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THE INFLUENCE OF KINEMATIC CONDITION AND LUBRICANT PROPERTIES ON FRICTION IN COMPLEX SLIDE–ROLL MOTION

WPŁYW WARUNKÓW KINEMATYCZNYCH I WŁAŚCIWOŚCI ŚRODKA SMAROWEGO NA TARCIE W RUCHU TOCZNO-ŚLIZGOWYM

Key words: friction, slide-rolling friction, grease, complex kinematics.

Abstract: The paper presents the results of preliminary studies into the influence of selected lubricants (greases) and the variable temperature of the friction joint on the value of friction during complex slide-roll motion. The experiment was carried out for three different types of lubricants: bentonite grease (Benterm 2), lithium grease (GREASEN ŁT4S2), and calcium grease with the addition of graphite (GREASEN GRAFIT) at different temperatures. Tribological investigations were carried out in a roller-plate system at a wide range of plate dislocation velocities and at a constant slip rate; rheological investigations consisted in determining the changes in shear stress as a function of shear time at constant average shear velocity of 50 mm/s. The results showed a significant influence of kinematic conditions on the value of friction. Four different cases of lubricant flow during friction were identified. The least resistance to motion was found when the lubricant was applied in the same direction along the surface of the roller and plate. It has been shown that the greatest influence of the kinematics of working elements on friction occurs at low temperatures, i.e. at -10°C. This phenomenon is closely related to the rheological properties of the lubricant. It was also found that the lubricant thickened with bentonite is the most susceptible to kinematic changes of the friction joint.

Słowa kluczowe: tarcie, tarcie toczno-ślizgowe, smar, złożony ruch.

Streszczenie: W pracy przedstawiono wyniki badań wstępnych wpływu wybranych środków smarnych (smarów plastycznych) i zmiennej temperatury węzła tarcia na wartość siły tarcia podczas złożonego ruchu toczno-ślizgowego. Eksperyment przeprowadzono dla trzech różnych rodzajów środków smarnych: smaru bentonitowego (Benterm 2), smaru litowego (GREASEN ŁT4S2) i smaru wapniowego z dodatkiem grafitu w postaci stałej (GREASEN GRAFIT) w różnych temperaturach. Przeprowadzono badania tribologiczne w układzie walec-płytka w szerokim zakresie prędkości przesuwu płytki przy stałym poślizgu oraz badania reologiczne polegające na wyznaczeniu zmian wartości naprężenia stycznego w funkcji czasu ścinania przy stałej średniej prędkości ścinania wynoszącej 50 mm/s. Wyniki wykazały istotny wpływ warunków kinematycznych na wartość siły tarcia. Zidentyfikowano cztery różne przypadki przepływu środka smarnego podczas tarcia. Najmniejsze opory ruchu występowały w przypadku podawania środka smarnego w tym samym kierunku przez powierzchnie walca i płytki. Wykazano, że największy wpływ kinematyki ruchu elementów trących na siłę tarcia występuje w niskiej temperaturze, tj. w -10°C. Zjawisko to ściśle związane jest z własnościami reologicznymi środka smarnego. Stwierdzono również, że środek smarny zagęszczany bentonitem jest najbardziej podatnym środkiem smarnym na zmiany kinematyki węzła tarcia.

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INTRODUCTION

The kinematics of particular elements of a friction joint is of great importance for processes occurring during frictional cooperation **[L. 1, 2]**. The motion velocity of particular elements in relation to the point contact is important. A distinction can be found in the literature between the straight and reverse friction pair **[L. 2]**. In the case of dry friction, the mechanical properties of the working materials are decisive for the friction process in complex kinematic conditions. This is particularly evident in the case of friction of polymers characterized by deformation hysteresis. Dynamic deformation of the material at the point contact significantly affects the occurring resistance of motion **[L. 1]**. In the case of sliding joints operating under mixed friction, the motion velocity of particular elements in relation to the point contact also influences the lubrication conditions in the friction joint. The lubricant is transferred to the friction joint on the surface of the working elements, so their velocity and mutual direction are important for the lubrication conditions. The studies carried out on lithium grease under the conditions of slide-roll friction described in the paper **[L. 3]** showed that there is a significant influence of the kinematics of the friction joint on the lubricating film thickness. The ball-on-disc experiment was performed at a constant temperature of 22°C, at a different slip to roll rate. The results obtained with the use of optical interferometer have shown that the occurrence of slip during rolling increases the amount of lubricant supplied to the point contact. This results in increased lubricating gap and decreased resistance to motion **[L. 3]**. Similar tests for various types of oils under elastohydrodynamic lubrication conditions are described in the paper **[L. 4]**. The authors also confirm that the lubrication gap increases with the increase of the slip in relation to the rolling velocity. The effect of the changes is different for different types of oils. For the tests described in the literature, the direction of rotation of the rolling element and the direction of slip are the same. In this paper, a very wide range of velocities of particular elements of the friction joint are applied, so that the velocity vectors of particular elements can also be differentiated.

An experiment was conducted to determine how the kinematics of particular elements of the friction joint and the lubricant used impact the resistance of motion. The tests were carried out for the steel-steel combination during the slide-roll motion. The roller-plate combination, in which the linear motion of the plate and the rotating motion of the roller are independent, enables the determination of the sliding velocity and the velocity of particular elements. In the experimental plan, the velocities of particular elements were selected in such a way that the slip velocity at the point contact was constant. In order to determine the impact not only of the thickener but also of the viscosity of the lubricant, tribological and rheological tests were conducted at three temperatures.

MATERIAL AND TEST METHOD

Lubricants

Friction tests during slide-roll motion were performed for 3 different lubricants, i.e. GREASEN ŁT4S2, GREASEN GRAFIT (Orlen Oil, Cracow, Poland), and BENTERM 2 (Naftochem, Cracow, Poland). These greases were thickened with lithium 12-hydroxystearate, calcium 12-hydroxystearate, and quaternary amine hydrophobic aluminosilicates, respectively. The second lubricant contained additionally 10% of natural graphite. The other lubricants did not contain any solid additives. All greases used in the study were manufactured on the basis of mineral oils with EP and AW additives and were of 2 NLGI consistency class. The physicochemical properties of lubricants are shown in **Table 1**.

Table 1. Physicochemical properties of tested lubricants according to manufacturer's data [L. 5–7]
Tabela 1. Własności fizykochemiczne badanych środków smarnych wg danych producenta **[L. 5–7]**

Parameter	**Value**		
	GREASEN ŁT4S2	GREASEN GRAFIT	BENTERM 2
Worked penetration, T = 25°C (mm/10)	285	286	260–300
Dropping point (°C)	190	210	220
Oil separation, 100°C/30 h (%)	2	5	5
Permissible operating temperature (°C)	-30 to +140	-20 to +120	-20 to +200
Structural stability (%)	2	3	8

Before each test, approximately 1 mm layer of lubricant was spread with a brush on the cooperating elements.

Friction joint kinematics

Having carefully considered possible motion configurations of various tribological joints operating in the conditions of slide-roll friction, it was decided to carry out the tests in a roller-plate system, the diagram of which is shown in **Fig. 1**.

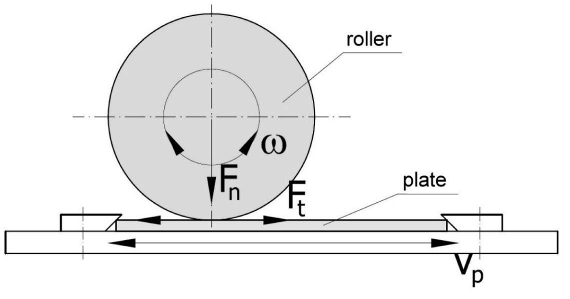

Fig. 1. Kinematic diagram of the friction joint used in tribological test
Rys. 1. Schemat kinematyczny węzła tarcia zastosowanego w badaniach tribologicznych

The value of the total slip *s* was determined as the differences in the component velocities resulting from the dislocation of plate v_p and the rotation of roller ω using the following formula:

$$s = \omega \cdot v_p \tag{1}$$

where *r* is the roller radius.

Tribological studies were carried out for a constant value of slip *s* and variable velocity of point contact dislocation relative to plate v_p. The constant value of the slip velocity *s* between the plate and the roller allowed the assessment of the direction and velocity of the lubricant delivery to the friction joint. In all cases tested, the velocity of geometric slip *s* was 50 mm/sec. The applied values of the plate velocity v_p and the angular velocity of the steel roller *ω*, calculated on the basis of correlation (1), are shown in **Table 2**. Due to the finite size of the plate, the tests were conducted in alternating motion. The normal force load on the friction joint was constant and equal to F_n = 20 N. The average roughness *Ra* of the surface of the plate and the roller was in the range of 0.53–0.62 µm. Both working elements were made of C45 steel in the standardized condition. Their hardness was 35±2 HRC. The working surfaces were sanded. The diameter of the roller was *D* = 50 mm and the width was *b* = 5 mm. The width of the steel plate was *B* = 10 mm.

As can be seen in the experiment, the negative values of plate dislocation velocity and angular velocity were also set. If there are opposite signs in the values of the angular velocity of the roller ω and the plate dislocation velocity v_p, the rotation of the roller in relation to the plate was inconsistent with the direction of the rolling motion. With reference to cylindrical milling, the differences in the directions of the particular velocity components are defined as concurrent or counter-rotating. The value and direction of particular velocity components (of the roller and plate) determined the mechanism of lubricant supply to the point contact. In the assumed kinematic states, 4 different cases of dislocation of friction joint elements influencing the lubricant flow were distinguished:

1. Rotation of only the roller with the stationary plate ($vp = 0$),
2. Dislocation of only the plate with the stationary roller (ω = 0),
3. Simultaneous dislocation of the plate and rotation of the roller in the same direction (concurrent motion), and
4. Simultaneous dislocation of the plate and rotation of the roller, but in opposite directions (counter-rotating motion).

Table 2. Values of roller rotation velocity *ω* and plate dislocation velocity v_p used during tribological tests
Tabela 2. Wartości prędkości obrotu walca ω oraz prędkości przesuwu płytki v_p zastosowane podczas badań tribologicznych

s (mm/s)	50										
v_p (mm/s)	-50	-40	-30	-20	-10	0	10	20	30	40	50
ω (rad/s)	0	0.4	0.8	1.2	1.6	2	2.4	2.8	3.2	3.6	4
kinematic case	II	IV				I	III				

The occurring kinematic cases are also indicated in **Table 2**. According to the assumption, the tests were carried out at three different air temperatures inside the chamber, and thus the friction joints: -10˚C, 20˚C, and 50˚C. The temperature values at which the tests were conducted were adopted so that the effect of temperature on the rheological properties of the lubricants used could be demonstrated. In order to find the correlation between viscosity and motion resistance values, the same temperature values were used in rheological studies.

Tribological studies were carried out on the author's stand for testing friction in slide-and-roll motion. The device is described in more detail in paper **[L. 8]**. For tests at different temperatures, the device was installed in a climate chamber. The test head and the device installed in the climate chamber are shown in **Figure 2**.

Fig. 2. Test stand placed in a climate chamber
Rys. 2. Stanowisko badawcze umieszczone w komorze klimatycznej

During the tests, the frictional force was recorded at 100 Hz. To calculate the mean value, from each motion cycle, the values of friction force taken after stabilization of kinematic conditions were accepted. For each measurement run, 50 operation cycles were performed.

Rheological studies

Rheological properties of lubricants were tested with the use of a Physica Anton-Paar MCR rotational rheometer with a torque range of 0.1 µNm to 150 mNm. The rheometer was equipped with an air bearing and connected to an oil-free piston compressor with a set of filters and air dryers. During the tests, the rheometer worked in a plate-plate system, with a fixed measuring gap of 1 mm. The accuracy of the measurement gap setting was ±0.001 mm. The rheometer also included a Peltier P-PTD200 thermostatic system and a H-PTD200 insulating and thermostatic collar with air circulation inside the measuring head. For the tests, a measuring spindle in the form of a plate made of AISI 316L steel (equivalent to PN: 00H17N14M2) with a diameter of 40 mm subjected to sanding was used. The use of a sanded plate with a roughness of Ra = 2 µm was intended to reduce lubricant slip. The diagram of the rheometer measuring head is shown in **Fig. 3**.

Lubricant samples were thermostated in the rheometer head at a constant temperature: -10, 20, and 50ºC (accurate to ±0.01ºC). Each sample was cooled/heated for 5 minutes (after the set temperature has stabilized). This was automatically followed by a measurement. In order to avoid changes in temperature and to obtain greater precision in thermostating the samples, an insulating and thermostatic collar was used during the measurement. A RHEOPLUS/32 (version 3.4) was used to acquire measurement data. The test was repeated 5 times, and the results were presented as arithmetic means (with confidence level 0.95). During rheological tests, the effect of temperature on the value of shear stresses as a function of shear time at a constant average shear velocity of 50 mm/s was evaluated. The shear time of each lubricant sample was 20 seconds.

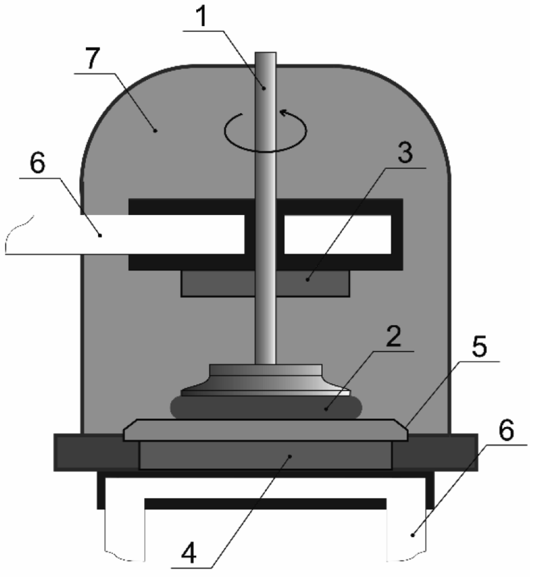

Fig. 3. Diagram of the measuring head of the rotational rheometer used for testing: 1 – measuring spindle (with an upper sanded plate with a diameter of 40 mm), 2 – lubricant, 3, 4 – Peltier module (P-PTD200), 5 – bottom plate, 6 – cooling system, 7 – insulating and thermostatic collar (H-PTD200)
Rys. 3. Schemat głowicy pomiarowej reometru rotacyjnego użytego do badań: 1 – wrzeciono pomiarowe (z płytką górną piaskowaną o średnicy 40 mm), 2 – środek smarny, 3, 4 – moduł Peltiera (P-PTD200), 5 – płytka dolna, 6 – układ chłodzenia, 7 – kołnierz izolująco-termostatujący (H-PTD200)

TEST RESULTS

The values of the friction force measured during tribological tests for particular temperatures are shown in the form of graphs (**Figs. 4–6**). The results obtained were compared to the plate dislocation velocity v_p.

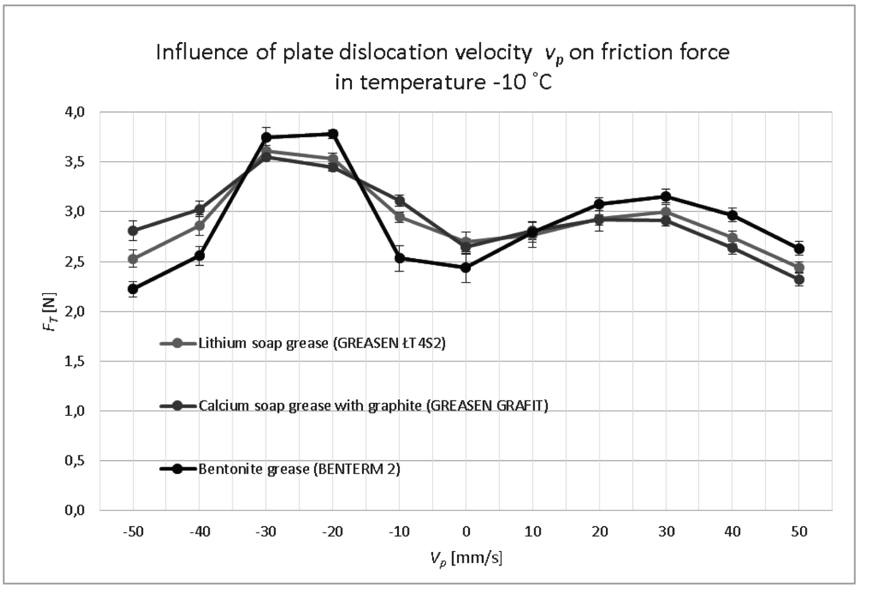

Fig. 4. Influence of plate dislocation velocity on the value of friction force during rolling with sliding movement at -10°C
Rys. 4. Wpływ prędkości przemieszczania płytki na wartość siły tarcia podczas ruchu toczno-ślizgowego w temperaturze -10°C

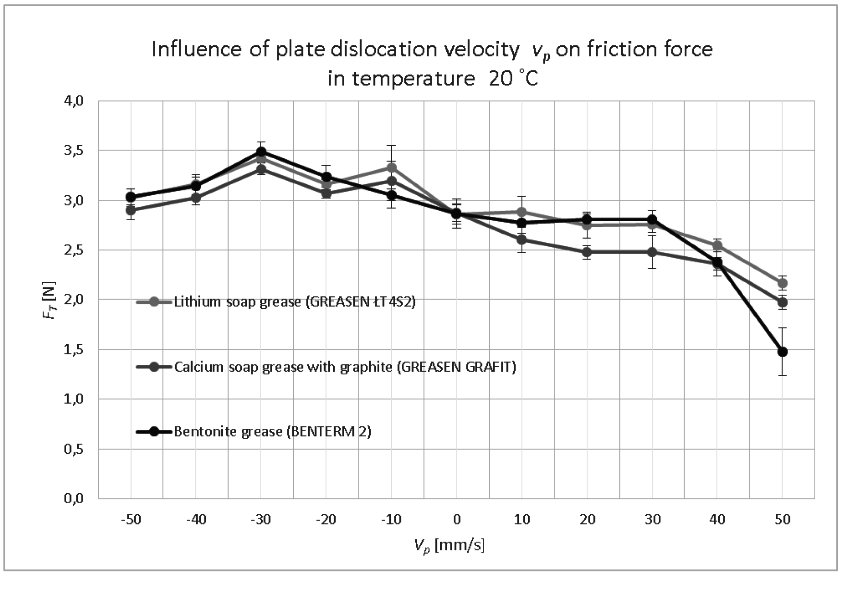

Fig. 5. Influence of plate dislocation velocity on the value of friction force during rolling with sliding movement at 20°C
Rys. 5. Wpływ prędkości przemieszczania płytki na wartość siły tarcia podczas ruchu toczno-ślizgowego w temperaturze 20°C

The kinematics of the lubricated friction joints is proved to have a large impact on the value of the friction force. Interestingly, the course of frictional force changes depending on the plate dislocation, and velocity v_p is similar for all the lubricants tested. The greatest differences in the course of $F_T(v_p)$ characteristics occur between particular temperatures of the friction joint included in the study. For kinematic Case IV, where the direction of the plate motion and the roller rotation is opposite, a characteristic course of changes in friction

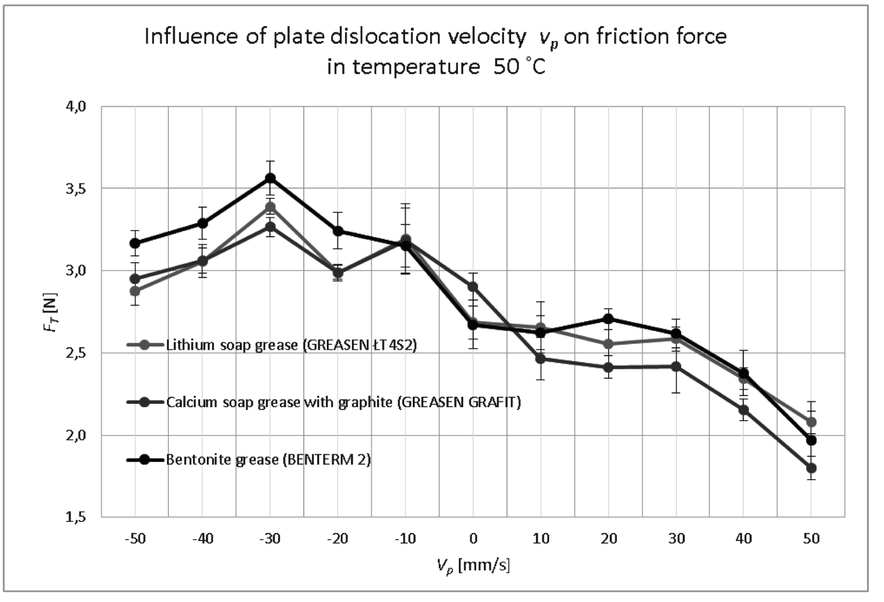

Fig. 6. Influence of plate dislocation velocity on the value of friction force during rolling with sliding movement at 50°C
Rys. 6. Wpływ prędkości przemieszczania płytki na wartość siły tarcia podczas ruchu toczno-ślizgowego w temperaturze 50°C

forces can be observed regardless of the type of lubricant and temperature. In the cases where the velocities of both components are similar in value (v_p = 30 mm/s and ω = 0.8 rad/s), the resistance to motion is the highest. At -10°C for kinematic Case III, where the plate and roller move in the same direction, the friction force increases and then decreases. This is different from the other temperatures for which the friction force decreases as the plate velocity increases. At -10°C, also for kinematic Case IV, the course of frictional force changes is similar. For positive temperatures of the friction joint, there are no such significant differences in the values of friction forces in particular kinematic cases. It can also be seen that the lowest friction force values (for positive temperatures) were found in kinematic Case III.

Rheological characteristics of the lubricants used are shown in **Figure 7**. The values of shear stress in the lubricating greases tested decreased with shear time due to structural changes occurring in them **[L. 9–11]**.

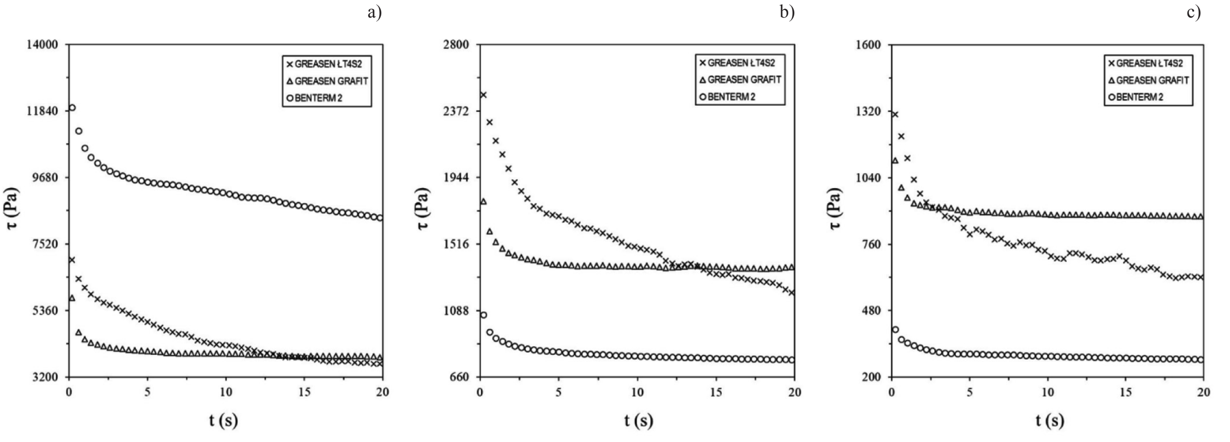

Fig. 7. Dependence of shear stress on grease shear time for an average shear velocity of 50 mm/s. Lubricant temperature: a) -10°C, b) 20°C, c) 50°C
Rys. 7. Zależność naprężenia stycznego od czasu ścinania środków smarnych dla średniej prędkości tego ścinania 50 mm/s. Temperatura smarów: a) -10°C, b) 20°C, c) 50°C

The highest value of shear stress at negative temperature was recorded for bentonite grease BENTERM 2. In the first phase of this lubricant flow, the stress value was 11,960 Pa. The lowest stress was recorded for GREASEN GRAFIT, i.e. 5,763 Pa. When shearing the lubricant at a constant shear velocity at higher temperatures, significant differences in rheological properties were noted. The bentonite grease had the lowest structural viscosity value, which indicates its rapid softening as the operating temperature increases. The highest value of shear stress was recorded for the lithium grease GREASEN ŁT4S2, and it was 2.475 Pa. The flow curves for lubricants sheared at 50°C were similar to those at 20°C.

DISCUSSION

For all the lubricants tested, the influence of changing kinematic conditions on the existing friction force was visible. It can be seen that the lubricant flow direction to the friction joint is significant, i.e. whether it is fed from one side or from two sides. Diagrams illustrating the mechanism of transferring the lubricant to the friction joint are shown in **Fig. 8**.

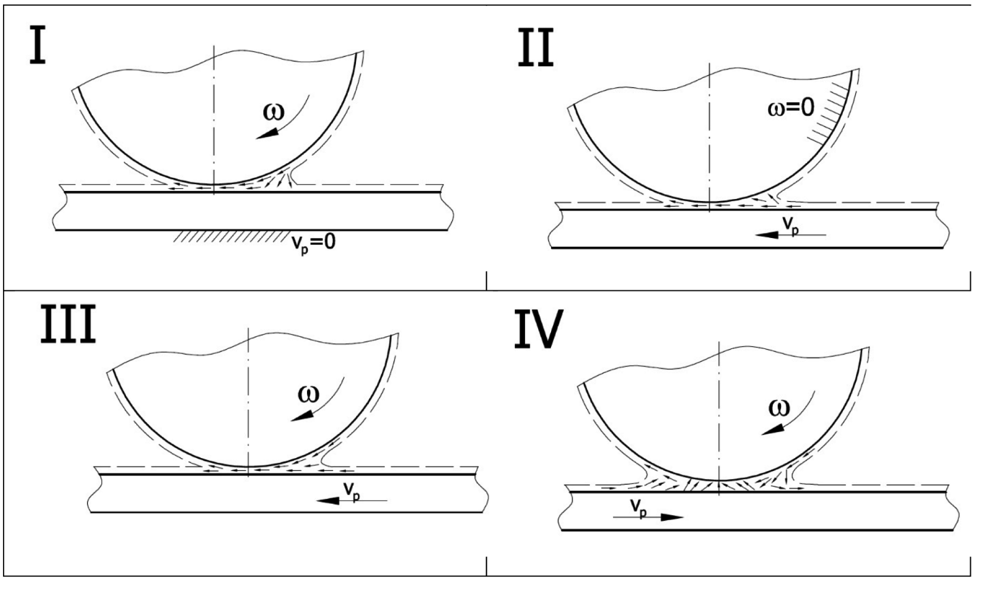

Fig. 8. The mechanism of lubricant flow in the friction joint (pair) for various kinematic cases: I – rotation of the roller with the stationary plate (v_p = 0), II – motion of the plate with the stationary roller (ω = 0), III – simultaneous motion of the plate and rotation of the roller in this same direction (concurrent motion), IV – simultaneous dislocation of the plate and rotation of the roller but in opposite directions (opposite motion). Own study

Rys. 8. Mechanizm przepływu środka smarnego w węźle tarcia dla różnych przypadków kinematycznych: I – obrót jedynie walca przy nieruchomej płytce (v_p = 0), II – przemieszczanie jedynie płytki przy nieruchomym walcu (ω = 0), III – jednoczesne przemieszczanie płytki i obrót walca w tym samym kierunku (ruch współbieżny), IV – jednoczesne przemieszczanie płytki i obrót walca, ale w przeciwnych kierunkach (ruch przeciwbieżny). Opracowanie własne

As noted in kinematic Case IV, where the motion of the plate and the roller is opposite and the values of the velocity of motion of both components are similar (v_p=-30 mm/s and ω=0,8 rad/s), the resistance to motion is the highest. This can be explained by the fact that the flow of the lubricant stops at the point contact as a result of the lubricant being fed from 2 sides at the same velocity (**Figure 8 IV**). The increase in the frictional force value for this case compared to Cases I and II, where one of the components is stationary, is highest at -10°C. This means that increased viscosity (which is confirmed by the results of rheological tests) has a greater impact on the phenomenon of limiting the flow of lubricant at the point contact.

The range within which kinematic Case III occurs is also interesting. In this case, both components (joint elements) move in the same direction, which causes the lubricant to be fed to the friction joint from one side (**Fig. 8 III**). In this case, at positive temperatures, the value of the friction force decreases with the increase of the plate dislocation velocity. Similar behaviour of the lubricated friction joint under slide-roll friction conditions was described in papers **[L. 3, 4]**. It was also noted that as the temperature increases and the viscosity of the lubricant decreases, and the resistance to motion decreases as well. This may result from placing more lubricant on the surface of the plate than on the roller, which increases the amount of lubricant in the friction joint. Interestingly, at a temperature of -10°C for Case IV, the friction force increases and then decreases as the plate dislocation velocity v_p increases. It may indicate that hydrodynamic lubrication predominates in the occurring mixed friction due to the high viscosity of the lubricant or due to the counter-rotating motion of the elements, since the lubricant is pressed in and retained in the point contact.

The correlation between the results of rheological studies and kinematic Cases III and II, i.e. simultaneous dislocation of the plate and rotation of the roller in the same direction (concurrent motion) and dislocation of only the plate with the stationary roller, seems interesting and calls for further studies. These correlations are particularly evident for the same shear and plate velocity, i.e. 50 mm/s at -10°C. For example, in Case III, the highest friction forces were recorded for a steel friction joint lubricated with BENTERM 2 grease (**Fig. 4**). The same lubricant showed the highest shear stress values in the first phase of flow, which is due to its flow curve (**Fig. 7a**). The lowest friction values were recorded for the joint lubricated with GREASEN GRAFIT, for which the shear stresses in the first seconds of shearing were the lowest. In kinematic Case II, an inverse correlation was noted.

SUMMARY

The tribological and rheological tests clearly indicate that the impact of the friction joint kinematics and the shear stresses in the lubricant on the resistance to motion are significant. The greatest influence of variable motions of the friction joint elements on the occurring friction force is visible at a negative temperature, which can be explained by the increase in the value of shear stress in lubricants and their structural viscosity. The results for the influence of kinematic conditions on the frictional resistance have shown that the most favourable situation occurs when both elements move in the same direction in relation to the point contact (Case III) with a low lubricant viscosity (20 and 50°C). Other kinematic cases investigated result in disturbances in the lubricant flow and increase the frictional force. It can also be noted that for kinematic Case IV at all temperatures, the frictional resistance is different than in Cases I, II, III. This is probably due to the mechanical interaction between the lubricant layers flowing into the point contact from different sides. All of the lubricants under investigation during the tribological tests behaved similarly, i.e. the courses of changes of friction force values depending on the plate dislocation velocity motion were comparable. The greatest differences in frictional force values for particular kinematic conditions were characteristic of BENTERM 2. Conclusions developed on the basis of the results of tribological and rheological studies require further investigations with, among others, the use of optical interferometer.

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