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Investigation of the effect of oil-based MWFs with enhanced tribological properties on cutting forces and roughness of the processed surfaces

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ABSTRACT

Introduction. One way to enhance the efficiency of the cutting process is to develop new effective compositions of metalworking fluids (*MWFs*), which will reduce cutting force and temperature, while increasing the durability of the cutting tool and the quality of the processed surface. One approach to address this challenge is the chemical activation of *MWF* using additives based on nanoclay minerals, which are characterized by low cost and abundant reserves in-Earth. In this regard, the theoretical rationale for the selection of this additive and its impact on the tribological properties of the *MWF* is given. **The purpose of the work** is to determine the effect of oil-based additives with nanoclay minerals on reducing the cutting force, as well as improving the quality of the processed surface when drilling corrosion-resistant steel. **Research methods.** Experimental investigations were conducted during a drilling operation, in which the components of the cutting force were recorded using a three-component dynamometer *M-30-3-6k*. The aim of the experiment was to determine the effect of oil-based *MWF* containing additives from nanoclay minerals on the component of the cutting force, as well as the roughness of the processed surface. A formula for calculating the friction coefficient in the drilling process was derived using mathematical modeling. **Results and Discussion.** The experimental investigations yielded results demonstrating the effectiveness of using oil-based *MWF* with additives made from nanoclay minerals. Experimental data was obtained for the friction coefficient, cutting force component, as well as the roughness of the processed surface during drilling. These results were obtained using the experimental *MWF*, supplied to the cutting zone. The results of the study showed the effectiveness of using the modified *MWF* compared to traditional compositions. **Conclusions.** The modified *MWF*, which includes sunflower oil and nanoclay minerals as additives, significantly reduces the friction coefficient, cutting force, as well as the roughness of the processed surface, which opens up further prospects for its use in the metalworking industry.

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Introduction

The development of domestic machine building is a priority task for the modern state. Therefore, it is important both to improve existing technologies and to explore new solutions that enhance the quality and productivity of machining processes while maintaining a low cost for the finished product.

One promising solution is the development of novel metalworking fluid (*MWFs*) compositions that combine high lubricating and cooling performance. Studying their influence on the machining process is essential to identify new avenues for their effective application. One approach is the use of environmentally safe *MWFs* based on vegetable oils. Critically, the production of such *MWFs* should be economically viable and avoid excessive financial expenditure.

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The primary function of oil-based *MWFs* is lubrication, which ensures the required quality of the processed surface. However, their cooling capacity is limited. In most production facilities, water-soluble *MWFs* (emulsions) are used; these effectively reduce the temperature in the cutting zone through convective heat exchange due to high-volume supplying, but their lubricating properties are less effective.

Numerous scientific studies have analyzed methods for activating and improving *MWFs* used in the blade machining of workpieces. The authors of these studies have made significant contributions to understanding the mechanism of action of *MWFs* in the cutting process [1–4].

In this case, *MWFs* activation involves adding functional additives of various natures and chemical structures, including active organic components containing phosphorus, chlorine, and sulfur. These elements form protective films on contact surfaces, preventing molecular bonding between the tool and the workpiece. Graphite, soft metal powders (molybdenum disulfite) and highly dispersed powders (e.g., serpentine), classified as nanostructured additives, are also viable. They reduce friction in the cutting zone due to antifriction properties by increasing the number of supporting contact areas between the tool and the workpiece. Additionally, some chemical compounds and additives used in *MWFs* exhibit carcinogenic properties, posing a negative impact on human health and the environment.

The analysis of the scientific and technical literature has shown that existing methods for activating oil-based *MWFs* can be significantly improved. Furthermore, the development of new, cost-effective oil-based *MWFs* possessing an endothermic (cooling) effect and improved tribological (lubricating) properties remains an important goal.

Achieving this goal is possible by adding nanoclay mineral additives to the composition of oil-based *MWFs*. Based on their physical and mechanical properties, these minerals are similar to additives such as molybdenum disulfite, graphite, and serpentine.

A key difference of these nanoclay mineral additives is their ability to undergo hydrocracking of their structural packet layers during hydrogenation. This results in hydro-lubrication between the layers, which contributes to increased tribological efficiency of the oil-based *MWF* [5].

Thus, the application of modified oil-based *MWFs*, using nanoclay mineral additives as a friction modifier, can positively affect the cutting process of hard-to-machine materials and stainless steels, with their inherent low thermal conductivity [6, 7].

Optimal cutting modes [8], the quality of the *MWFs* used, and the method of its supply [9, 10] influence the plastic deformation process, leading to a decrease in temperature and cutting force, as well as improving the quality of the machined surface and tool durability [11–15].

Consequently, there is a need for theoretical studies, laboratory tests, and practical experiments aimed at developing a modified *MWFs* that uses nanoclay mineral additives (*NMAs*) as a friction modifier, combining both high lubricity and a cooling effect, which is necessary for processing hard-to-machine materials and stainless steels.

The aim of this work is to determine the effect of oil-based *MWFs* with nanoclay mineral additives on reducing cutting force and improving the quality of the machined surface during the drilling of stainless steel.

Tasks to be solved to achieve this aim:

1) to justify the selection of additives to oil-based *MWFs* to improve their tribological efficiency;

2) to theoretically and experimentally confirm the effectiveness of using nanoclay mineral additives as a friction modifier in oil-based *MWFs* and their influence on increasing tribological properties;

3) based on current principles of cutting theory, to analyze the effect of nanoclay mineral additives, present in the oil-based *MWFs* as a friction modifier, on the components of cutting force and the roughness of the machined surface.

Research methodology

During blade machining of hard-to-machine materials, as well as stainless steels, the various *MWFs'* compositions require the technological medium supplied to the cutting zone to provide both lubrication and cooling. However, increasing the lubricating effect often leads to a deterioration of the cooling effect of such *MWFs*. This circumstance necessitates the search for alternative solutions that result in *MWFs* possessing both high lubricating and cooling properties.

Based on the above considerations, it became necessary to conduct experimental studies aimed at developing modified oil-based *MWFs* using *NMAs* as the primary modifying element. The objective is to reduce energy consumption in the cutting process, improve the quality of the machined part, and extend tool life.

The use of *NMAs* offers several advantages. For instance, they are naturally occurring minerals found in abundant quantities within the Earth's interior and are relatively inexpensive. One type of nanoclay mineral is bentonite, which is primarily composed of montmorillonite (a nanodispersed silicate with a sheet-like structure).

From a physicochemical perspective, *NMAs* exhibit positive characteristics: they can undergo hydrocracking of their structural packet layers during hydrogenation, providing hydro-lubrication between the layers. This contributes to an increase in the tribological efficiency of the *MWFs*. This phenomenon distinguishes the tribological properties of montmorillonite from those of the friction modifiers described earlier.

During hydrogenation of this additive, compared to the aforementioned friction modifiers, the unclinching action of surface-sorbed water causes the friction between mineral packets to transition from dry to liquid or boundary lubrication. When hydrated mineral particles enter the contact zone between the tool and the workpiece, carried by the oil-based *MWF*, they function as "nanoscale sliding bearings" [16, 17], allowing the tool and workpiece to be in contact, which reduces the probability of adhesive wear of the tool.

The temperature generated in the contact zone of the tool and the workpiece acts on the surface water-sorbed *NMA* packets contained in the oil-based *MWF*, resulting in moisture evaporation and providing an endothermic effect. A unique characteristic of nanoclay minerals is that the released vapor remains in the system during the evaporation process. When the temperature decreases, the vapor condenses, returning to the mineral structure.

Improving the tribological characteristics of *MWFs* is particularly important in the process of cutting hard-to-machine materials, including stainless steels, because access of the *MWF* to the contact zone is often limited when processing these materials.

Consider the case where a standard *MWF*, without additives to prevent adhesive setting, is used when machining hard-to-machine materials.

Due to the high specific loads present in the cutting process acting on the tool contact surfaces, displacement of the *MWF* and subsequent adhesion of the chip to the tool base occurs.

Thus, conditions for adhesive bonding between the front face of the cutting tool and the chip are created (Fig. 1, *a*).

In the second case, using an oil-based *MWF* with graphite or molybdenum disulfide additive in the cutting process (Fig. 1, *b*), the additive enters the contact zone and counteracts the adhesion of chips to the cutting tool, thereby improving friction conditions in the cutting zone. This is achieved by preventing adhesive bonding of graphite or molybdenum disulfide layer packets with each other.

Given the similarity of crystal lattices between graphite or molybdenum disulfide and nanoclay minerals, shear between layers is possible. In the case of graphite or molybdenum disulfide, this shear occurs "dry", while in the case of nanoclay minerals, liquid friction conditions are created, accompanied by hydrocracking (Fig. 1, *c*), which directly influences the tribological properties of the *MWFs*.

To evaluate the thermodynamic transformations of *NMA* that can occur in oil-based *MWFs* during machining by cutting, we will analyze their behavior during hydration and dehydration. This additive possesses a crystal lattice consisting of three layers, forming negatively charged packets that create repulsive forces, providing a wedging effect [5].

The aforementioned nanoclay minerals' inherent thermodynamic properties enable their use as additives to oil-based *MWFs*.

In reference [18], a detailed thermal analysis of montmorillonite is presented, highlighting the temperature range (80–220 °C), in which the endothermic (heat-absorbing) effect is manifested. At the

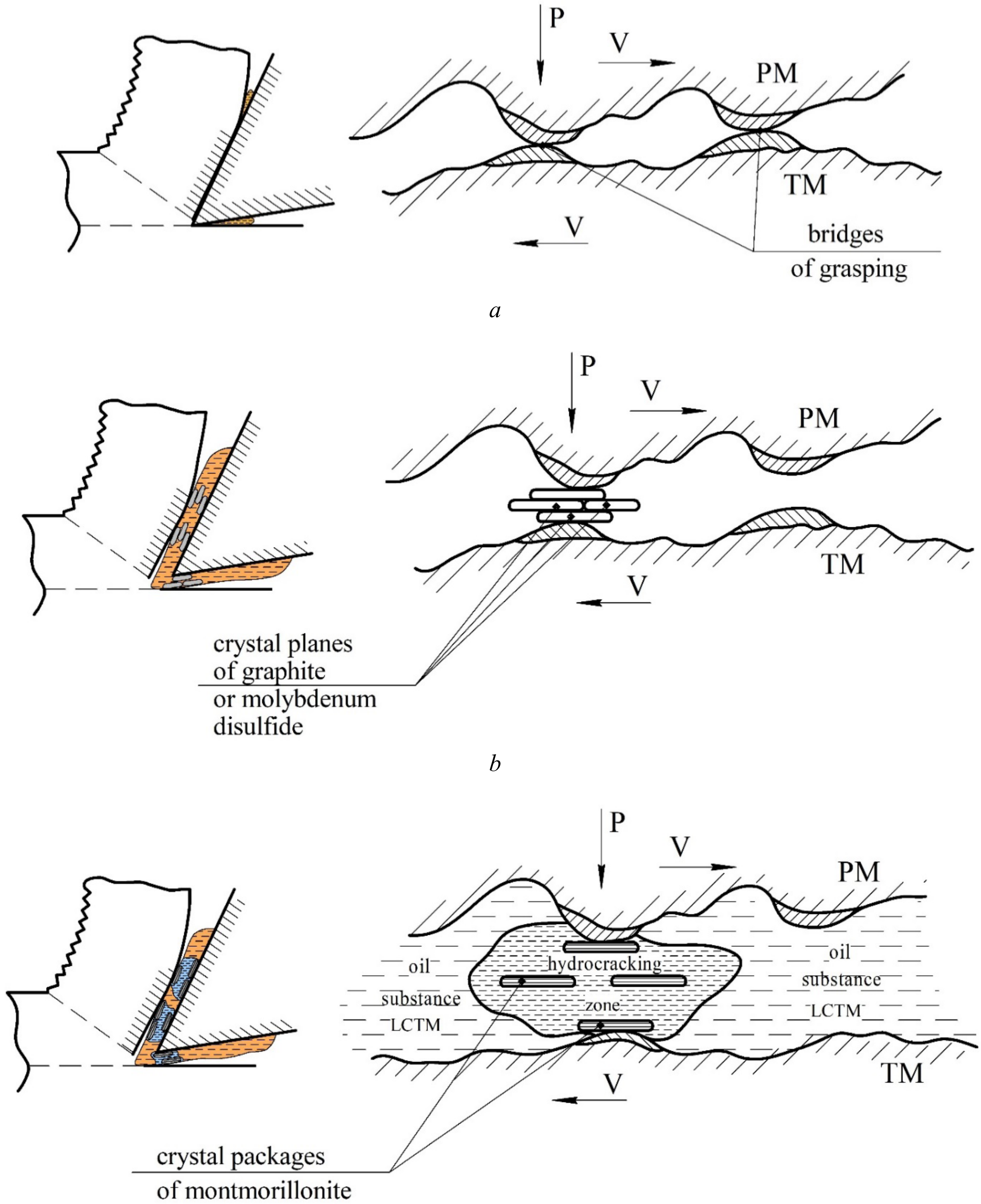


Fig. 1. Examples of possible contact interactions on the rake face of a cutting tool:

a – without *MWF* feeding (“dry” cutting); *b* – with graphite in the oil-based *MWF*, acting as an additive; *c* – with an additive of a hydrogenated nanoclay mineral in the oil-based *MWF*; ▨ – the area of high local deformation; *WM* – work material; *V* – linear velocity; *TM* – tool material

initial stage of this range, the adsorption layer of water is removed, followed by the removal of interpacket water from the mineral surface. When the temperature increases to 600 °C, complete destruction (sintering) of the mineral’s crystal lattice occurs, caused by the removal of the structural water layer.

It is known that boundary friction occurs during cutting at low contact loads [19], while intensive plastic deformation leads to “grabbing” of chips by the front face of the tool.

To evaluate the effectiveness of the *NMA* described above in the composition of oil-based *MWFs*, laboratory tests were conducted to determine the empirical friction coefficient under conditions approximating the drilling process.

References [20, 21] describe various methods for determining the friction coefficient of lubricants, noting that it is not always possible to assess the actual friction coefficient using a particular machining method, due to the inherent characteristics of each method. Furthermore, the widely used four-ball machine methodology for determining the friction coefficient does not allow for reproducing the friction process occurring, for example, in the contact zone between the cutting tool and the workpiece during drilling.

Experimental evaluation of the effectiveness of the developed oil-based *MWF* with *NMA* as a friction modifier, as well as evaluation of its tribological properties, was conducted using the "cone spinning on the cone" method for determining the friction coefficient, performed on a radial drilling machine*2Co522*.

The experimental stand functioned as a tribometer, allowing for the determination of the empirical friction coefficient approximating the drilling process. A spiral drill bit made of steel *B6Mo5* with a modified cutting edge geometry was used as an indenter (Fig. 2). This provided friction between the indenter (drill bit) and the conical surface of the counterbody (workpiece).

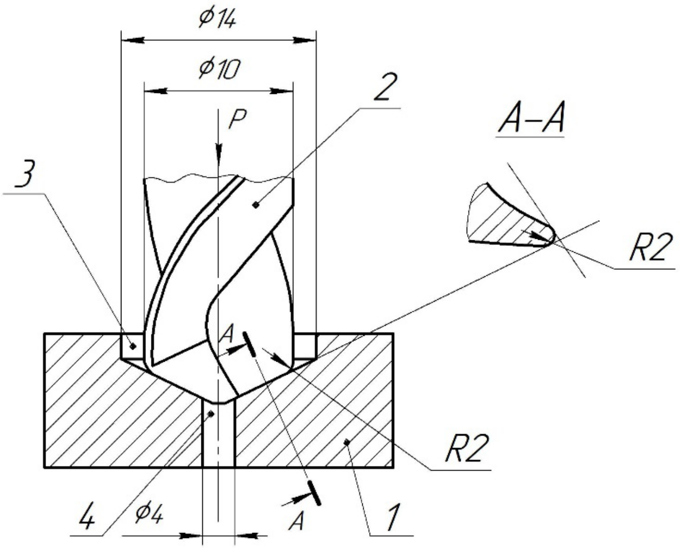


Fig. 2. Geometry of the cutting edge of a modified drill (indenter):

1 – counterbody (workpiece); **2** – indenter (spiral drill); **3** – circular groove for supplying to the cutting zone; **4** – through-hole for removing *MWF*

During the research process, a three-component dynamometer *M-30-3-6k* was mounted on the machine table to register both axial force and torque. The workpiece, made of corrosion-resistant steel *0.12 C-18 Cr-10Ni-Ti* with a previously drilled hole, was fixed on the dynamometer using a flange and a three-jaw chuck. The indenter was a spiral drill bit with a diameter ***D*** = 10 mm and a point angle of **2φ** = 118°, made of high-speed steel *6 W-5 Mo-4 Cr-2 V*, featuring rounded cutting edges (see Fig. 2).

Axial force and torque values were recorded using the three-component dynamometer *M-30-3-6k*. The signal from the dynamometer was transmitted to a personal computer through an amplifier and analog-to-digital converter for subsequent generation of dependence diagram.

Fig. 6 illustrates the general view of the experimental stand. A protective screen was used to prevent the measuring equipment from being splashed with *MWF* during the research process.

The laboratory testing procedure was as follows: the counterbody **4** was fixed on the dynamometer using a three-jaw chuck and a flange. The indenter **1** was fixed in the machine spindle using a chuck. After starting the machine and subsequent feeding the tested modified *MWF* through slot **2** into the contact zone, the axial load on the counterbody was gradually increased to the required value P_0, followed by measuring the friction torque. The spindle speed was 500 rpm with an axial load on the indenter of P_0 = 2,000 N.

To compare effectiveness, the following *MWF* compositions were used: vegetable oil (sunflower oil), industrial oil *I-20A*, vegetable oil (sunflower oil) with *NMA*, and industrial oil *I-20A* with *NMA*, at a constant *MWF* supply rate of 0.5 l/min.

Fig. 3 presents the results of experimental studies to determine the empirical friction coefficient, using the methodology described above.

During friction between a rotating indenter (drill bit) and a stationary counterbody, using the friction torque M_{fr} is more effective than using the friction force. The force of resistance to the movement of the indenter (drill bit's) relative to the counterbody surface is a distributed force, directed opposite to the velocity vector of the body under consideration.

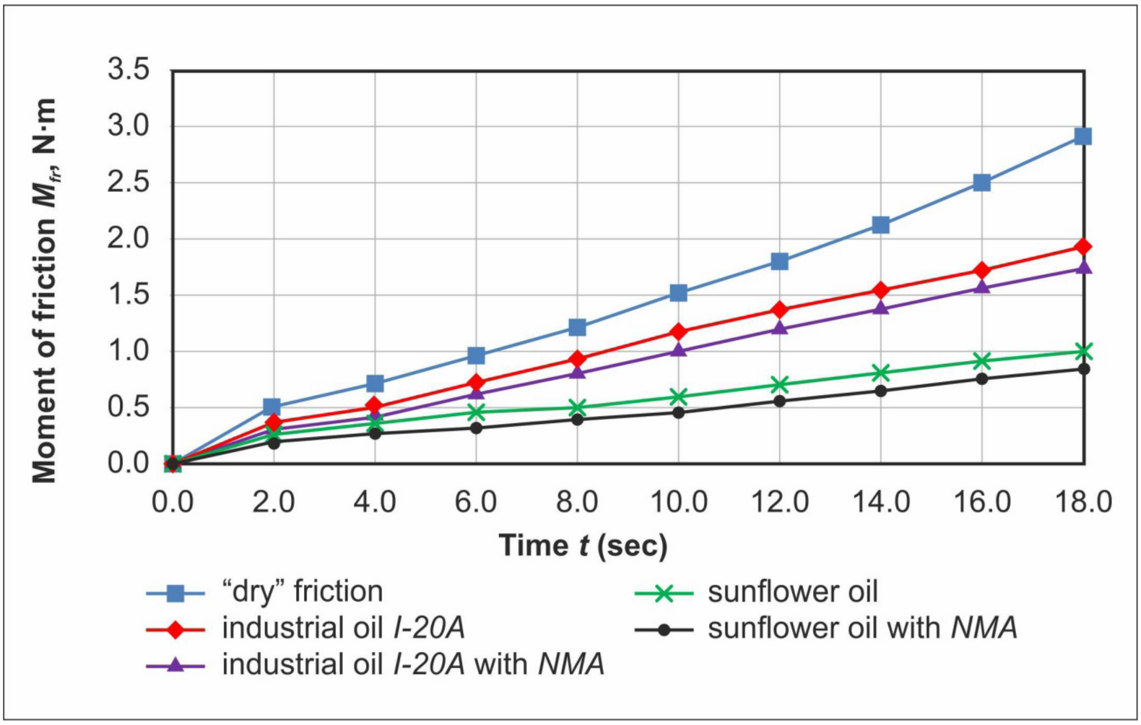


Fig. 3. Friction torque values in various *MWF* environments

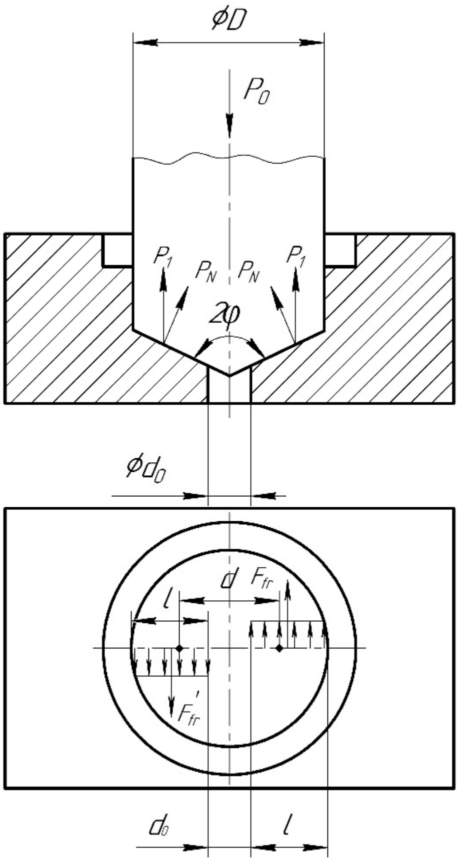


Fig. 4. Design scheme of the analyzed friction pair:
2φ – drill apex angle, deg; $\boldsymbol{F_{fr}}$ – friction force, H; $\boldsymbol{P_0}$ – axial force, H

According to the calculation scheme (Fig. 4), the friction force $\boldsymbol{F_{fr}}$ is an equivalent force, which can be determined according to the principle of finding equivalent forces for parallel distributed forces. Let us determine its magnitude and the point of its application, which is located at the center of the contact line **l** between the drill bit and the workpiece.

According to the scheme of the friction unit, a pair of forces $\{-F_{fr}; F_{fr}\}$ with a moment acts on the indenter (drill bit):

$$M_{fr} = \frac{F_{fr} \cdot (D + d_0)}{2}, \quad (1)$$

where $\boldsymbol{D}$ is the diameter of the indenter (drill bit); $\boldsymbol{d_0}$ is diameter of the hole in the counterbody or

$$F_{fr} = \frac{2M_{fr}}{D + d_0}. \quad (2)$$

For the unit under consideration, Equation (2) relates the moment and friction force.

The axial force $\boldsymbol{P_N}$ acting on the contact surface of the tool is the projection of the axial force P_N by the sine of the angle between the forces. Using the equilibrium condition, and taking into account the normal pressure force on the indenter (drill) surface $\boldsymbol{P_N}$, which is in contact with the counterbody, we obtain:

$$P_N = \frac{P_0 \cdot \sin\varphi}{2}, \quad (3)$$

where $\boldsymbol{P_0}$ is the axial force, N.

According to the *Amont-Coulomb* law, the normal force $\boldsymbol{P_N}$ is related to the friction force $\boldsymbol{F_{fr}}$, which can be defined by the following equation:

$$F_{fr} = \mu \cdot P_N = \frac{\mu \cdot P_0 \cdot \sin\varphi}{2}, \qquad (4)$$

where **μ** is the empirical coefficient of friction.

After transformation, we obtain:

$$\mu = \frac{4M_{fr}}{(D + d_0) \cdot P_0 \cdot \sin\varphi}. \qquad (5)$$

Then, using the maximum values of the friction torque, as well as the applied axial force, the empirical coefficient of friction for the considered case is determined.

Results and their discussion

The measured friction torque $\boldsymbol{M_{fr}}$ at a constant axial load $\boldsymbol{P_0}$ = 2,000 N using various metalworking fluids (*MWFs*) is presented graphically in Fig. 5.

Analyzing the obtained data (Fig. 5), the maximum empirical coefficient of friction (**μ** = 0.48) was observed under “dry” friction conditions, without *MWF*. The addition of *NMA* as a modifier to *MWFs* reduces the empirical coefficient of friction. The most significant reduction occurred with sunflower oil (**μ** = 0.11) compared to mineral oil-based *MWF* (**μ** = 0.19). This suggests that the sunflower oil-based *MWF* with *NMA* exhibits improved lubricity, providing boundary lubrication, and possibly even liquid lubrication.

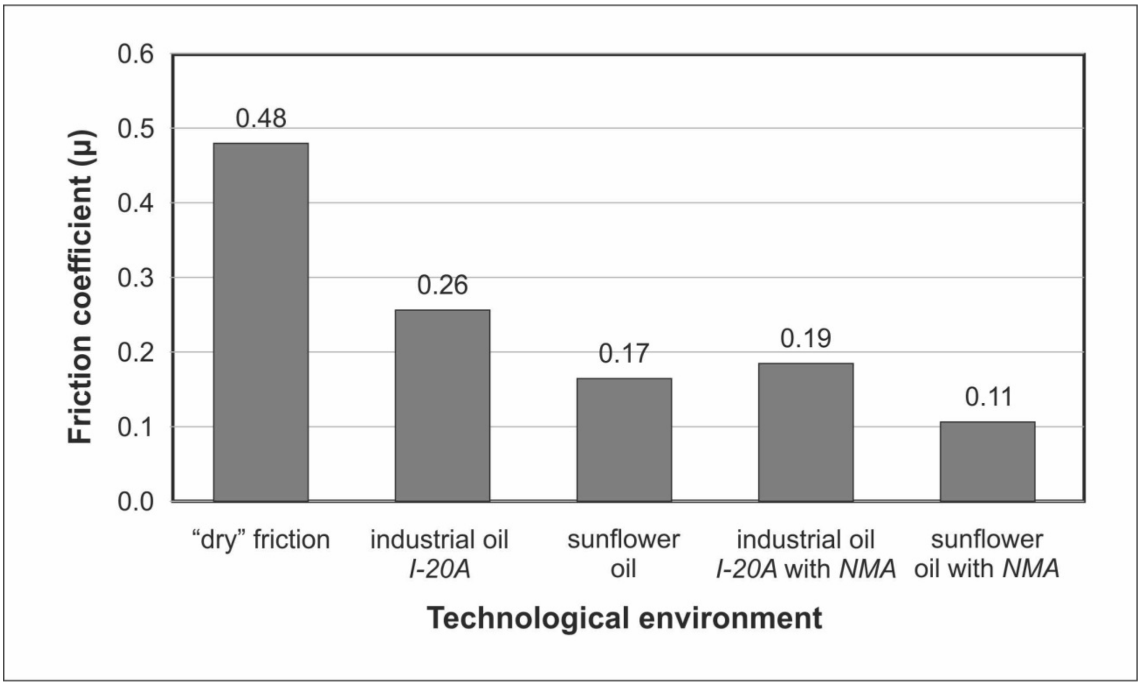


Fig. 5. Empirical friction coefficient (**μ**) values in various *MWF* environments

Therefore, sunflower oil modified with *NMA* is the most effective *MWF*, compared to sunflower oil without *NMA*, mineral oil *I-20A* without *NMA*, and mineral oil *I-20A* modified with *NMA*. This indicates the high lubricating and bearing capacity of the experimental *MWF*.

Determining the empirical friction coefficient using the described methodology provides a quantitative assessment of the tribological properties of the modified *MWFs* and allows for a more comprehensive understanding of the influence of modifiers, in this case *NMA*, on the friction force.

Following the investigation of the influence of modified *MWFs* on the empirical friction coefficient, the cutting force during drilling was determined using similar *MWFs*. To accomplish this, an experimental stand (Fig. 6) equipped with a three-component dynamometer *M-30-3-6k* with data output to a personal computer was used. This allowed for objective evaluation of the effect of different *MWFs* on cutting forces during the drilling operation.

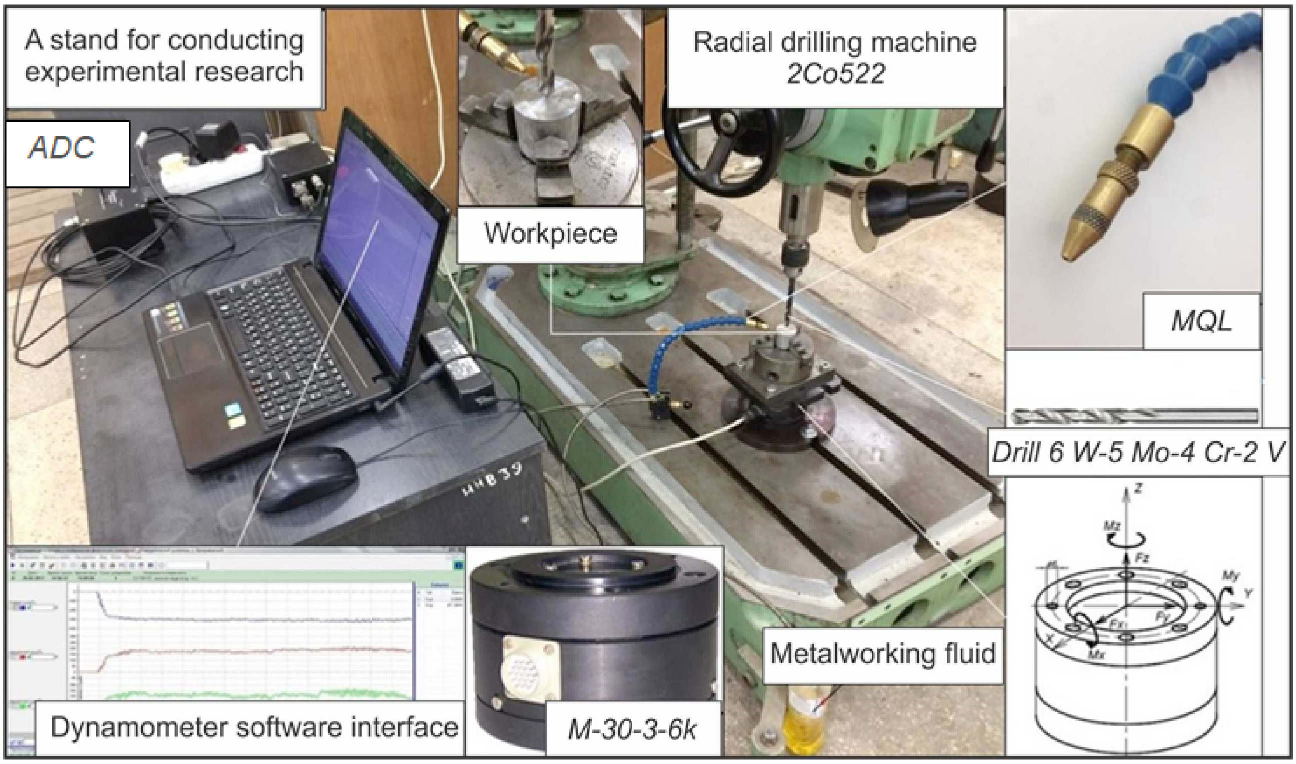


Fig. 6. Experimental stand for studying cutting forces during drilling

As a result of experimental studies of the machining of stainless steel *0.12 C-18 Cr-10Ni-Ti*, the cutting force values were obtained as a function of machining time and cutting speed (Fig. 7, *a*, *b*).

The analysis of the obtained data shows that drilling without *MWF* results in a high cutting force. Using mineral and sunflower oil-based *MWFs* as cutting agents reduces the cutting force by 10–20 %. Adding *NMA* to these oils results in a further reduction in cutting forces (by 9–10 %) compared to the oils without the additive. The smallest cutting force was achieved when using sunflower oil with *NMA*.

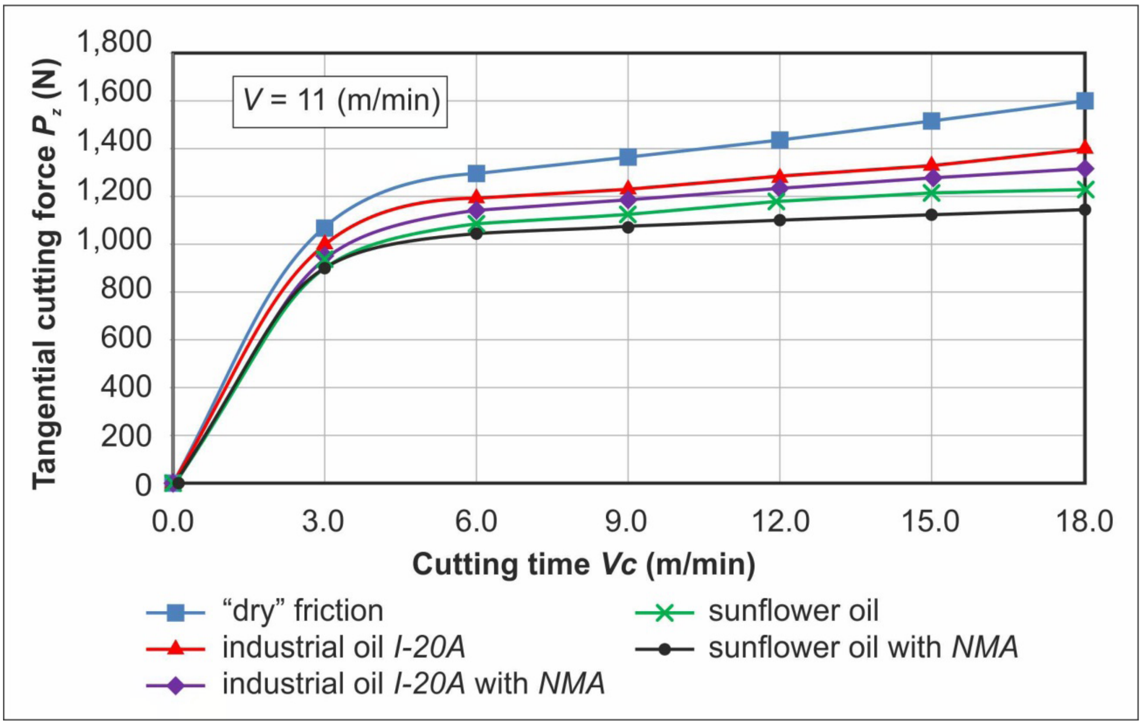
NMA, acting as a modifier, improves the tribological properties of oil-based *MWFs*, contributing to a reduction in temperature within the cutting zone and increasing the lifespan (durability) of the cutting tool [22].

The data presented in the graph (Fig. 7, *b*) demonstrate that at cutting speeds up to 20 m/min, the type of *MWF* significantly affects the cutting force P_Z. However, as the cutting speed increases, the effectiveness of the *MWF* decreases. This is attributed to the increased proportion of friction forces generated on the back surface of the tool.

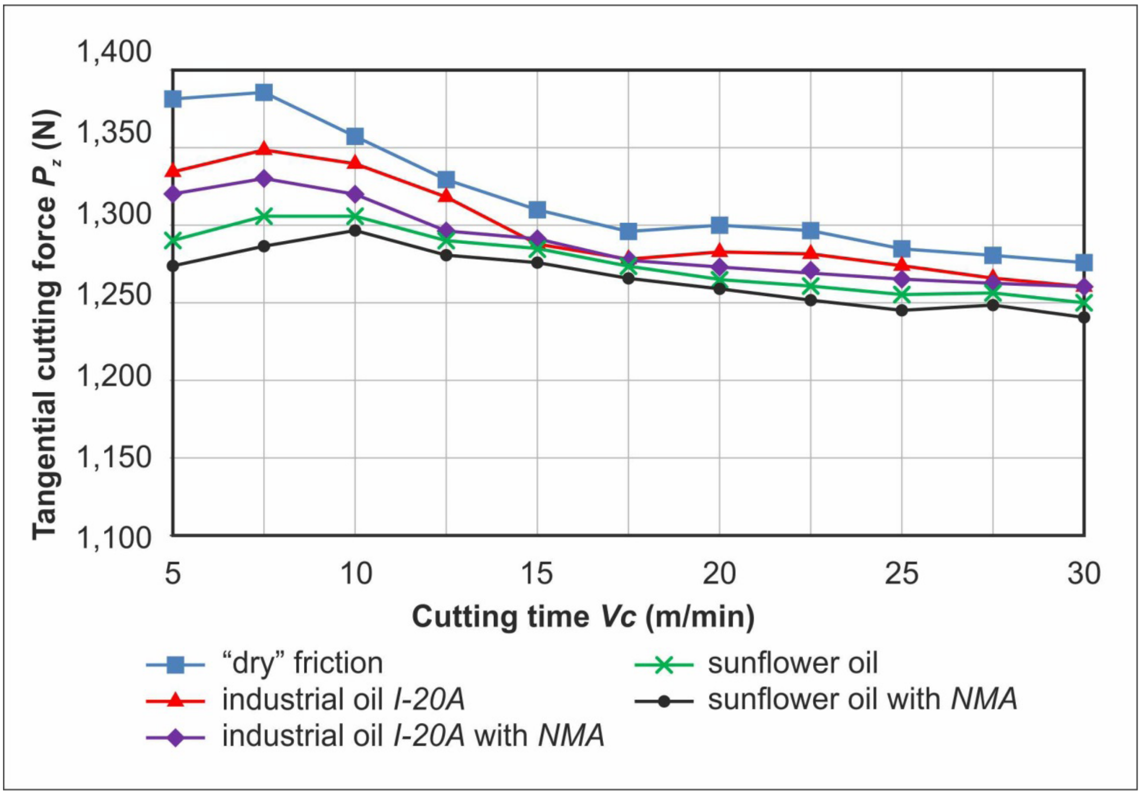
Definition of roughness. The influence of *NMA* on the machined surface surface roughness, which is a critical quality parameter, is also of interest. The roughness of the machined surface is affected by various factors, including cutting modes, the type of *MWF* and its supply method to the cutting zone, and cutting temperature , etc. [23, 24].

The use of modified oil-based *MWFs* in drilling workpieces of stainless steel *0.12 C-18 Cr-10Ni-Ti*, with *NMA* as a modifier, enables a reduction in both the cutting temperature and the roughness of the machined surface.

Fig. 8 shows the arithmetic mean surface roughness ***Ra***, measured with a profilometer *TR-200*. ***Ra*** reflects the surface roughness of the machined surface.



a



b

Fig. 7. Tangential cutting force $\boldsymbol{P_Z}$ values as a function of processing time (*a*) and cutting speed (*b*) with various *MWF* compositions applied. Tool feed $\boldsymbol{S}$ = 0.076 mm/rpm. Cutting tool – Spiral drill (*HSS*). $\boldsymbol{D}$ = 22 mm. *MWF* consumption – 0.5 l/min

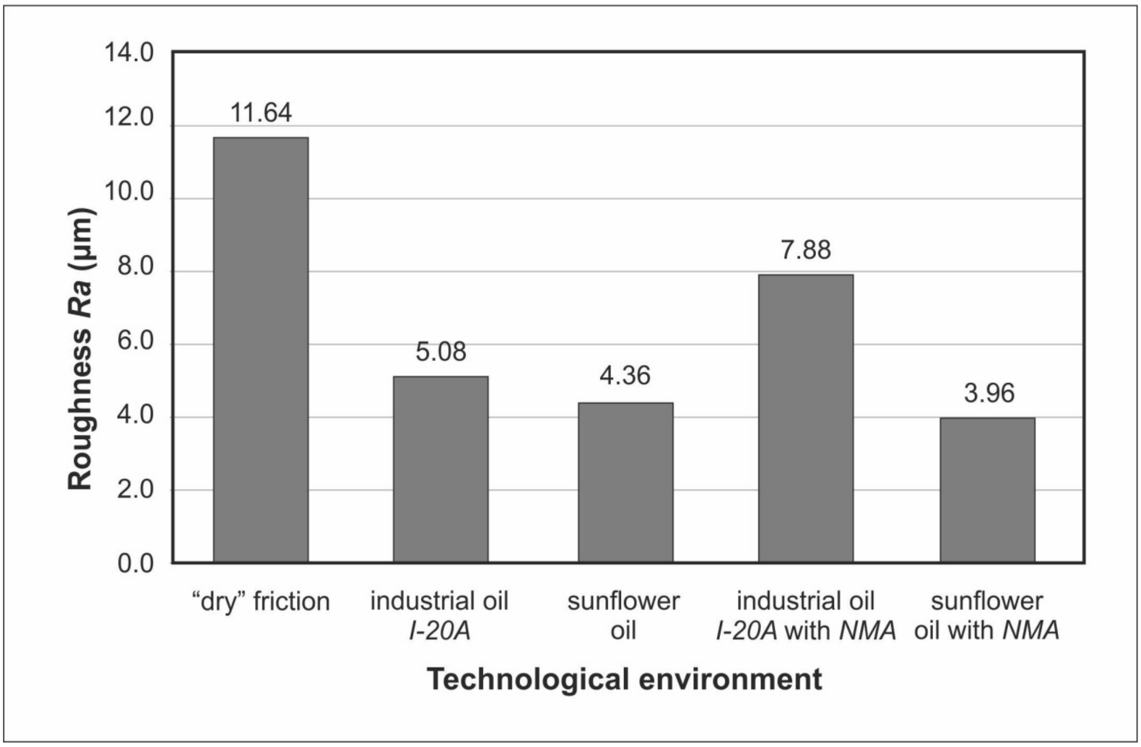


Fig. 8. Results of the arithmetic mean deviation of the ***Ra*** profile of the processed surface

Conclusions

The application of *NMA* during their hydrogenation, enables the transition to liquid interpacket friction of the mineral layers, creating a hydrobranching zone and improving the tribological properties of oil-based *MWFs*. This composition allows for the reduction of temperature in the cutting zone through of convective heat distribution within the volume of the *MWF* with its subsequent removal from the system into the environment.

Conducted laboratory studies have shown that, when supplying the oil-based *MWF* with *NMA*, the empirical friction coefficient has the lowest value ($\mu = 0.11$) compared to other compositions.

NMA included in the composition of oil-based *MWF* also had a positive effect on the reduction of cutting force during drilling of steel *0.12 C-18 Cr-10 Ni-Ti* (by 10 %), compared to using *MWF* without additives. Furthermore, it reduced the surface roughness of the machined surface to $Ra = 3.96$ µm.

Based on these findings, we conclude that the use of *NMA* in combination with environmentally safe oils opens fundamentally new ways of their effective use in the cutting process. The primary effects of *NMAs* are aimed at enhancing the lubricating, cooling, as well as resource-saving action of *MWFs*.

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Conflicts of Interest

The authors declare no conflict of interest.