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AN EXAMINATION OF OIL FILM THICKNESS IN A BALL-ON-DISC ASSEMBLY

BADANIE GRUBOŚCI FILMU OLEJOWEGO W STYKU KULA–TARCZA

Key words:

surface topography, oil film thickness, elastohydrodynamic lubrication

Słowa kluczowe:

struktura geometryczna powierzchni (SGP), grubość filmu olejowego, smarowanie elastohydrodynamiczne

Abstract

The results of oil film thickness investigations in non-conformal contact in sliding pairs with modified surfaces are presented in the article. The investigations were realized on a ball-on-disc instrument with colorimetric interferometry. Balls were made from 100Cr6 steel of hardness 60–62 HRC. The diameter of balls was 19.05 mm. The tests were carried out at the applied loads of 20 N and 30 N. The glass disc rotated at speeds from 0.1 m/s to 0.2 m/s. At the highest speed (0.2 m/s) the highest maximum value of the oil film thickness of 217 nm was obtained. At 0.2 m/s, the oil film thickness was up to 82% greater

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than at 0.1 m/s. At 0.1 m/s the maximum oil film thickness values were 100–157 nm. The greatest maximum values of the oil film thickness were received by balls with the smaller surface height application in all of the studied cases.

INTRODUCTION

The tribological performance of the machines depends on many factors connected both with machine design and with operating conditions. The lowest friction values occur when the mating surfaces are separated by a lubricating substance. Complete separation of mating surfaces is in the fully flooded conditions. Full film formation could be obtained by providing the lubricating substance between co-acting elements under a high pressure from an external source (hydrostatic or aerostatic lubrication) or by relative surface movement (hydrodynamic lubrication) **[L. 1]**. Full film formation also occurs in the case of elastohydrodynamic lubrication that is characteristic for moving, lubricated non-conformal contact. In such a case, due to the high pressure, the viscosity of the oil increased significantly, enabling the elastic deformation of the co-acting surfaces and a specific pressure film is formed **[L. 2]**.

In the range of full film lubrication, the lowest friction is when the oil film thickness obtained minimum. The fluid thickness, like the friction coefficient, depends on load, sliding velocity, the viscosity of lubricating substance, the properties of mating materials, surface roughness, and others.

There are some methods to assess the film thickness. We can built theoretical models and run tests **[L. 3]**. Analytical methods are an approximation of phenomenon happening in real objects. In calculations, some simplifications are assumed, such as laminar flow or ideally smooth surfaces, etc. Experimental investigations also could have their own limitations, such as the range of parameter values or element dimensions and properties. But an experiment could verified the theoretical investigations and deliver new information about tribological processes **[L. 2, 4]**. There are several methods that can be used to measure the oil film thickness that uses such techniques as electrical resistance **[L. 5]**, and ultrasonic **[L. 6]** or light beam refraction **[L. 7]**, but each one has its own limitations. The electrical resistance method is quite often used, but its disadvantage is the disruption due to wear debris and contaminants and because of the triboelectrical phenomenon **[L. 6]**. Acoustic methods are difficult to implement in the case of some specific materials and with a thin fluid film of a thickness lower than 1 micrometre. The optical method has found an application in fluid film measurement, especially in elastohydrodynamic lubrication conditions **[L. 7, 8]**.

The aim of this study was the analysis of the oil film thickness in non-conformal contact of mating elements with differential surface topography of steel balls. The surface irregularities were described by selected topographic parameters.

EXPERIMENTAL PROCEDURE

Tests were realized with EHD System application. This instrument measures the lubricant film thickness properties in the contact formed between a steel ball of diameter 19.05 mm and a rotating glass disc ($E = 7.5 \cdot 10^4$ MPa, $\nu = 0.22$) with chromium semi-transparent coating. Standard balls were made from carbon chrome steel ($E = 2.07 \cdot 10^5$ MPa, $\nu = 0.293$) of approximately 61 HRC of hardness and had a high-grade surface finish. The glass discs thickness was 10 mm and the diameter was 100 mm. The chromium coating on the glass had approximately 130 nm of thickness.

The white light interferometer Talysurf CCI Lite was used for surface irregularities measurement. The surfaces were characterized by selected topographic parameters from height, spatial, and functional groups calculated according to ISO 25178 standard.

Selected surface topography parameters:

Sq	[µm]	root mean square roughness
Ssk	-	skewness
Sku	-	kurtosis
Sp	[µm]	maximum peak height
Sv	[µm]	maximum valley depth
Sz	[µm]	maximum height of the surface
Sa	[µm]	average roughness
Str	-	texture aspect ratio
Vv	[mm^3/mm^2]	void volume
Vmp	[mm^3/mm^2]	peak material volume
Vmc	[mm^3/mm^2]	core material volume
Vvv	[mm^3/mm^2]	dale void volume
Spd	[$1/mm^2$]	peak density
Spc	[1/mm]	peak curvature

The EHD System for film thickness measurement with the ball-on-disc assembly was equipped with the microscope and a colour camera of high resolution **(Fig. 1)**.

The oil film thickness tests were realized at loads of 20 N and 30 N. Sliding velocity was in the range of 0.1 to 0.2 m/s. The contact was lubricated by mineral machine oil CAS 8042-47-5 at ambient temperature. The Thin Film Measurement System uses a high-resolution colour camera to grab an image of the whole contact. The software uses a previously determined colour-space calibration to match the colours in the image to oil film thickness values in the pointed contact zone.

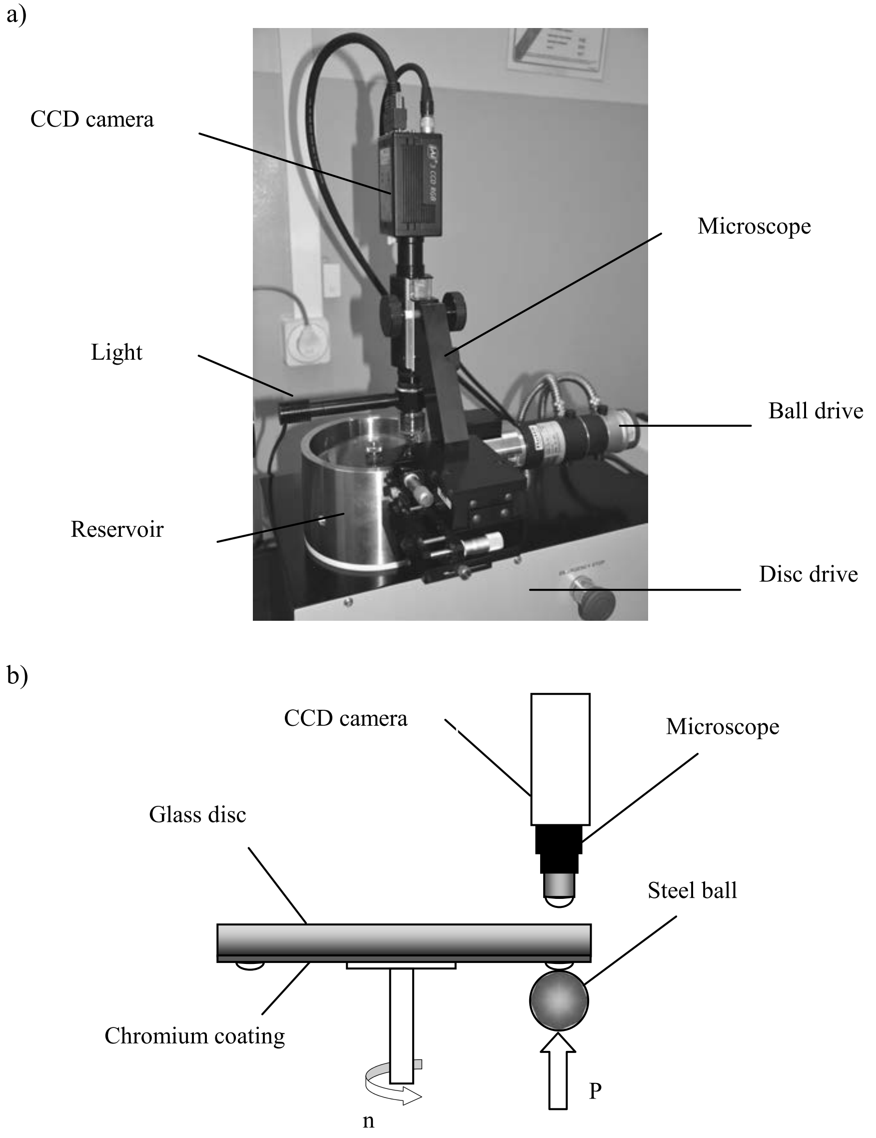
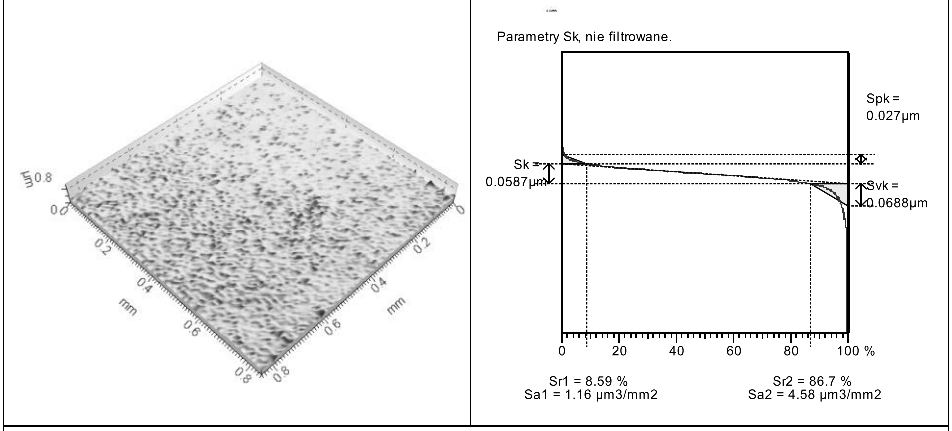


Fig. 1. Photo of main components of the EHD System (a) and scheme of friction assembly ball-on-disc (b)

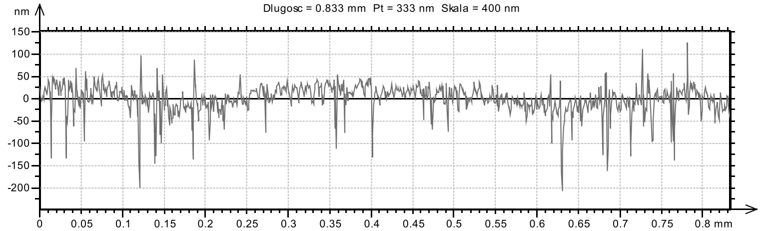
Rys. 1. Zdjęcie modułu do pomiaru grubości filmu olejowego urządzenia EHD System (a) oraz schemat węzła tarcia typu kula-tarcza (b)

RESULTS AND DISCUSSION

Figures 2 and **3** present Abbott-Firestone curves with Sk-family parameters and example profiles and topography parameters of examined surfaces. Surface #1 was assumed as a base, because it was factory new, and surface #2 was obtained after an additional polishing process and is called a modified surface. The base surface was characterized by a low value of height parameters, such as Sa = 0.0219 µm (Sq = 0.0326 µm) and small asymmetry equal to about -2. Values of maximum surface peak height comprise almost 80% of valley depth Sv. The volume of the valley voids of surface #1 was over 4-times greater in comparison to peak material volume.


View of base surface #1

Abbott-Firestone curve


Profile of surface #1

Values of selected surface topography parameters

Sq = 0.0326 µm
Ssk = -1.76
Sku = 12.2
Sp = 0.371 µm
Sv = 0.469 µm
Sz = 0.839 µm
Sa = 0.0219 µm

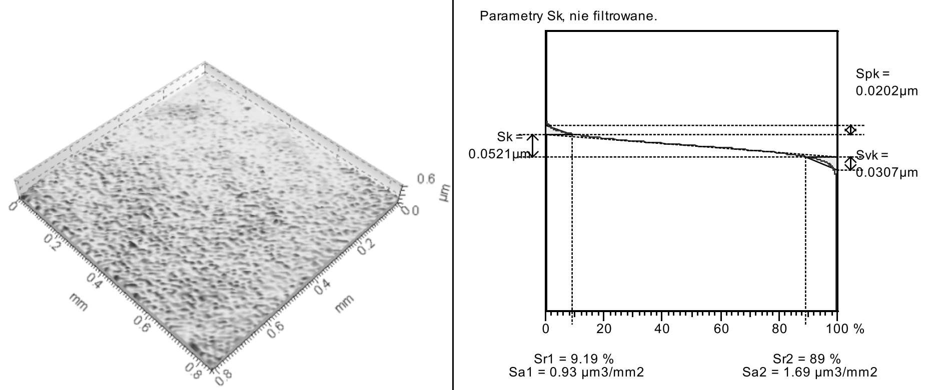
Str = 0.175
Vv = 3.32e-005 mm^3/mm^2
Vmp = 1.35e-006 mm^3/mm^2
Vmc = 2.12e-005 mm^3/mm^2
Vvv = 5.74e-006 mm^3/mm^2
Spd = 5481 $1/mm^2$
Spc = 0.147 1/mm

Fig. 2. The 3D view of the surface #1, Abbott-Firestone curve, selected profile with the topography parameters

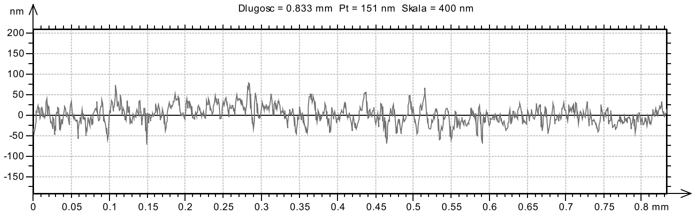
Rys. 2. Widok powierzchni nr 1, krzywa Abbott'a-Firestone'a, przykładowy profil wraz z wybranymi parametrami SGP

View of modified surface #2

Abbott-Firestone curve



Profile of surface #2



Values of selected surface topography parameters

Sq	= 0.0216 µm	Str	= 0.831
Ssk	= -0.35	Vv	= 2.74e-005 mm^3/mm^2
Sku	= 5.96	Vmp	= 1.02e-006 mm^3/mm^2
Sp	= 0.268 µm	Vmc	= 1.81e-005 mm^3/mm^2
Sv	= 0.382 µm	Vvv	= 2.77e-006 mm^3/mm^2
Sz	= 0.651 µm	Spd	= 6207 1/mm^2
Sa	= 0.0166 µm	Spc	= 0.0696 1/mm

Fig. 3. The 3D view of the surface #2, Abbott-Firestone curve, selected profile with the topography parameters

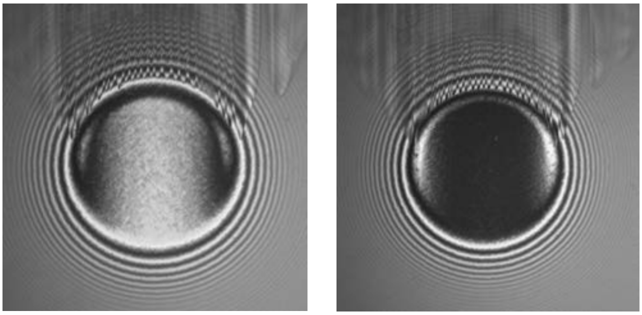
Rys. 3. Widok powierzchni nr 2, krzywa Abbott'a-Firestone'a, przykładowy profil wraz z wybranymi parametrami SGP

Surface #2, after modification by polishing process, was characterized by much smaller irregularities than the base surface. Maximum peak height of surface #2 decreased almost 30%, due to the modification process, and it comprises about 70% of valleys depth Sv. However, asymmetry of the modified surface was not great, and the Ssk parameter value increased to -0.35.

Both analysed surfaces were characterizing by leptokurtic distribution, but the kurtosis of the modified surface was over 2 times smaller in comparison to the Sku of the base surface. The valley volume of modified series (#2) was 2 times smaller than adequate volume Vvv of surface #1. Peak density after additional surface polishing increased, but their curvature decreased significantly. As a result of surface irregularity changes due to the polishing process, the 4-times increase in texture aspect ratio of surface #2 was obtained compared to the Str of the base. The maximum height of the profile received from the modified surface was over two-times smaller compared to the base series. Maximum valley depth of the base surface was approximately 200 nm, and the maximum valley depth of the modified surface was up to 70 nm.

In **Fig. 4**, selected images of oil film thickness formed between steel ball and rotating glass disc are presented.

a) P = 20 N, V = 0.2 m/s b) P = 20 N, V = 0.1 m/s



c) P = 30 N, V = 0.2 m/s d) P = 30 N, V = 0.1 m/s

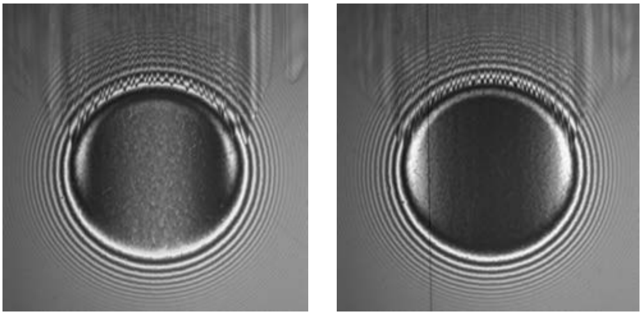
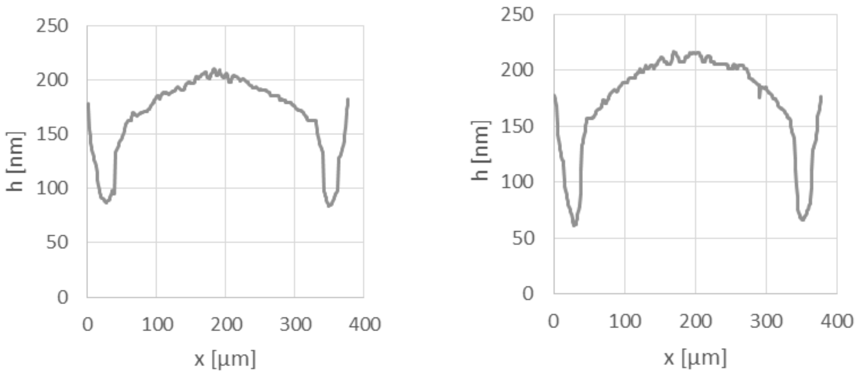


Fig. 4. Images of the oil film formed between the glass disc and surface #2 at different operating conditions

Rys. 4. Obrazy filmu olejowego ukształtowanego pomiędzy szklaną tarczą a powierzchnią nr 2 przy zróżnicowanych warunkach pracy

Based on the obtained images, one can see that a different oil film is created depending on load and sliding velocity. Oil film images represent a qualitative difference in film shape and thickness in specific operating conditions. Oil film thickness distributions determined in the cross section area perpendicular to rotating disc direction at a load of 20 N are presented in **Fig. 5**.

a) V = 0,2 m/s, surface no. 1 b) V = 0,2 m/s, surface no. 2



c) V = 0.1 m/s, surface #1 d) V = 0.1 m/s, surface #2

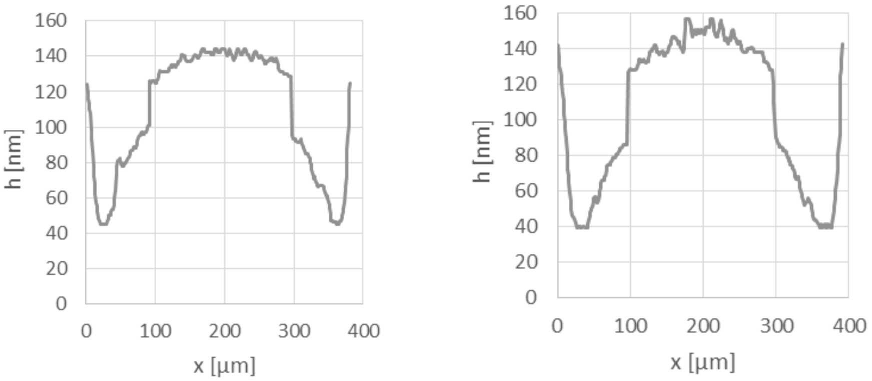


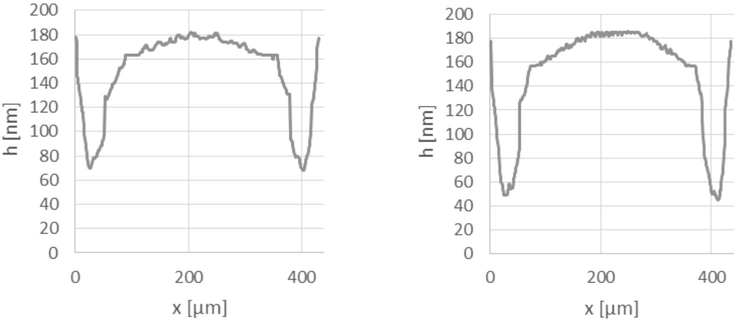
Fig. 5. Oil film thickness distributions in the non-conformal contact at load P = 20 N, different sliding speeds V and for surface topography in two variants

Rys. 5. Rozkłady grubości filmu olejowego w styku skoncentrowanym przy obciążeniu P = 20 N, zróżnicowanej prędkości poślizgu V i SGP w dwóch wariantach

A greater maximum oil film thickness was obtained in non-conformal contact with the steel element of lower surface irregularities (Sa = 0.0166 µm). At the sliding velocity of V = 0.2 m/s, the differences between the film values were small and stayed within the standard deviation limits. Maximum values of oil film thickness in central zones of the contact were in the range of 210–217 nm (at P = 20 N and V = 0.2 m/s). Maximum values of oil film thickness obtained at the higher velocity of 0.2 m/s **(Figs. 5a** and **b)** were about 37–47% greater than at a velocity of 0.1 m/s **(Figs. 5c** and **d**). Oil film thickness at the lower velocity of 0.1 m/s was approximately 10% lower for the surfaces of higher irregularities compared to the smoother steel surface application (Sa = 0.0166 µm). Oil film thickness distribution at load P = 30 N is presented in **Fig. 6.**

a) V = 0.2 m/s, surface #1

b) V = 0.2 m/s, surface #2



c) V = 0.1 m/s, surface #1

d) V = 0.1 m/s, surface #2

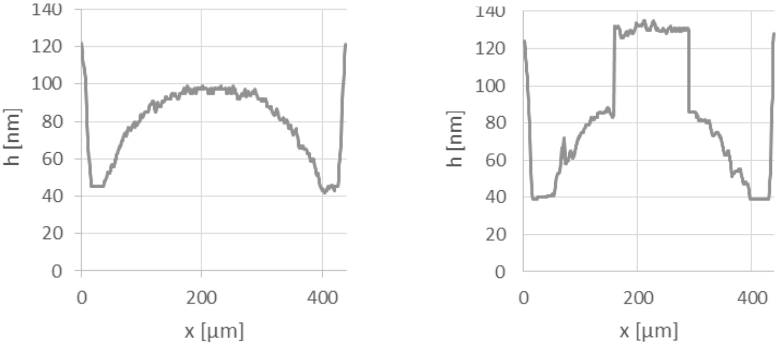


Fig. 6. Oil film thickness distributions in the non-conformal contact at load P = 30 N, different sliding speeds V, and for surface topography in two variants

Rys. 6. Rozkłady grubości filmu olejowego w styku skoncentrowanym przy obciążeniu P = 30 N, zróżnicowanej prędkości poślizgu V i SGP w dwóch wariantach

At higher load of 30 N **(Fig. 6)** and velocity equalled 0.2 m/s, the oil film thickness in the central contact zones were almost the same for both examined surfaces. The substantial difference in oil film thickness due to the roughness decrease was obtained at the sliding velocity of 0.1 m/s. Maximum oil film thickness in the central zone of the contact was equal to 138 nm when the smooth ball was tested (Sa = 0.0166 μm) and 100 nm when the base sample was in the contact (Sa = 0.0219 μm).

A significant difference between obtained film thickness values was obtained at varied loads. In **Fig. 7**, the oil film thickness values in the non-conformal contact at loads P = 20 N and P = 30 N at different sliding speeds V and for surface topography in two variants are presented.

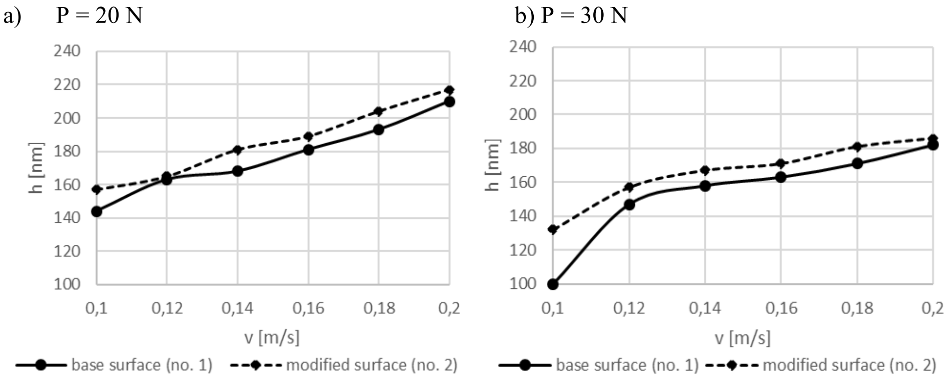


Fig. 7. Oil film thickness values in the non-conformal contact at loads P = 20 N and P = 30 N, different sliding speeds V, and for surface topography in two variants

Rys. 7. Grubość filmu olejowego przy obciążeniu P = 20 N i P = 30 N, zróżnicowanej prędkości poślizgu i topografii powierzchni w dwóch wariantach

A higher film thickness of 14.5 – 43% was formed at the lower load of 20 N than at 30 N (when V = 0.1 m/s). The film thickness increased with the sliding velocity increase. The greater oil film was formed in the whole range of operating conditions when the modified surface was applied compared to thickness of the base surface.

It is well known that valleys (in shape of oil pockets) in sliding surfaces effect on the tribological performance and cause friction and wear reduction by the limitation of the mating surfaces' contact **[L. 9, 10]**. Valleys in surfaces, especially in starved operating conditions such as at low speeds and high loads, retain the lubricating substance that could separate the co-acting surfaces. The obtained results prove that valleys (or we sometimes call them pits, holes or dimples) in the surface can increase the oil film thickness under condition that they are in the adequate depth and shape. The deep valleys lead to lower film formation, but the shallow ones with higher pits density and with non-determined arrangement allowed one to obtain greater oil film thickness in elastohydrodynamic lubrication.

As the result of the conducted experiment, the better performance in non-conformal contact was obtained for surfaces of the lower roughness height and with greater texture aspect ratio of surface Str.

CONCLUSIONS

The main conclusions drawn from the investigation are as follows:

- It is possible to assess the influence of surface topography on the oil film thickness in non-conformal contact.
- A significant effect of both operating conditions and surface topography parameters on the oil film thickness was found.
- At a higher velocity (0.2 m/s), the differences in film thicknesses were not substantial in a dependence on the surface finishing in the examined series. However, at a lower velocity (0.1 m/s), surface topography was important in the higher oil film formation effect. Surfaces characterized by smaller irregularities and smaller oil capacity of valleys (Sa = 0.0166 μm, Vvv = 2.77e-006 mm^3/mm^2) obtained up to a 38% higher film thickness in comparison to the base surface with higher irregularities (Sa = 0.0219 μm, Vvv = 5.74e-006 mm^3/mm^2).
- The oil film thickness measurement, especially of thin layers like in EHD lubrication, is still a challenge because of the limitations in technical facilities, but oil film thickness measurement delivers objective evidence on how the oil film looks between real mating surfaces.

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Streszczenie

W artykule przedstawiono wyniki badań grubości filmu olejowego w styku skoncentrowanym w węzłach ślizgowych z modyfikowanymi powierzchniami roboczymi. Badania zrealizowano z wykorzystaniem urządzenia z węzłem typu kula–tarcza. Zastosowano kulki z materiału 100Cr6 o twardości 60–62 HRC. Średnica kulek wynosiła 19,05 mm. W wyniku realizacji określonych technologii powierzchnie kulek charakteryzowały się zróżnicowaną strukturą geometryczną. Próby prowadzono przy obciążeniu siłą równą 20 N oraz 30 N. W badaniach odwzorowujących pracę węzła ślizgowego ruch obrotowy realizowany został przez obrót szklanej tarczy. Prędkość tarczy zmieniano w zakresie 0,1 do 0,2 m/s co 0,02 m/s. Przy wyższych prędkościach poślizgu otrzymano największe maksymalne wartości grubości filmu olejowego wynoszące do 217 nm przy V = 0,2 m/s. Przy największej badanej prędkości poślizgu 0,2 m/s wartości grubości filmu olejowego były większe nawet o 82% w porównaniu z wartościami otrzymanymi przy V = 0,1 m/s. Przy prędkości V = 0,1 m/s maksymalne grubości filmu olejowego wynosiły 100–157 nm. Dzięki zastosowaniu kulek o mniejszej wysokości nierówności powierzchni otrzymano większe maksymalne wartości grubości filmu olejowego w porównaniu z wielkościami filmu ukształtowanego z wykorzystaniem kulek o większych nierównościach powierzchni.