The application of copper nanoparticles as an additive in oil to reduce wear in areas with insufficient lubrication

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The results of a study on a suspension containing industrial oil I-20A and copper nanopowder at concentrations of 0.05, 0.1, 0.2, 0.3 and 0.5 (wt.%) are presented in the paper. The work simulated a mode of insufficient lubrication in the friction zone – 0.1 ml of lubricant was added to the friction zone and the lubricant was not renewed throughout the experiment. The tests were carried out on a friction machine SRV-3 at a load of 200 N, an amplitude of 3 mm and a frequency of 5 Hz. The addition of 0.1% by weight copper nanoparticles to industrial oil showed the best results in reducing the coefficient of friction and wear compared to the base oil. The mechanism is explained by the deposition of small copper particles in the wear area and the improvement of tribological characteristics, this is confirmed by the analysis of wear surfaces on a scanning electron microscope. At concentrations above 0.1%, particle aggregation occurs and, as a result, abrasive wear increases. At copper concentrations less than 0.1%, only partial film formation occurs, and the uneven distribution of particles does not provide any advantages over the base oil.
Copper nanoparticles are a promising material for improving the lubricating properties of oils and restoring surfaces. Their use allows you to reduce friction, reduce wear and extend the service life of mechanisms. However, for widespread adoption, issues of aggregation and cost need to be addressed, and further research into long-term effects needs to be conducted.

Key words: Tribological properties, anti-wear, friction coefficient, nanoparticle, cupper, industrial oil.
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Introduction

Traditional lubricants often fail to meet the required standards, and adding small amounts of certain materials is one way to significantly improve their tribological properties [1, 2]. Nanomaterials added to oil in this way are also known as nanolubricants. Due to their small size, these particles exhibit unique properties, including high chemical activity, a low melting point and high thermal conductivity [3, 4]. Copper nanoparticles are among the most extensively researched and are widely used as additives in lubricants to reduce friction and wear, and for surface restoration [5–7]. In [8], iron, copper and cobalt nanopowders were used as additives in SAE 10 oil, both separately and in combination. The nanopowder concentration was 0.25% by mass. According to the results of the tribological analysis, copper produced better results than iron and cobalt.

The unique properties of copper powders, including high thermal conductivity, anti-friction characteristics, and the capacity to form protective layers on friction surfaces, render them highly promising for utilisation in various mechanical systems [9–11]. Below are the main aspects of the application of copper nanoparticles in oil, examples of studies, and their results.

In [12], CuO nanopowders were utilised in concentrations ranging from 0.5 to 1.5% by mass, with the addition of these powders to oil occurring under low loads of 40N and 60N. A reduction in the friction coefficient was obtained at all concentrations listed, with a 1.5% concentration being 50% lower than the base value. It is noteworthy that throughout all experiments, the friction coefficient ranged from 0.04 to 0.08.

The impact of incorporating nanoparticles on the viscosity of motor oil has been a subject of investigation in various studies [13, 14]. In the aforementioned publication [14], experiments were conducted to ascertain the effect of copper nanoparticles on the viscosity of 20W50 motor oil at temperatures of 40 and 100 (°C). The pour point and flash point of the oil were also determined, with concentrations of 0.1, 0.2, and 0.5% by mass used in the study. It was demonstrated that up to a concentration of 0.5% of copper nanoparticles in oil does not result in a substantial increase in oil viscosity at 40 °C (+6%) and at 100 °C (+1%), but there is a propensity for a pronounced increase at concentrations exceeding 0.5%.

As outlined in [15], the utilisation of copper nanopowders in concentrations ranging from 0.5 to 1.5% by mass in oil has been examined, with loads ranging from 100 to 400 (N). The study has demonstrated a reduction in the friction coefficient by 20–30%, accompanied by a decline in temperature within the friction zone by an average of 10 degrees.

In [16], copper nanopowder was added to 15W40 motor oil at a concentration of 0.5% by mass, and the coefficient of friction and wear were investigated at loads ranging from 100 to 600 (N). The greatest effect was achieved at a load of 300 N. The study claims that wear was reduced by a factor of 10 and friction was halved.

In addition to reducing friction and wear, the incorporation of nanoparticles into oil has been shown to significantly reduce the temperature in the contact zone. As demonstrated in [17], the incorporation of copper nanopowders into oil resulted in a substantial reduction of the friction coefficient from 0.03 to 0.01, and a concomitant decrease in the temperature within the friction zone from 120 to 80 °C, under a load of 300 N and over a duration of one hour. It has been demonstrated that a reduction in the temperature of the friction zone has a beneficial effect on the durability of the oil, as well as a concomitant reduction in its consumption during combustion.

The most significant issue when utilising lubricants is the prolongation of their service life and the subsequent disposal. The employment of nanoparticles as additives in motor oils has been demonstrated to markedly diminish the quantity of wear products emanating from the friction of mechanical components, thereby prolonging the service life of the oil. Furthermore, the utilisation of nanopowders as additives results in the characteristics of biodegradable oils converging towards those of conventional synthetic oils. In [18], the use of nanoparticles in biodegradable oils is studied not only in steady-state wear conditions, but also in terms of the time to failure after the lubricant supply is shut off. The author posits that the utilisation of vegetable-based oils in conjunction with nanopowder additives is only feasible in lightly loaded assemblies. This assertion is predicated on the premise that even a minimal decrease in the quantity of oil within the friction zone results in an unacceptably precipitous increase in the friction coefficient, a phenomenon that occurs at a rate that is substantially faster than that observed when employing traditional oils.

It is noteworthy that, with the exception of work [18], the friction coefficient in all other works was minimal, ranging from 0.025 to 0.06 (approximately 10 times lower than in our work). Additionally, an excess of oil was observed in the friction zone, indicating that fluid friction was the primary focus of study. In the present study, we simulated a mode of insufficient lubrication in the friction zone – an emergency mode – and the friction coefficient was in the range of 0.2 to 0.6. Such a mode can occur in the event of: oil pump failure, oil casing rupture, low oil level, extreme wear of friction parts, at the moment of starting the mechanism, when the lubricant has not yet filled all the cavities.

Materials and methods

The present paper sets out the findings of research conducted on the impact of incorporating copper nanopowders (**Fig. 1**) into I-20A industrial oil on the friction coefficient and wear. I-20A industrial oil (viscosity 20 mm^2/s at 40 °C) is a widely utilised lubricant in industrial gearboxes, centrifugal pumps and bearings.

In [2], industrial oil I-20A was selected as the base oil due to its minimal additives. The work was conducted on an SRV-3 friction machine. A 10 mm diameter ball, composed of SHX 15 steel, exhibited a movement amplitude of 3 mm and a frequency of 5 Hz when subjected to a constant vertical load of 200 N. This movement occurred on a stationary ring plate, with a diameter of 25 mm and a composition of 40 steel. The initial 10 seconds of the experiment saw the load maintained at 10 N. The studies were conducted for nanopowder concentrations of 0.05, 0.1, 0.2, 0.3 and 0.5 (mass%). A rim was fabricated in order to retain the oil on the sample **(Fig. 2)**.

The precise quantity of copper nanopowder was ascertained by means of weighing on electronic laboratory scales, following which it was introduced into I-20A industrial oil. The copper powder was initially mixed with the oil in an ultrasonic machine for a duration of 30 minutes.

Friction tests were conducted for each concentration for 60 minutes. The friction coefficient and wear values were recorded every second. Sample wear was determined using a vertical displacement sensor. The measurement accuracy was 1 μm. 0.1 ml of lubricant was added to the friction zone at the start of the experiment and was not replenished during the subsequent 60 minutes. Tests were

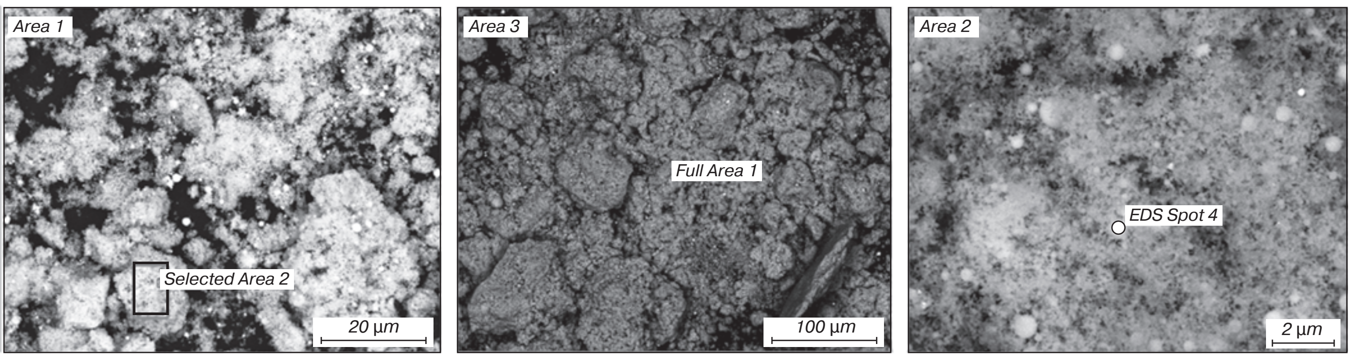


Fig. 1. Photographs of copper nanopowders obtained using a scanning electron microscope

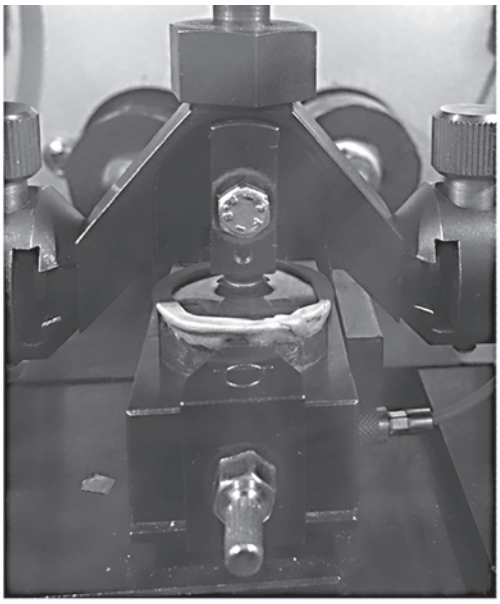
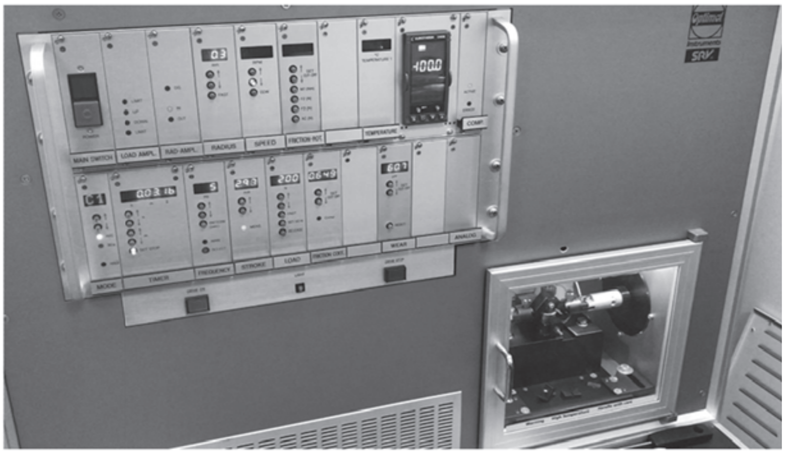


Fig. 2. The ring plate sample with a diameter of 25 mm with a rim for retaining oil, installed in a friction machine (left), SRV-3 friction machine (right) (*photo by authors*)



performed three times for each copper concentration and oil composition. This article presents the average values obtained for the friction and wear coefficients.

Result and discussion

The graphs illustrating the dependence of the friction coefficient and wear on test duration at varying concentrations of copper nanopowders in oil, obtained using the SRV-3 friction machine, are presented in **Figs. 3, 4**.

The optimal concentration of copper, in terms of reducing the coefficient of friction and wear, is 0.1% by mass. This concentration ensures minimal wear and friction coefficient. The outcomes of this study are attributable to the uniform distribution of copper nanoparticles on the surface, coupled with the partial restoration of surfaces (i.e. copper deposition in wear areas).

An "overload" effect is observed at copper concentrations above 0.3%. Particle aggregates act as an abrasive, with wear increasing by 5% when 0.3% copper is added, and by 22% when 0.5% is added, relative to the base oil. At 0.5%, wear exceeds the base level due to a disruption in the oil's rheological properties.

In summary, the experiments demonstrate good temporal stability. At 0.1%, wear remains low (13.5 μm)

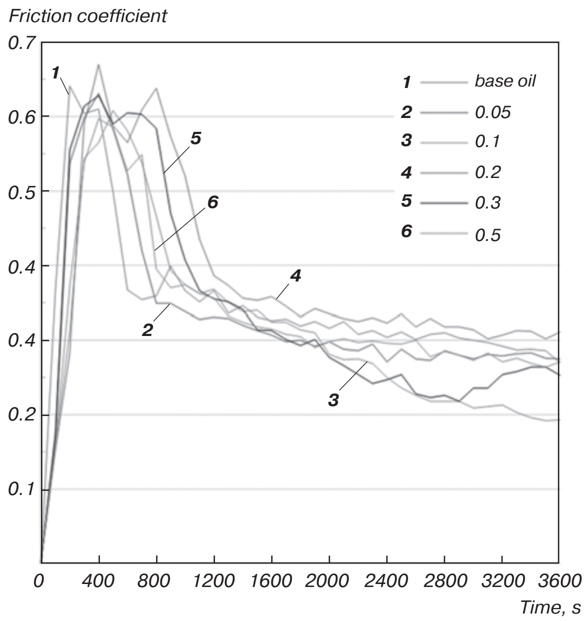


Fig. 3. Friction coefficient dependence on test duration at various copper nanopowder concentrations in I-20A oil, as obtained on the SRV-3 friction machine

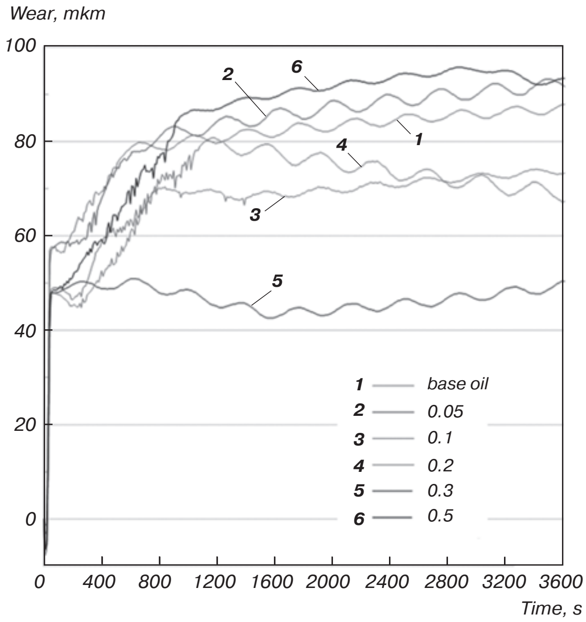
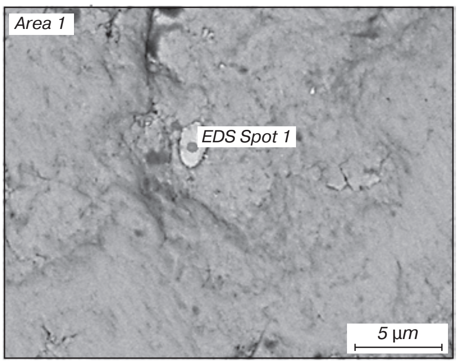


Fig. 4. The dependence of wear on test duration at various concentrations of copper nanopowders in I-20A oil, obtained on an SRV-3 friction machine

from 600 to 3600 seconds, confirming the durability of the tribofilm. Furthermore, a visible trend towards a further decrease in the friction coefficient is evident. Wear progresses linearly in the base oil (0.087 μm/s), while in the modified oil it slows down after 2000 seconds of testing. Notably, the wear graph at 0.2% begins to decline after 1200 seconds and continues to show a downward trend.

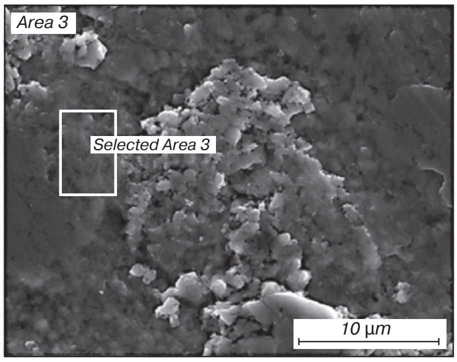
The morphology of the samples' wear surfaces was studied using a Thermo Fisher Scientific Quattro S scanning electron microscope equipped with a field emission electron gun and an energy dispersive microanalysis system based on an EDAX Octane Elect Plus EDS spectrometer. Elemental analysis was performed on ten areas of each sample. **Figs. 5–7** show the most significant images obtained. Tables of elemental analysis are provided below the images, where MDL is the minimum detectable level and Error is the margin of error in determining the element. **Fig. 5** shows a photograph of the sample surface with a copper content of 0.05% in oil, obtained using an electron microscope. The image shows the initial stages of copper film formation. At a copper concentration of 0.05%, it is worth noting that copper particles only appear locally on the surface in the form of agglomerations of particles measuring 2–3 μm (**Fig. 5, *a***). As a result of the adhesion of dispersed copper particles, larger "secondary particles" are formed. At a copper concentration of 0.05%, copper is not detected across the entire sample surface (**Fig. 5, *b, c, d***).

As the copper concentration in the oil increases to 0.1%, the size of the visible localised copper agglomerates decreases to 0.3 μm or less (**Fig. 6, *a***), and copper is



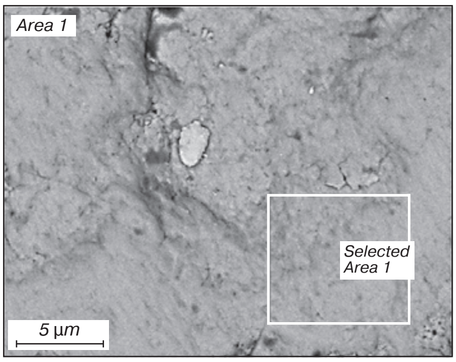
eZAF Quant Result - Analysis Uncertainty: 23.08%				
Element	Weight %	MDL	Atomic %	Error %
Fe K	5.1	1.18	5.8	18.2
Cu K	94.9	8.22	94.2	22.4

a



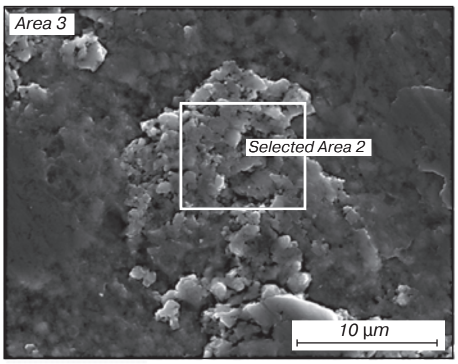
eZAF Quant Result - Analysis Uncertainty: 3.29%				
Element	Weight %	MDL	Atomic %	Error %
Si K	0.8	0.15	1.6	13.5
S K	1.8	0.16	3.1	9.4
Cr K	1.0	0.2	1.0	16.2
Mn K	0.5	0.32	0.5	35.6
Fe K	95.8	0.62	93.7	2.2

c



eZAF Quant Result - Analysis Uncertainty: 10.29%				
Element	Weight %	MDL	Atomic %	Error %
S K	0.9	0.24	1.5	23.1
Cr K	1.6	0.82	1.7	33.7
Fe K	97.6	2.09	96.8	7.7

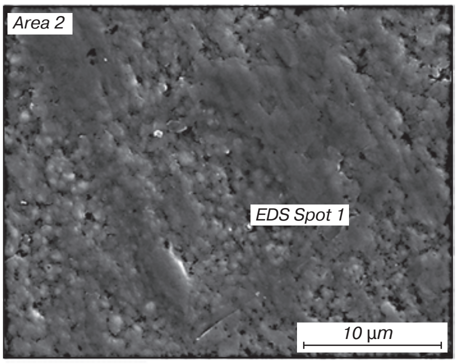
b



eZAF Quant Result - Analysis Uncertainty: 3.03%				
Element	Weight %	MDL	Atomic %	Error %
Si K	0.7	0.14	1.4	13.3
S K	1.8	0.15	3.1	8.9
Cr K	1.0	0.2	1.1	12.5
Fe K	96.4	0.65	94.4	2.2

d

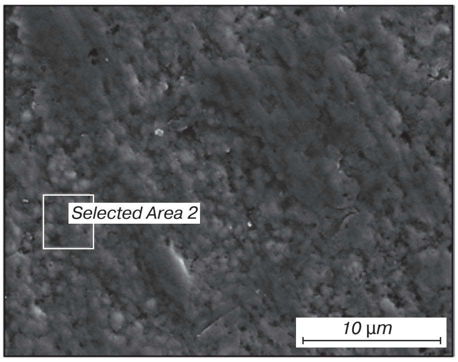
Fig. 5. Photograph of the sample surface with 0.05% copper content in oil, obtained using an electron microscope



eZAF Quant Result - Analysis Uncertainty: 3.35%

Element	Weight %	MDL	Atomic %	Error %
S K	1.3	0.15	2.3	11.5
Cr K	0.9	0.21	1.0	13.6
Fe K	81.5	0.34	82.3	2.3
Cu K	16.2	0.55	14.4	4.8

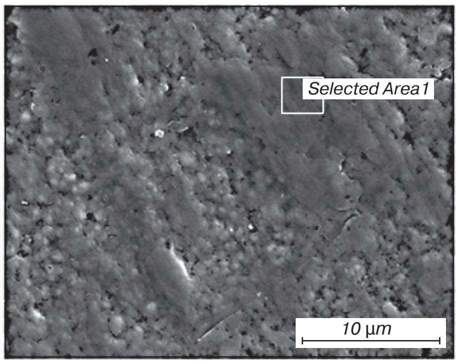
a



eZAF Quant Result - Analysis Uncertainty: 3.18%

Element	Weight %	MDL	Atomic %	Error %
Si K	0.6	0.13	1.3	12.5
S K	1.4	0.14	2.5	9.7
Cr K	1.1	0.19	1.1	11.4
Fe K	95.0	0.36	93.6	2.2
Cu K	1.8	0.49	1.6	15.5

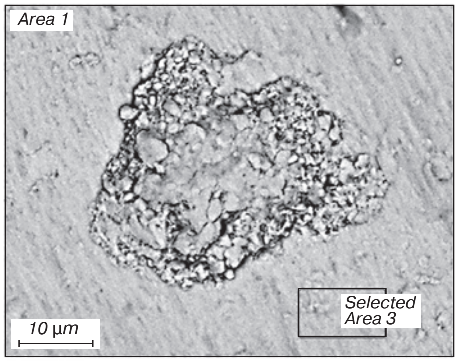
b



eZAF Quant Result - Analysis Uncertainty: 3.30%

Element	Weight %	MDL	Atomic %	Error %
S K	1.5	0.14	2.6	9.1
Cr K	1.1	0.19	1.2	11.3
Fe K	95.9	0.35	94.9	2.2
Cu K	1.4	0.5	1.2	17.4

c

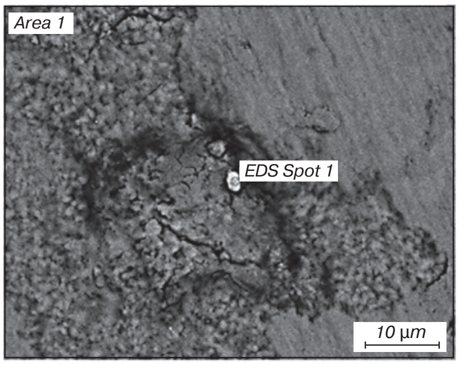


eZAF Quant Result - Analysis Uncertainty: 3.31%

Element	Weight %	MDL	Atomic %	Error %
Si K	1.1	0.13	2.1	10.4
S K	0.8	0.14	1.4	12.7
Cr K	1.1	0.19	1.2	10.9
Fe K	95.9	0.4	94.4	2.2
Cu K	1.1	0.5	1.0	19.6

d

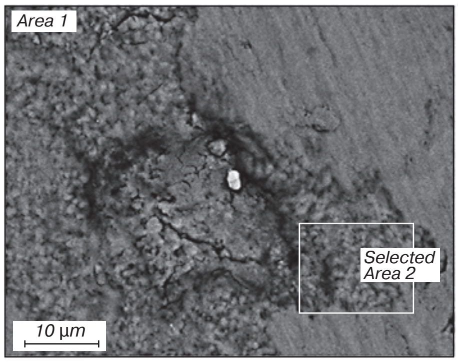
Fig. 6. Photograph of the sample surface with 0.1% copper content in oil, obtained using an electron microscope



eZAF Quant Result - Analysis Uncertainty: 10.87%

Cr K	0.6	0.23	0.7	21.4
Fe K	25.8	0.34	28.3	3.6
Cu K	73.6	0.67	71.0	2.8

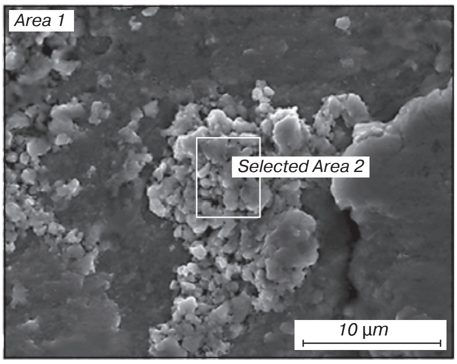
a



eZAF Quant Result - Analysis Uncertainty: 3.35%

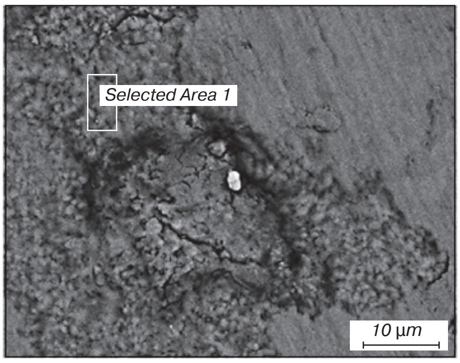
Element	Weight %	MDL	Atomic %	Error %
S K	1.4	0.14	2.4	9.4
Cr K	1.1	0.19	1.2	11.8
Fe K	95.9	0.36	95.0	2.2
Cu K	1.6	0.51	1.4	18.0

b



eZAF Quant Result - Analysis Uncertainty: 3.26%				
Element	Weight %	MDL	Atomic %	Error %
Si K	0.8	0.13	1.5	13.0
S K	0.8	0.14	1.4	12.6
Cr K	1.3	0.2	1.3	10.8
Fe K	95.1	0.55	94.0	2.2
Cu K	2.0	0.49	1.7	13.9

c



eZAF Quant Result - Analysis Uncertainty: 3.35%				
Element	Weight %	MDL	Atomic %	Error %
S K	1.8	0.14	3.1	8.1
Cr K	1.0	0.2	1.1	11.8
Fe K	94.9	0.36	93.8	2.2
Cu K	2.2	0.5	1.9	15.0

d

Fig. 7. Photograph of the sample surface with 0.2% copper content in oil, obtained using an electron microscope

detected across the entire surface of the sample at a concentration of approximately 1.1–1.8% (**Fig. 6, *b–d***).

At a copper powder concentration in oil of 0.2%, as with a 0.05% concentration, large visible copper agglomerates measuring 1–2 µm appear (**Fig. 7, *a***), and copper is detected across the entire sample surface at a concentration of 1.6–2.2% (**Figs. 7, *b–d***). Thus, as the copper concentration in oil increases from 0.1% to 0.2%, the uniformity of copper distribution across the surface deteriorates in the form of 1–2 µm agglomerates.

Conclusion

The results of a study on a suspension containing industrial oil I-20A and copper nanopowder at concentrations of 0.05, 0.1, 0.2, 0.3 and 0.5 (wt.%) are presented in the paper. The tests were conducted on an SRV-3 friction machine under a load of 200 N, with an amplitude of 3 mm and a frequency of 5 Hz. Adding 0.1% by mass of copper nanoparticles to industrial oil produced the best results in terms of reducing the coefficient of friction and wear, compared to using the base oil alone. This is explained by the deposition of fine copper particles in the wear area improving the tribological characteristics, as confirmed by scanning electron microscopy of the wear surfaces.

At copper concentrations above 0.1%, particle aggregation occurs, resulting in increased abrasive wear. Below 0.1%, only partial film formation occurs and the uneven distribution of particles provides no benefit over the base oil.

Copper nanoparticles are a promising material for enhancing the lubricating properties of oils and for restoring surfaces. Using them reduces friction and wear, extending the service life of mechanisms. However, in order for them to be implemented more widely, the problems of aggregation and cost need to be solved, and additional research needs to be conducted on their long-term effects.

References

1. Bolotov A. N., Novikova O. O. The Effect of the Nanodisperse Phase of Magnetic Oils on Their Lubricating Properties. *Physical and Chemical Aspects of the Study of Clusters, Nanostructures and Nanomaterials*. 2022. Iss. 14. pp. 545–560.

2. Kuksenova L. I., Kuleshova E. M., Polyakov S. A. Assessment of the Influence of Nanomodified Additives on the Wear Resistance of Materials of Friction Pairs “Steel-Copper Alloy”. *Bulletin of Science and Technical Development*. 2024. Vol. 175. pp. 11–19.

3. Duan L., Li J., Duan H. Nanomaterials for Lubricating Oil Application: a Review. *Friction*. 2023. Vol. 11. pp. 647–684.

4. Tursunov A. A., Hasanova M. M., Umirov N. N. Improving Lubrication Quality Using Nanoscale Additives. *Universum: Technical Sciences*. 2024. Iss. 11. pp. 29–32.

5. Guo Z., Zhang Y., Wang J., Gao C., Zhang S., Zhang P., Zhang Z. Interactions of Cu Nanoparticles with Conventional Lubricant Additives on Tribological Performance and Some Physicochemical Properties of an Ester Base Oil. *Tribology International*. 2020. Vol. 141. 105941.

6. Gondolini A., Mercadelli E., Zin V., Barison S., Sanson A. Easy Preparation Method of Stable Copper-Based Nanoparticle Suspensions in Lubricant Engine Oil. *Lubrication Science*. 2020. Vol. 32. pp. 205–217.

7. Uflyand I. E., Zhinzhilo V. A., Burlakova, V. E. Metal-Containing Nanomaterials as Lubricant Additives: State-of-the-Art and Future Development. *Friction*. 2019. Vol. 7. pp. 93–116.

8. Padgurskas J., Rukuiza R., Prosyčevas I., Kreivaitis R. Tribological Properties of Lubricant Additives of Fe, Cu and Co Nanoparticles. *Tribology International*. 2013. Vol. 60. pp. 224–232.

9. Peng R., Wang W., Wang P., Liu J., Liu S., Zhai H., Guo J. Preparation of Graphene-Loading Copper Nanoparticles by Freeze Drying and Its Tribological Properties. *Lubrication Science*. 2023. Vol. 35, Iss. 4. pp. 270–278.

10. Chen F., Yan Z., Wu X., Liu B., Liu Y. Microstructures and Properties of Cu - 10 Sn Oil Bearings Reinforced by Al_2O_3 Nanoparticles. *Advanced Powder Technology*. 2021. Vol. 32, Iss. 3. pp. 710–717.

11. Bahrom M. Z., Manshoor B., Talib N. et al. Tribological Performance of Hexagonal Boron Nitride (h-BN) Nanoparticle Additives in Multigrade Motorcycle Engine Oils. *Journal of Advanced Research in Micro and Nano Engineering*. 2025. Vol. 29, Iss. 1. pp. 91–103.

12. Jatti V. S., Singh T. P. Copper Oxide Nano-Particles as Friction-Reduction and Anti-Wear Additives in Lubricating Oil. *Journal of Mechanical Science and Technology*. 2015. Vol. 29, Iss. 2. pp. 793–798.

13. Aravindakshan R., Afnas V. M., Reghuraj A. R., Kiran C. Characterization of Engine Oil-Based Nano Lubricant Prepared Using CuO and ZnO Nanoparticles. *AIP Conference Proceedings*. 2024. Vol. 3134. 130020.

14. Ettefaghi E., Ahmadi H., Rashidi A., Mohtasebi S. S., Alaei M. Experimental Evaluation of Engine Oil Properties Containing Copper Oxide Nanoparticles as a Nanoadditive. *International Journal of Industrial Chemistry*. 2013. Vol. 4. 28.

15. Ghaednia H., Jackson R. L., Khodadadi J. M. Experimental Analysis of Stable CuO Nanoparticle Enhanced Lubricants. *Journal of Experimental Nanoscience*. 2013. Vol. 10, Iss. 1. pp. 1–18.

16. Zhang M., Wang X., Liu W., Fu X. Performance and Anti-Wear Mechanism of Cu Nanoparticles as Lubricating Oil Additives. *Industrial Lubrication and Tribology*. 2009. Vol. 61, Iss. 6. pp. 311–318.

17. Kim S. Ch., Reva V. P. Application of Copper Nanoparticles as an Additive io Lubricanting Oil. *Computational Nanotechnology*. 2019. Iss. 1. pp. 23–25.

18. Bagdasarov L. N., Mikhailov E. R. Overview of Modern Works in the Field of Lubricants Production. *Sciences of Europe*. 2021. Vol. 69. pp. 3–18.

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