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Dariusz OZIMINA[a], Monika MADEJ[a], Tomasz DESANIUK[a,*], Magdalena ŻÓŁTY[b], Andrzej KULCZYCKI[c]
[a] Faculty of Mechatronics and Mechanical Engineering, Kielce University of Technology, Poland
[b] Oil and Gas Institute – National Research Institute, Cracow, Poland
[c] Air Force Institute of Technology, Warsaw, Poland
* Corresponding author: desaniuk@gmail.com

EFFECTS OF A GRAPHENE-ENHANCED LUBRICANT ON THE PERFORMANCE OF A TRIBOSYSTEM

Key words: graphene, friction, wear, acoustic emission.

Abstract: The aim of the study was to determine how the presence of graphene in a lubricant (SN-500) affects the behaviour of a tribosystem. The tribological tests were conducted in lubricated, boundary lubricated, and dry sliding friction conditions using a tribometer with the pin and disc made of 100Cr6 steel. The pin and disc wear was monitored using the acoustic emission method. SpectraPLUS was employed to analyse the sampled signals written in the 16-bit linear pulse-code modulation format. Sound level measurements required applying an A-weighting filter and then 1/1 and 1/3 octave filters. The microstructural observations of the pin and disc that followed the tribological tests were performed using a scanning electron microscope. The surface texture of both specimens was measured with an optical profiler. Identification of the elements before and after tribological tests was performed using a scanning electron microscope equipped with an EDS X-ray microanalyser. The experimental data show that the most effective performance of the analysed tribosystem was observed in the presence of the graphene-enhanced lubricant.

Wpływ dodatku grafenu w olejach smarowych na właściwości systemów tribologicznych

Słowa kluczowe: olej bazowy, stal 100Cr6, grafen, zużycie, tarcie, pomiar dźwięku.

Streszczenie: Celem badania było porównanie wpływu grafenu w olejach smarowych na działanie systemów tribologicznych. Testy tribologiczne zostały zrealizowane na tribometrze TRB3 w ruchu ślizgowym w warunkach tarcia technicznie suchego, ze smarowaniem olejem SN-500 oraz z dodatkiem grafenem. Węzeł tarcia stanowiła próbka i przeciwpróbka wykonane ze stali 100Cr6. Dźwięk został zarejestrowany w standardzie Linear PCM 16-bit, a następnie poddany analizie w programie Spectra-Plus. Dla kolejnych chwil czasu wyznaczono wartości poziomu dźwięku, a także poziomy dźwięku w poszczególnych pasmach oktawowych i 1/3-oktawowych. Obserwacje struktury tarczy i kulki po testach tribologicznych wykonano mikroskopem skaningowym Phenom. Strukturę geometryczną powierzchni obu elementów zbadano za pomocą Profilometru optycznego Leica. W wyniku przeprowadzonych badań stwierdzono, że użycie środka smarowego wpłynęło na zmniejszenie zużycia badanych par trących w systemach tribologicznych.

Introduction

The operation of the tribological system boils down to providing energy in the amount necessary to overcome the resistance caused by the phenomenon of friction. It is transformed into other forms of energy, i.e. thermal, electrical and mechanical, then accumulate and dissipate (Figure 1). The tribochemical reactions occurring under its influence have an important role in the transformation of the technological surface layer into an exploitation layer with new functional properties.

Graphene is a two-dimensional material consisting of carbon atoms that have been hybridized. It has very good optical, thermal, mechanical, and electrical properties. Therefore, it has been used in many areas of technology: electronics, power engineering, automation, medicine, and others. Graphene is an auxiliary substance as a component in organic photovoltaic cells and energy-accumulating materials [1]. It can potentially be used to reduce friction and wear between structural elements [2–6].

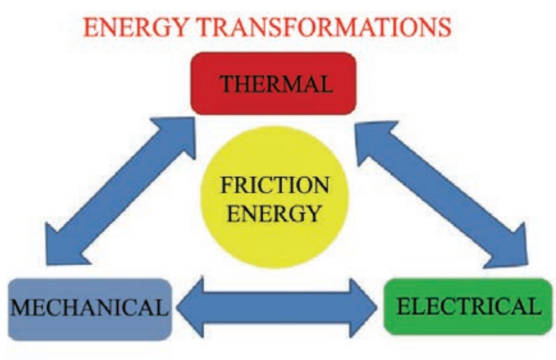


Fig. 1. Main forms of energy occurring during friction between the elements of a tribosystem

An important use of multilayer graphene is in systems operating in boundary friction conditions. Therefore, the influence of graphene addition in lubricating oils on the friction of steel elements was analysed [7–9].

This article compares the results of experimental research carried out during technically dry friction, boundary friction with the use of base oil SN-500 and SN-500 with the addition of graphene and the simultaneous identification of acoustic emission (AE), which was also used to identify the friction conditions.

1. Test materials

The material for the tests were discs made of 100Cr6 steel with a diameter of 42 mm and a height of 6 mm. The chemical composition of the tested discs is presented in Table 1.

Table 1. Chemical composition of steel 100Cr6

Element									
C	Si	Mn	P	S	Cr	Mo	Cu	Al	O
0.93– –1.05	0.15– –0.35	0.25– –0.45	max. 0.025	max. 0.015	1.35– –1.60	max. 0.10	max. 0.30	max. 0.050	max. 0.0015

The material used as a counter-sample in the friction junction were 100Cr6 steel balls with a diameter of 6 mm, loaded with a normal force of 10 N. The most important mechanical properties of 100Cr6 steel are shown in Table 2.

Table 2. Mechanical proporties of steel 100Cr6

Material	Young's modulus E [GPa]	Tensile strength R_m [MPa]	Compressive Strength [MPa]	Hardness [Vickers]	Density [g/cm^3]
steel 100Cr6	243	520	454	210	7.83

Tribological tests were carried out on a tribometer Anton Paar TRB^3 ball-on-disc type in sliding motion. A photograph of the friction junction is shown in Figure 2a.

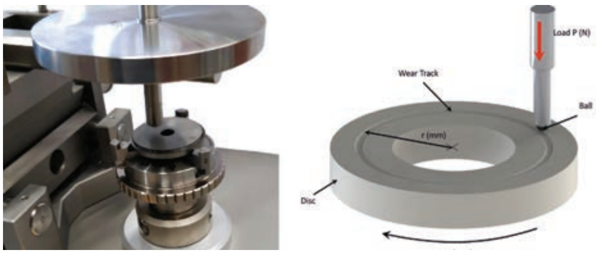
The tribological tests were carried out with the technical and environmental parameters presented in Table 3. Resistance to motion was determined during Technically Dry Friction (TDF). The lubricant was SN-500 base oil under boundary friction conditions (BF) and SN-500 oil with an addition of graphene in the amount of 0.23 wt. %, designated as boundary friction with graphene (BFG). The chemical composition of the oil used is shown in Table 4.

Table 3. Technical and environmental parameters of test

Parameters	Units	Values
Load	N	10
Slide speed	m/s	0.07
Number of cycles	–	1000
Humidity	%	55 ± 5
Temperature	°C	25±1
Radius	mm	12.5

Table 4. Technical specifications of the sn-500 base oil [16]

Parameters	Units	Typical values
Density at 15°C	g/cm^3	0.886
Kinematic viscosity at 40°C	mm^2/s	min. 95
Kinematic viscosity at 100°C	mm^2/s	10.512.0
Viscosity index		90
Flow temperature	°C	9
Ignition temperature, o.c.	°C	220
Coke residue	%(m/m)	0.08
Incineration residue	%(m/m)	0.01
Acid number	mgKOH/g	0.05
External appearance 20+5°C		Transparent, free of suspended solids and sludges
Colour according to pattern		2.5
Oil/water emulsion separation time at 54°C	mg/kg	200
Oil/water emulsion separation time at 82°C	min.	30
Oxidation resistance – viscosity quotient at 40°C		1.5
Resistance to oxidation — coke growth	%(m/m)	1.1



a) b)

Fig. 2. a) photo of the Anton Paar TRB³ tribometer in the ball-on-disc configuration, b) view of ball-on-disc

The sound was recorded with the OLYMPUS PCM RECORDER LS-P1 *linear PCM recorder*. Then, using SpectraPlus, the RMS (*Root Mean Square*) level was determined for 1-second sections of the signal corrected by A-weighting characteristics [17], expressed in full scale decibels (dBFS).

The A-weighting characteristic is used for measurements of industrial noise with low sound level. The next step was to determine the RMS signal levels for 10-second intervals of time, according to the following formula for equivalent sound level L_{Aeq} [13]:

$$L_{Aeq} = 10 log\left(\frac{1}{N}\sum_{i=1}^{N}10^{0.1L_{A,i}}\right) \tag{1}$$

where L_{Aeq} means the signal RMS level (corrected by A-weighting characteristic) in i-th second and $N = 10$ is the number of 1-second intervals in 10 seconds.

2. Research methodology

The aim of the tests was to compare the influence of graphene in lubricating oils on the performance of tribological systems and to determine the surface morphology of the tested samples together with the evaluation of the connection between acoustic emission and the friction junction.

The next stage of the study was the assessment of surface damage after tribological tests. Figure 3 shows isometric images and primary profiles of surfaces before (Figure 3a) and after (Figures 3b, c, d) tribological tests.

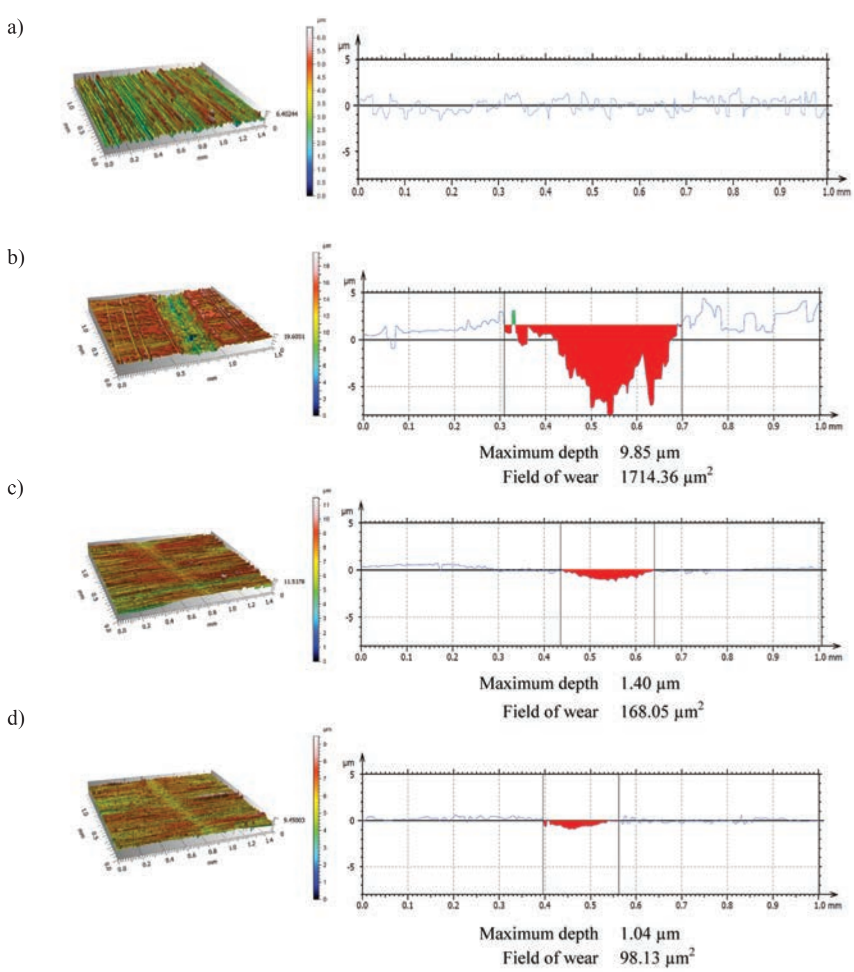
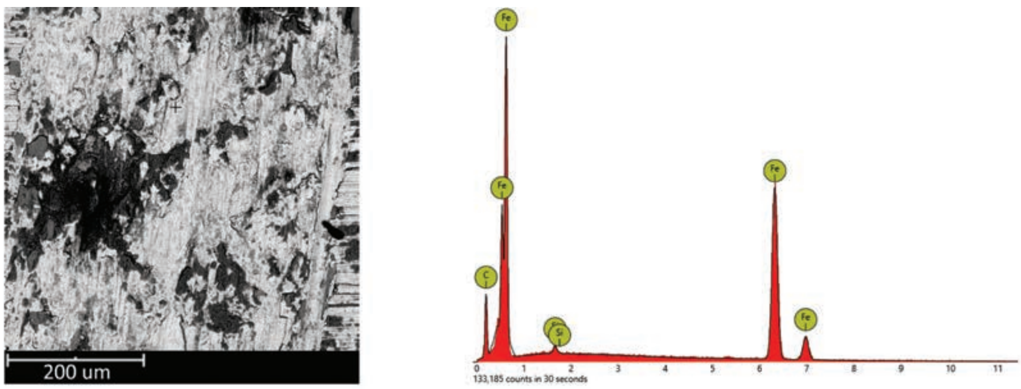


Fig. 3. The isometric image of the trace of wear and the wear profile in a cross-section: a) before friction, b) technically dry friction, c) BF, d) BFG

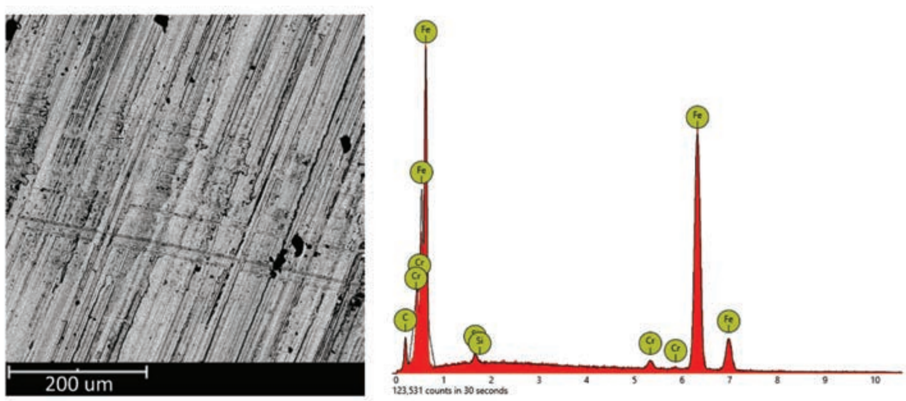
Three-dimensional images of the surface of the tested elements made it possible to analyse their shaping after tribological tests. Knowledge of the characteristics of surface topography is important for the assessment of its functional properties. By comparing the obtained isometric images and surface primary profiles (Figure 3), it was observed that the smallest wear track was formed after friction with lubrication with the base oil with graphene BFG (Figure 3d). Its maximum depth was 1.04 µm and its width was approximately 0.17 mm. After friction with BF base oil lubrication, the abrasion trace depth was 1.40 µm and the width was approx. 0.2 mm. The deepest (9.85 µm) and the widest (0.39 mm) abrasion traces were obtained after technically dry friction.

Using the Phenom XL scanning electron microscope with an EDS microanalyser, the elements forming the discs made of 100Cr6 steel were observed and identified.



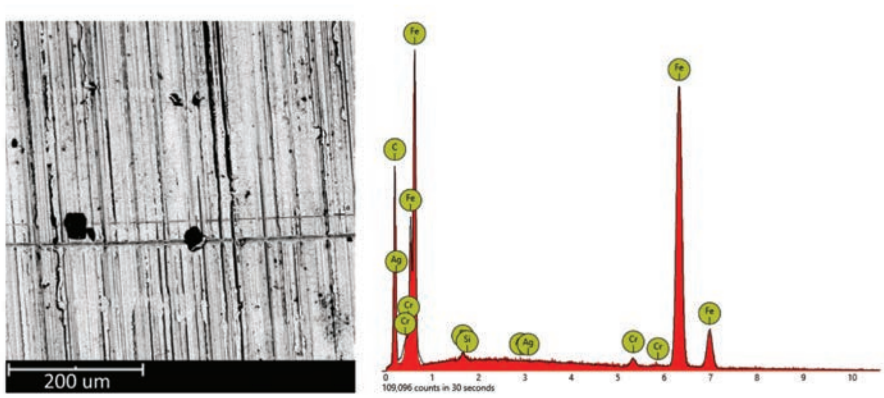
a) b)

Fig. 4. SEM image: a) surface morphology, b) characteristic spectrum in a micro-area for a steel 100Cr6 after technically dry friction (TDF)



a) b)

Fig. 5. SEM image: a) surface morphology, b) characteristic spectrum in a micro-area for a steel 100Cr6 after boundary friction (BF)



a) b)

Fig. 6. SEM image: a) surface morphology, b) characteristic spectrum in a micro-area for a steel 100Cr6 after boundary friction with graphene (BFG)

The microstructure of the surface of the disc made of 100Cr6 steel (Figure 4) after BFG showed an iron content of 96.96% and a silicon content 0.81% by mass. The remaining 2.23% was carbon. After friction with base oil lubrication (Figure 5), the following elements were observed at the wear track: iron – 97.07%, chromium – 1.52%, silicon – 0.67%, and the rest was carbon 0.74%.

On the other hand, after friction with lubrication with base oil with graphene (Figure 6), the following elements were observed: iron – 93.92%, chromium – 1.22%, silicon – 0.44%, and the rest was carbon 4.33%.

On the sample after lubrication with SN-500 base oil with graphene, the highest carbon content accumulated at the lowest point of the wear track. This can be caused by carbon deposits from the lubricant.

Figure 7 shows the level of acoustic emission, linear wear, and the friction coefficient after technically dry friction (TDF), with lubrication with base oil SN-500 (BF) and lubrication with oil SN-500 with graphene (BFG).

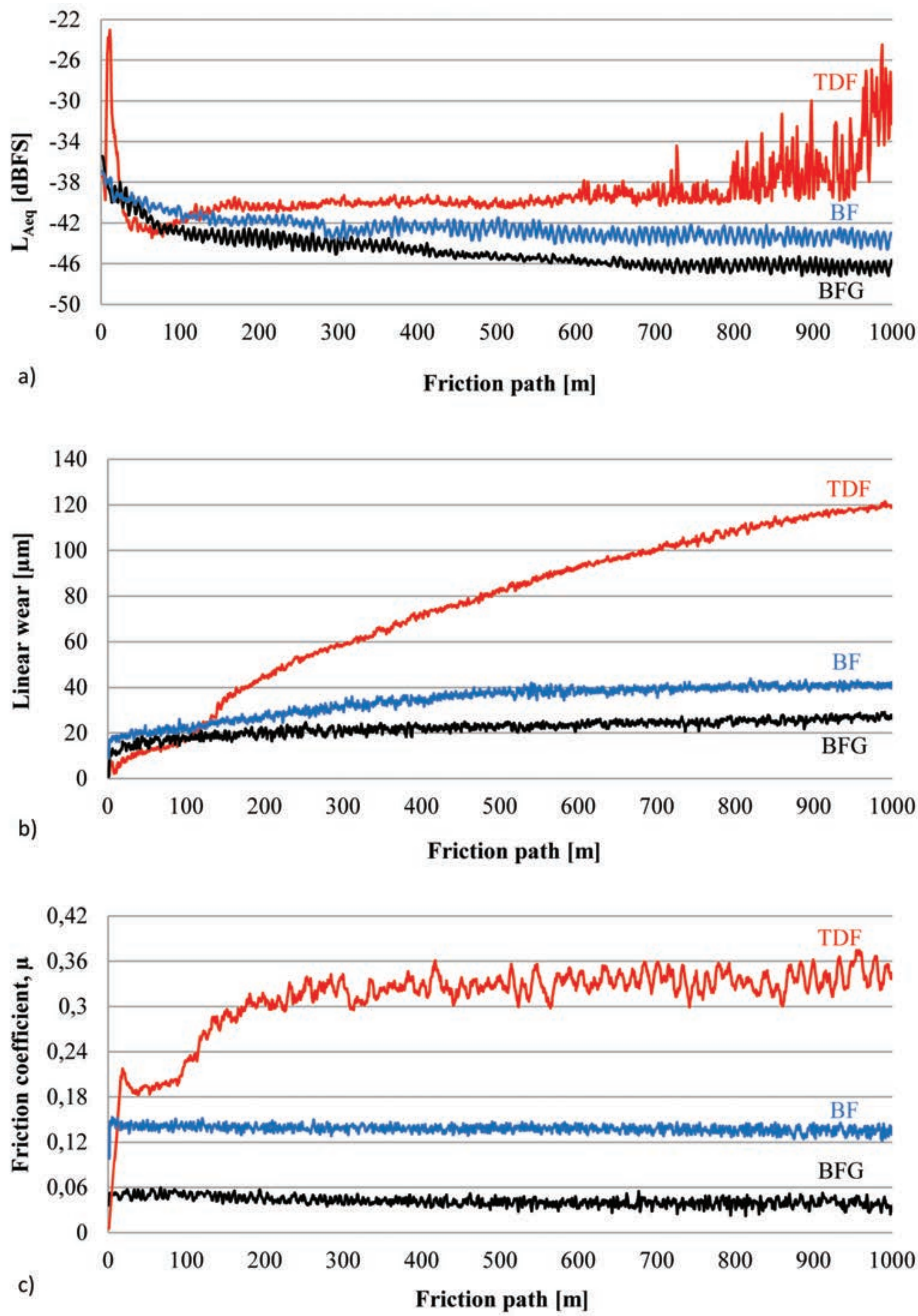


Fig. 7. Acoustic and tribological characteristics of the ball on disc tests: a) acoustic emission, b) linear wear, c) coefficient of friction

In the course of analysing the obtained characteristics (Figure 7), it was found that the phenomenon of sample running-in occurs at about 150 m of the wear truck. After a period of mutual running-in, the coefficient of friction stabilises as a result of oxidation and exposure to ambient humidity, which can be observed on Figure 7a by reading the acoustic emission level. At the end of the TDF test, at the friction length of 750 m, the destabilisation of frictional processes, characterised by a high-frequency cyclic emission, takes place.

Figure 8 shows graphs of average linear wear, the average coefficient of friction, the friction field, and the average sound level. These values were determined after the running-in of the abrasive elements (from approx. 200 m). Average linear wear and the average coefficient of friction were determined by averaging the obtained measurement data from the tribometer. The average sound level was obtained using the Formula [13], while the friction field was determined from the formula for the volume of wear during the rotary motion test, where r is- the friction radius (Table 3), and A is the surface area of the abrasion mark (Figure 3).

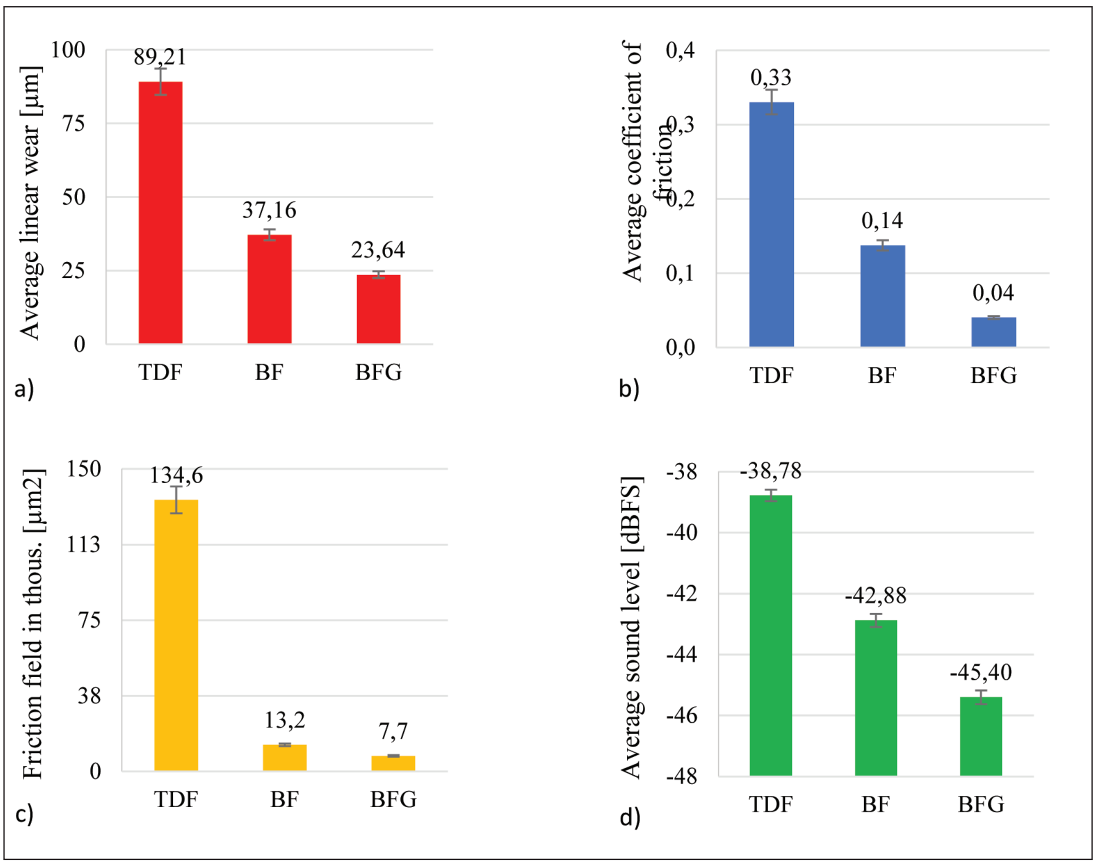


Fig. 8. Bar charts: a) average linear wear, b) average coefficient of friction, c) friction fields, d) medium sound level

When comparing the graphs presented in Figure 8, a correlation was observed that the lowest values of average linear wear, the average coefficient of friction, the friction field, and the average sound level were obtained after friction with lubrication with SN-500 oil with added graphene. The highest values of average linear wear, the average coefficient of friction, the friction field, and the average sound level were obtained after technically dry friction. In turn, the friction field, average sound level and linear wear for SN-500 base oil were about 50% higher than for SN-500 with graphene addition, and the coefficient of friction was as much as 2.5 times lower.

Conclusions

As a result of the conducted studies, it was found that the acoustic emission AE is closely related to the performance of the tribological system. On the basis of the recorded characteristics of AE, it was found that it is possible to monitor the course of phenomena and processes accompanying friction *in situ*.

The use of a lubricant with graphene significantly reduces the friction coefficient, the wear of rubbing elements and the intensity of changes in the acoustic emission of AE.

The results of the observed and studied surface shape (surface topography) indicate that the friction field on the friction junction elements after additive graphene into the lubricating oil is almost 50% of the friction field when using the base oil alone.

Application of lubricating oil with graphene ensures stable working conditions of the tested tribological system. Therefore, the influence of graphene as a modifying additive in lubricating oils on friction and wear of metal elements of tribological systems was investigated.

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