagram of the influence of both of these interactions presented from the literature **[L. 4, 6]**.

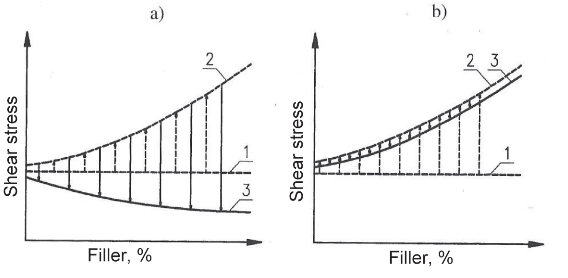


Fig. 1. The main physicochemical (a) and geometric (b) impact on the shear stress value in the plastic grease composition with the filler: 1 – the course of shear stress in the grease without a filler, 2 – the influence of the geometrical factor on the shear stress value in the lubricant composition, 3 – the total effect of the geometric and physicochemical factor on the value of this stress [L. 4, 6]

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. 4, 6]**

As results from **Fig. 1a**, the introduction of the filler into the lubricant composition caused a decrease in the shear stress value, although the formed lubricant composition was "thickened" by the share of the powdered filler. In other words, the addition of active filler particles caused such a modification of the bonds in the lubricant structure that the shear stress value decreased.

If the filler particles are not very active or completely inactive, then only the influence of the geometric factor thickening the formed lubricant composition occurs, and the physicochemical interaction of these particles is negligible. As a result, the values of structural viscosity and shear stress increase (**Fig. 1b**).

Previous publications **[L. 6, 7]** presented the results of earlier studies of the impact of fillers in the form of PTFE and MoS_2 powders on the shear stress values of the resultant lubricating compositions at different shear rate gradients at a fixed temperature and shearing time. The author's paper **[L. 4]** also included the results of further research on lubricating compositions containing the mentioned fillers and graphite. All of the research was carried out with a pairing of a steel wall and lubricating compositions.

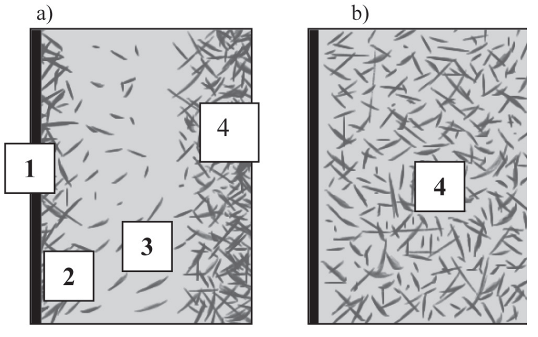


Fig. 2. Formation of the surface and boundary layers in the grease flowing near the wall made of material, which (a) has the ability to adsorb the thickener particles, (b) does not have the ability to adsorb the thickener particles: 1 – material wall, 2 – surface layer (adsorbed particles of the grease thickener on the surface of the material wall), 3 – boundary layer (the area depleted of the thickener, with smaller structural viscosity), 4 – grease mass [L. 12]

Rys. 2. Kształtowanie się warstw powierzchniowej i przyściennej w smarze płynącym w pobliżu ścianki materiału, który a) posiada zdolność do adsorpcji cząstek zagęszczacza, b) nie posiada zdolności do adsorpcji cząstek zagęszczacza: 1 – ścianka materiału, 2 – warstwa powierzchniowa (zaadsorbowane cząstki zagęszczacza smaru na powierzchni ścinaki materiału), 3 – warstwa przyścienna (obszar zubożały w zagęszczacz, o mniejszej lepkości strukturalnej), 4 – masa smaru **[L. 12]**

This article presents studies of the flow of the above-mentioned lubricant compositions through ducts made of various "non-steel" materials, i.e. copper, polyamide, and PTFE.

During the start-up of a tribological node or lubrication system, the grease starts flowing close to the wall of a lubricated or grease-transporting component. Rheological properties of the lubricant cause that the greatest value of its structural viscosity occurs at the start of its flow. As can be seen from many literature references **[L. 2, 3, 11–14]**, two layers are formed by the lubricant at the wall: the surface and boundary (near-wall) layers with rheological properties other than the lubricant layers located further away from the walls. The formation of the boundary layer results from the clustering of the thickener particles on the surface of the wall material, with which the flowing lubricant is in direct contact (**Fig. 2a**).

The greatest intensity of the phenomenon is found in "soap" lubricants **[L. 12]**, where the anisometric-shaped thickener particles (in the form of strips or threads), and having active "centres" at their ends, catalyse this process mainly through physicochemical interactions. Due to the diffusion of the thickener particles on the surface of the wall, an area depleted of the thickener with reduced structural viscosity is formed in its vicinity. Some of the associates are "extracted" from the mass of the lubricant, and the thickener structure is thinned in this area adopting rheological properties similar to Newtonian fluid **[L. 1]**. As a result, the lubricant slippage and a decrease in its flow resistance occur near the wall. The influence of the boundary layer on the decrease in the resistance of the lubricant flow is particularly visible in the case of axisymmetric ducts with small diameters when the flow is laminar. With the increase in the diameter of the duct, the influence of the boundary layer decreases. **Figure 3** schematically shows the influence of the created boundary layer on the distribution of velocity and shear stresses in the grease during its flow through a pipeline.

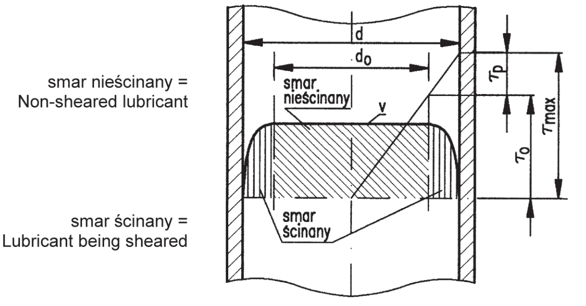


Fig. 3. Distribution of shear stresses and velocities in grease flowing through a pipeline [L. 8]

Rys. 3. Rozkład naprężeń stycznych i prędkości w smarze plastycznym przepływającym przez przewód rurowy **[L. 8]**

As can be seen on the diagram, there are two zones in the flowing plastic grease, namely:

1) The zone of lubricant being sheared, where shear stress has exceeded the flow limit, and subsequent layers move at speeds with values determined by the influence of the wall material on this lubricant; and,
2) The grease zone, in which the stress does not exceed the flow limit and where entire lubricant moves in the form of a "stopper" at the same speed.

The main factor determining the start of the lubricant flow is the value of the shear stress in this lubricant. This value is influenced by the type of grease, temperature, its shear time in the lubrication system, and even its production technology. Results of many studies show that the value of shear stress in the lubricant flowing in a pipeline or in a bearing gap is the smallest in the area right next to the surface of these elements **[L. 2, 8, 9]**. The value of this stress increases with the growing distance from the wall surface until, at a certain distance, a constant value is achieved, corresponding to the value of the stress in the grease mass. As emphasized earlier, the mechanism of forming the boundary layer is the result of physicochemical interactions between the grease and the wall material, i.e. it depends both on the type of grease and the type of wall material.

Therefore, the aim of the study presented in this paper is to assess the impact of the type of wall materials on the formation of the boundary layer in lubricant compositions flowing near these walls.

SUBJECT MATTER, METHODOLOGY AND COURSE OF TESTS

The tests were carried out on "pure" lubricants (without additives), as well as on the compositions of these lubricants with fillers. The fillers were PTFE and MoS_2 powders. The percentages (by volume) of these fillers in the compositions were 15%, since, as was proved by earlier tests carried out at steel walls, the effect of fillers on the shear stress values at this concentration in the lubricant composition was the greatest. Measurements were carried out in a rotational rheometer (Rheotest 2.1), and its measuring head is shown in **Fig. 4**. Replaceable internal Cylinders (1) were used made of copper and plastics (polyamide and PTFE), which are more often used in supply lines of central lubrication systems. Measuring surfaces of these cylinders were made with the same surface roughness as in the "original" cylinder of the device. To examine the influence of fillers on rheological properties of the composition in the boundary layer, the tests were carried out at very low values of shear rate gradients, i.e. from $D = 0.0167\ s^{-1}$ to $D = 1\ s^{-1}$. Tests presented in the paper were carried out at 25°C. Measurements were repeated five times and the results were statistically elaborated with a confidence level of 0.95.

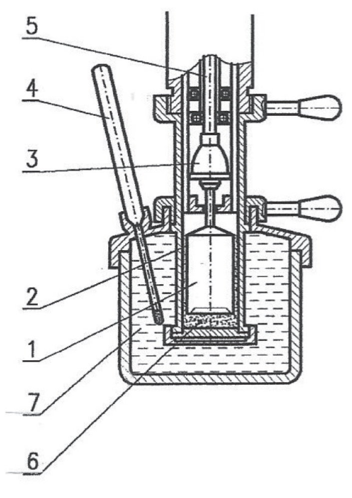


Fig. 4. Measuring head of the Rheotest 2.1 rheometer: 1 – internal measuring cylinder, 2 – external measuring cylinder, 3 – coupling, 4 – thermometer, 5 – drive shaft, 6 – lubricant tested, 7 – thermostatic agent

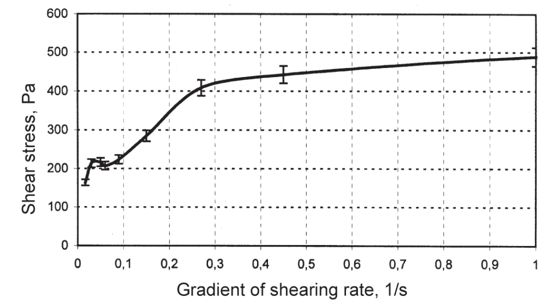
Rys. 4. Głowica pomiarowa reometru Rheotest 2.1: 1 – cylinder pomiarowy wewnętrzny, 2 – cylinder pomiarowy zewnętrzny, 3 – sprzęgło, 4 – termometr, 5 – wałek napędowy, 6 – badany smar, 7 – czynnik termostatujący

Figs. 5–6 present research results of pairing the copper wall with "pure" lithium grease and its compositions containing MoS_2 and PTFE powders.

Fig. 7 shows the results of research on the relationship between the shear stress and the percentage of the above-mentioned fillers in bentonite grease. For both cases, the relationships between shear stress and shear rate gradients were determined within the range $D = 0.0167\ s^{-1}$ to $D = 1\ s^{-1}$.

A clear difference is visible in the shapes of curves describing the relationship between shear stress and the shear rate gradient.

a)



b)

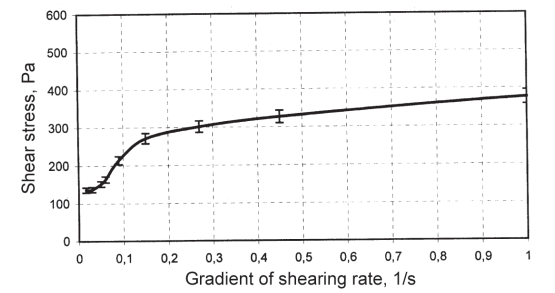


Fig. 5. Relationship between the shear stress and the shear rate gradient near the copper wall, in lithium grease: a) "pure" without inhibitors and fillers, b) with a filler in the form of 15% of MoS_2

Rys. 5. Zależność naprężenia stycznego od gradientu prędkości ścinania w pobliżu ścianki miedzianej smaru litowego: a) „czystego" bez inhibitorów i wypełniaczy, b) z wypełniaczem w postaci 15% MoS_2

In the case of lithium grease, the characteristic "inflection" of the curve occurs at shear rate gradient values $D = 0.2–0.3\ s^{-1}$, while in the case of bentonite grease, the "inflection" appears already at $D = 0.05\ s^{-1}$ (**Fig. 7**).

This confirms the existence of various mechanisms of boundary layer formation during the flow of these two lubricants. Lithium grease has very active lithium soap particles in its structure, many of which move towards the wall and settle on its surface (**Fig. 2a**) creating a “thinned” boundary layer. In the case of bentonite grease, low-active particles do not deposit on the wall but move in its proximity together with MoS_2 particles at small resistances.

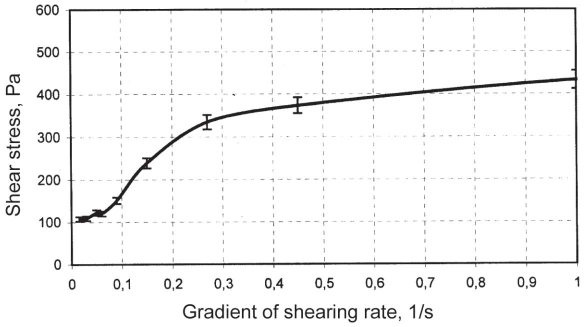
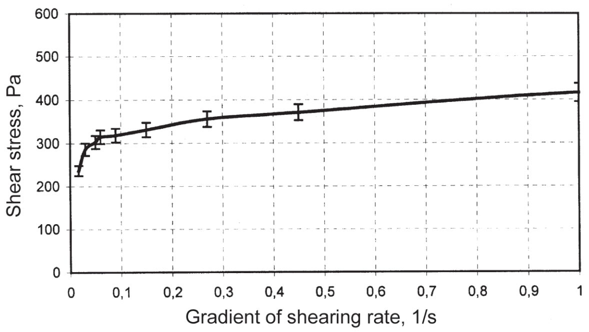


Fig. 6. Relationship between the shear stress and the shear rate gradient in lithium grease with a filler in the form of 15% PTFE powder, near the copper wall

Rys. 6. Zależność naprężenia stycznego od gradientu prędkości ścinania, w pobliżu ścianki miedzianej, smaru litowego z wypełniaczem w postaci 15% proszku PTFE

a)



b)

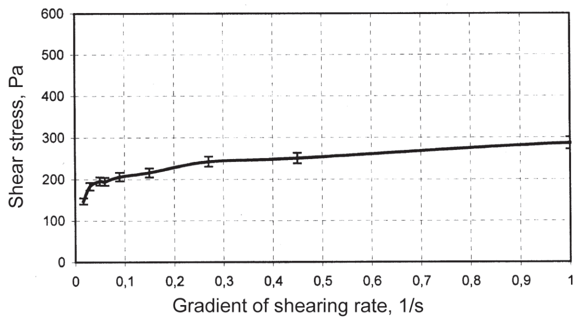


Fig. 7. Relationship between the shear stress and the shear rate gradient in bentonite grease, near the copper wall: a) in “pure” form without inhibitors and fillers, b) with a filler in the form of 15% of MoS_2 powder

Rys. 7. Zależność naprężenia stycznego od gradientu prędkości ścinania w pobliżu ścianki miedzianej smaru bentonitowego: a) w postaci „czystej” bez inhibitorów i wypełniaczy, b) z wypełniaczem w postaci 15% proszku MoS_2

As can be seen from the comparison of the forms of curves presented in these drawings, the ranges of shear stress values and changes of these values at the rise in shear rate gradients differ considerably. In the case of lithium grease and its composition (with MoS_2 and PTFE), the values of minimum shear stresses are from ca. 160 Pa in the case of “pure” grease (without inhibitors and fillers) to ca. 100 Pa for lithium grease with PTFE powder. At the shear rate gradient equal to 1 s^{-1}, the lowest shear stress value occurred in the composition of lithium grease containing MoS_2, and the highest in this “pure” lubricant, i.e. without additives and fillers. The greatest increase in the shear stress value in both of these lubricants was observed in the range of shear rate gradients $D = 0.2 – 0.3$ s^{-1}. The range of these values can be considered as the area of flow in the boundary layer.

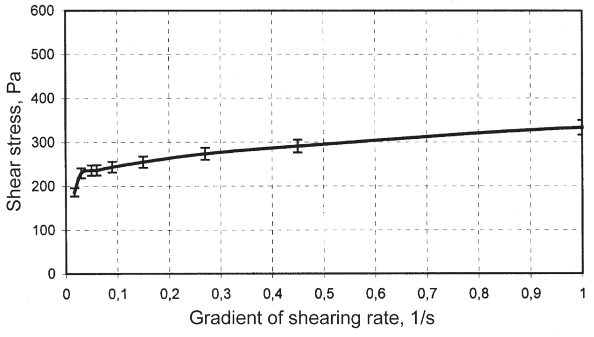


Fig. 8. Relationship between the shear stress and the shear rate gradient, near the copper wall, of bentonite grease with a filler in the form of 15% PTFE powder

Rys. 8. Zależność naprężenia stycznego od gradientu prędkości ścinania w pobliżu ścianki miedzianej, smaru bentonitowego z wypełniaczem w postaci 15% proszku PTFE

Other values of rheological parameters for the boundary layer were found in the case of bentonite grease, and its compositions containing MoS_2 and PTFE moved close to the copper wall. As shown in **Figs. 7** and **8**, the values of shear stresses in the area of the boundary layer and the layers slightly distant from the wall were in the range from τ = ca. 150 Pa (for bentonite grease composition with MoS_2 powder) at $D = 0.0167$ s^{-1} (**Fig. 7b**) to τ = approx. 415 Pa (for “pure” grease) at $D = 1$ s^{-1} (**Fig. 7a**). Values of these stresses at a minimum shear rate “gradients” ranged from τ = ca. 225 Pa for “pure” bentonite grease to τ = ca. 150 Pa for bentonite grease composition containing 15% of MoS_2. Thus, the values are almost 50% higher than the corresponding values relating to lithium grease or its composition.

The growth in shear stresses in bentonite grease or in its compositions containing fillers compared to lithium grease was much smaller. It mainly applied to the composition of bentonite grease containing molybdenum disulphide, in which the shear stress value at a shear gradient of 1 s^{-1} was just under 300 Pa. In the author's opinion, it is due to the fact that bentonite grease containing a non-polar thickener produces a boundary layer with a small range (reach), and also that molybdenum disulphide weakens structural bonds of the bentonite thickener.

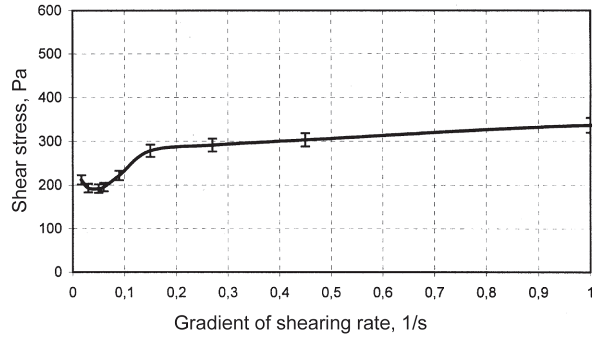


Fig. 9. Relationship between the shear stress and the shear rate gradient, close to the wall made of polyamide, in lithium grease in a "pure" form without inhibitors and fillers

Rys. 9. Zależność naprężenia stycznego od gradientu prędkości ścinania, w pobliżu ścianki wykonanej z poliamidu, smaru litowego w postaci „czystej" bez inhibitorów i wypełniaczy

Compared to metals (steel and copper), plastics have a completely different effect on the formation of the boundary layer and the one near the surface of the wall, and this was observed during tests involving polyamide and PTFE. As shown in **Figures 9** and **10**, the minimum stresses at a wall made of polyamide at the shear rate gradient D = 0.0167 s^{-1} were much higher in the case of lithium grease than in the case of metal walls. In both cases, i.e. "pure" grease and its composition containing molybdenum disulphide, they reached approximately 200 Pa.

Only in the composition of this grease with PTFE powder, the stresses on the wall were smaller and amounted to approx. 130 Pa. The interaction of the lithium lubricant compositions with PTFE powder, in their contact with metal walls, was also different than in other compositions. It probably results from the fact that the surface energy of PTFE is several times smaller than the surface energy of molybdenum disulphide. Therefore, the composition containing PTFE exhibits lower interaction forces with the wall surface and "slides" more easily on the surface of this wall. Similarly, when the grease flows near a wall made of PTFE, it also "slides" on this wall (**Fig. 11**). Values of shear stress on the polyamide wall at the shear rate gradient of 1 s^{-1} were also lower than in the case of metal walls, i.e. approx. 330 Pa.

Significantly different values of shear stresses as compared to polyamide were found during the research on rheological properties of the boundary layer of lithium grease and its compositions flowing close to the wall made of PTFE. In the case of a wall made of PTFE, the measured values of the minimum shear stresses were in the range from slightly below 100 Pa in the pairing of PTFE wall with a composition of lithium grease and PTFE powder (**Fig. 12b**) to approx. 130 Pa for the pairing of this wall with lithium grease with added MoS_2 filler (**Fig. 12a**). In the case of walls made of PTFE used in conjunction with lithium grease and other compositions of this grease, the shear stress values at the shear rate gradient D = 1 s^{-1} were the same as in the shearing of this grease and its composition at a polyamide wall.

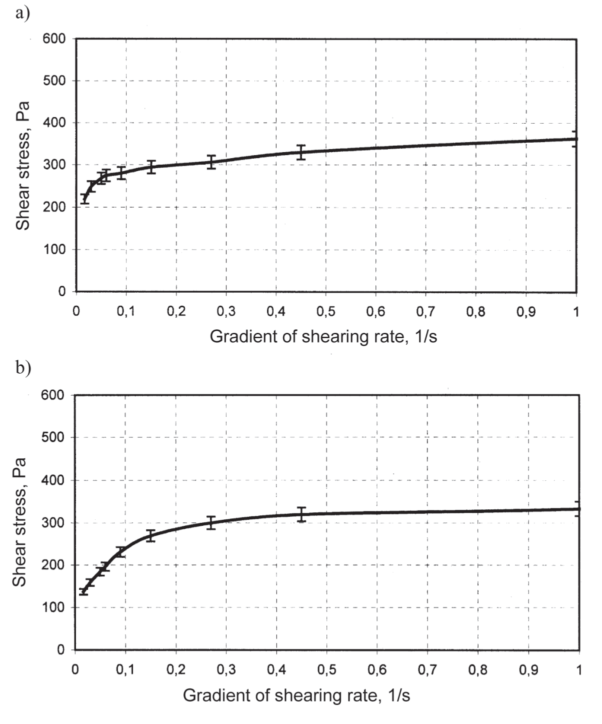


Fig. 10. Relationship between the shear stress and the shear rate gradient near the wall made of polyamide, in lithium grease: a) with filler in the form of 15% of MoS_2 powder, b) with filler in the form of 15% of PTFE powder

Rys. 10. Zależność naprężenia stycznego od gradientu prędkości ścinania w pobliżu ścianki wykonanej z poliamidu, smaru litowego: a) z wypełniaczem w postaci 15% proszku MoS_2, b) z wypełniaczem w postaci 15% proszku PTFE

In other words, the lithium grease and its compositions with the previously mentioned fillers in the boundary layer near PTFE exhibit rheological properties similar to metals; whereas, in more distant layers, it has properties similar to polyamide. It weights in favour of using PTFE in the designing of ducts or applying PTFE on internal surfaces of ducts used in automated lubrication systems.

In the case of bentonite grease or its composition with fillers flowing near a polyamide wall, similar values of minimum stresses and changes of these stresses were

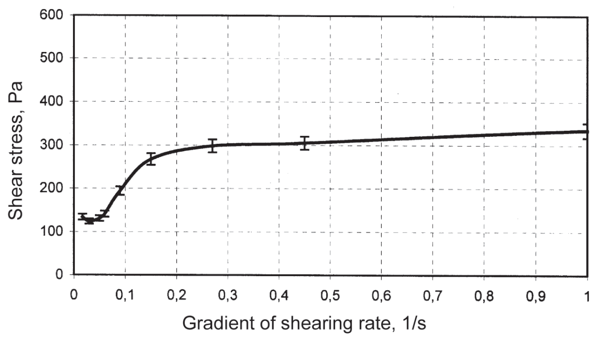


Fig. 11. Relationship between the shear stress and the shear rate gradient, near the PTFE wall, in lithium grease in the "pure" form without inhibitors and fillers

Rys. 11. Zależność naprężenia stycznego od gradientu prędkości ścinania, w pobliżu ścianki wykonanej z PTFE, smaru litowego w postaci „czystej" bez inhibitorów i wypełniaczy

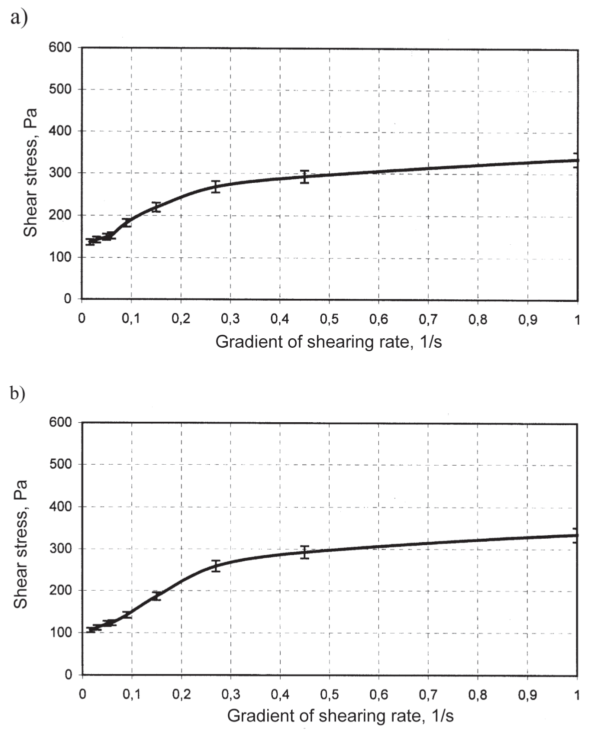


Fig. 12. Relationship between the shear stress and the shear rate gradient, near the PTFE wall in lithium grease: a) with a filler in the form of 15% of MoS_2, b) with a filler in the form of 15% of PTFE powder

Rys. 12. Zależność naprężenia stycznego od gradientu prędkości ścinania w pobliżu ścianki wykonanej z PTFE, smaru litowego: a) z wypełniaczem w postaci 15% MoS_2, b) z wypełniaczem w postaci 15% proszku PTFE

observed together with the increase in the shear rate gradient, as in the case of metal walls. Here, as in the case of for instance copper, the minimum shear stress in the "pure" grease was about 250 Pa (**Fig. 13**), and in the composition of this grease containing 15% of MoS_2 filler, it was about 175 Pa (**Fig. 14a**). The stress values at the shear rate gradient of 1 s^{-1} were equal to 400 Pa for the pairing of polyamide with "pure" bentonite grease (**Fig. 13**) and ca. 300 Pa and slightly below, in the case of other pairings.

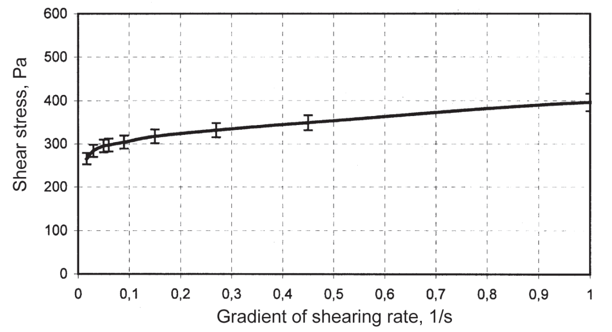


Fig. 13. Relationship between the shear stress and the shear rate gradient, near the wall made of polyamide, in "pure" bentonite grease without inhibitors and fillers

Rys. 13. Zależność naprężenia stycznego od gradientu prędkości ścinania, w pobliżu ścianki wykonanej z poliamidu, smaru bentonitowego w postaci „czystej" bez inhibitorów i wypełniaczy

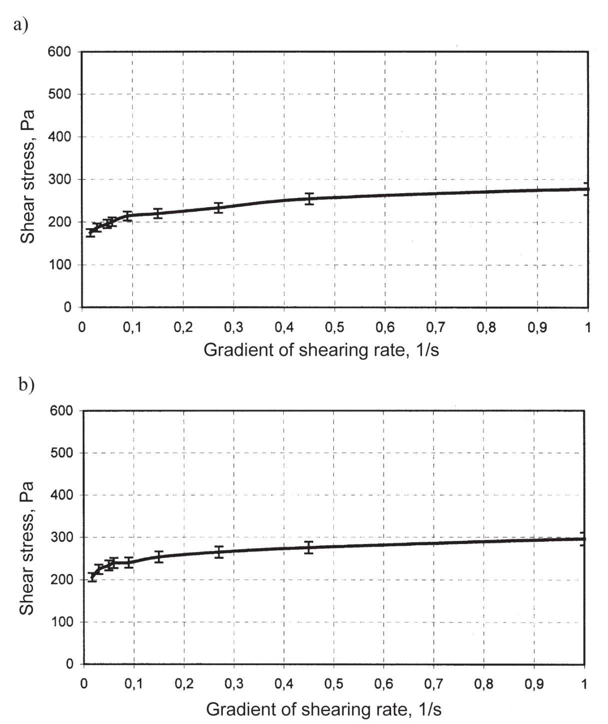


Fig. 14. Relationship between the shear stress and the gradient of flow velocity close to the wall made of polyamide, in bentonite grease: a) with a filler in the form of 15% of MoS_2, b) with a filler in the form of 15% of PTFE powder

Rys. 14. Zależność naprężenia stycznego od gradientu prędkości przepływu obok ścianki wykonanej z poliamidu smaru bentonitowego: a) z wypełniaczem w postaci 15% MoS_2, b) z wypełniaczem w postaci 15% proszku PTFE

Research results presented in **Figures 13** and **14** show that bentonite grease generates a boundary layer with a limited range of action near a polyamide wall. The addition of fillers in the form of PTFE powder or molybdenum disulphide does not change its properties in this respect. Therefore, when using polyamide lubrication piping, we should remember that its resistance to bentonite grease being pumped at low values of shear rate gradient, i.e. during the start-up, will be relatively high.

The research was also carried out on another material classified as plastics that might be used to build lubrication piping. These were studies on the effect of PTFE, as a wall material, on the formation of a boundary layer in bentonite grease or its compositions with fillers.

The research on rheological properties of bentonite grease and its compositions with fillers in the form of PTFE powder and molybdenum disulphide flowing near the wall made of PTFE was undertaken due to the beneficial results of this pairing demonstrated in earlier studies. Tests, similar to those described previously, were carried out in the rotational rheometer (Rheotest 2.1) using internal cylinders made of PTFE. These cylinders had identical geometric parameters as the original cylinder offered by the manufacturer.

Figures 15 and **16** present the test results of these pairings. Values of shear stresses, depending on shear rate gradients of "pure" bentonite grease and its compositions containing fillers, in comparison with corresponding stress values exhibited by these lubricants used with a polyamide wall, are slightly smaller. They are at the level of corresponding stresses appearing in this lubricant during its flow near metal walls. These stresses at the shear rate gradient D = 0.0167 s^{-1} are the highest in "pure" bentonite grease and amount to approximately 225 Pa (**Fig. 15**). The addition to this grease of the previously mentioned fillers contributes to the lowering of this value, and at the above-mentioned gradient value, the shear stress is about 150 Pa. The increase in the shear stress value as the shear rate gradient is increased to D = 1 s^{-1} in the case of both "pure" grease and grease containing fillers is small, and for "pure" grease amounts to about 360 Pa (**Fig. 15**). For compositions of this grease with PTFE powder, the shear stress value is about 300 Pa (**Fig. 16b**), and the lowest is the value of the composition containing MoS_2 filler, and is slightly over 200 Pa (**Fig. 16a**). These results indicate that there is a need to undertake extensive applied research to introduce the ducts made of PTFE or steel with an inner surface coated with a PTFE layer into industrial solutions. In the author's opinion, further work is recommended both for materials with other percentage compositions as well as for other temperatures, especially at sub-zero temperatures.

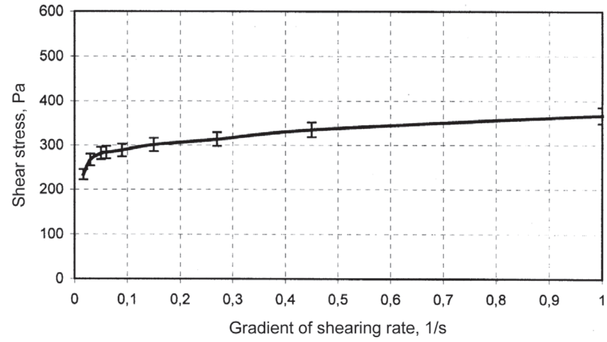


Fig. 15. Relationship between the shear stress and the shear rate gradient, near a wall made of PTFE, in bentonite grease in a "pure" form, without inhibitors and fillers

Rys. 15. Zależność naprężenia stycznego od gradientu prędkości ścinania w pobliżu ścianki wykonanej z PTFE, smaru bentonitowego w postaci „czystej" bez inhibitorów i wypełniaczy

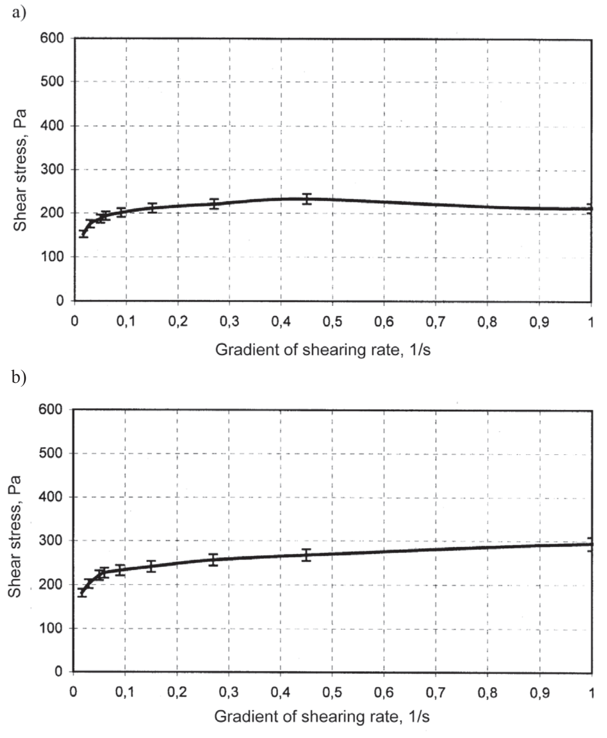


Fig. 16. Relationship between shear stress and shear rate gradient near a PTFE wall, in bentonite grease: a) with filler in the form of 15% of MoS_2, b) with filler in the form of 15% of PTFE powder

Rys. 16. Zależność naprężenia stycznego od gradientu prędkości ścinania w pobliżu ścianki wykonanej z PTFE, smaru bentonitowego: a) z wypełniaczem w postaci 15% MoS_2, b) z wypełniaczem w postaci 15% proszku PTFE

SUMMARY

The conducted research concerns the influence of the wall material type on rheological properties of the boundary layer in lithium and bentonite greases as well as their compositions with fillers in the form of PTFE powder and molybdenum disulphide. Research has demonstrated that rheological parameters of the boundary layer are significantly influenced by the fillers, which reduce the value of shear stresses in the layers of lubricating compositions flowing near walls made of metal or some plastics (PTFE). As shown schematically in **Fig. 1**, the change in the value of shear stress in a composition of grease with a filler depends both on the type of grease and the type of filler. If the filler works only "geometrically" by thickening the lubricant composition, then the shear stress increases. If it is a physicochemical interaction (resulting from both the type of grease and the type of filler), then despite the "geometric thickening" with the filler powder, shear stresses in the lubricant composition decrease, i.e. changes occur in the structure of the lubricant composition probably as early as at the stage of preparing this composition. Then, the reduction in shear stress values occurs both in the mass of the grease **[L. 5, 6]** and in the boundary layer as shown in the tests presented in this paper. The reduction in shear stresses in the boundary layer of the lubricating composition flowing near the wall made of polyamide was insignificant, which reduces its value as a material that can be used for the construction of pipes in central lubrication systems.

On the basis of these tests, it can be concluded that the basic factor causing the formation of the boundary layer is the polarity of both the duct wall and the grease thickener. Lithium grease, thickened with polar soap made of lithium 12-hydroxystearate, forms a boundary layer near the copper wall in which the shear stresses are much smaller than those in the lubricant layers more distant from the wall. The soap particles in lithium grease close to the wall are attracted to the polar surface, thus forming a surface layer with rheological properties significantly different from the properties of the lubricant layers located further away, and most of all they have much greater viscosity. This adsorption of the soap particles into the metal surface results in the formation of a thinned layer with reduced viscosity and a reduced value of the flow limit of the lubricant "near" the wall. This mechanism causes that shear stresses at the metal wall are much smaller than corresponding stresses in the layers more distant from the wall in the case of lithium grease.

Bentonite grease, thickened (as it is known) by non-polar clay (its polarity is caused only by additives) does not produce a "clear" boundary layer. Therefore, shear stresses in bentonite grease or its compositions with fillers are (both near a metal and plastics wall) much higher than corresponding stresses in lithium grease. That is why, bentonite grease, as well as its composition containing fillers, show greater flow resistance during the start-up of a lubrication system. This aspect should be taken into account when making decisions regarding the optimisation of a lubricants and lubrication methods used.

A separate topic concerns the relatively low shear stresses during the flow of a lubricant, particularly lithium grease, but also bentonite grease near the wall made of PTFE, as well as a lubricating composition made with PTFE powders. PTFE as a material with low surface energy that weakly affects the grease thickener, and as a filler in the lubricant, it limits the interaction of polar thickener particles with the surface of the duct wall. On the one hand, the ensuing boundary layer has a very limited range. On the other hand, the limited interaction causes the grease or its composition with PTFE powder to "slide" on the wall surface and thus the resistance of the lubricant flow is lower than in the case of substances with greater surface energy. It indicates that, in the construction of automated lubrication systems, it would be beneficial to use ducts made of PTFE or steel (or other elements of the system) with an internal surface coated with a PTFE layer.

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