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ECOLOGICAL CUTTING FLUIDS

Key words

Cutting fluids, aqueous solutions of surfactants, tribological and operational properties.

Abstract

Industrial cutting fluids are used in the form of emulsions and microemulsions of the o/w type. They pose a hazard for the natural environment and the personnel working with them. This paper presents a new type of safe cutting fluids: aqueous solutions of surfactants. Physicochemical, tribological and operational tests were carried out in order to optimize the compositions of the cutting fluids. Physicochemical and operational properties of the optimized cutting fluid are comparable to those of the best equivalents available on the market.

Introduction

Cutting fluids are commonly used in the processing of materials. Their basic functions are cooling and lubrication of cutting tools. Cutting fluids include cutting oils, emulsions, and microemulsions as well as *aqueous solutions of chemical substances,* which are the subject of our interest [1–10].

Cutting oils may be of mineral, animal, plant, or synthetic origin or their mixtures. It is common to introduce additives to the oils that improve their physicochemical, tribological, and functional properties. Thus modified oils can be used at high rotational velocities and high pressures. The share of oils on the market has been decreasing. They are used when there is a need to precisely machine shapes. Compared to water, the oils are characterized by a low thermal conductivity and a low specific heat. Therefore, they ineffectively remove heat from the friction zone. This is a major disadvantage that may lead to excessive overheating of the device and the material being machined. Another disadvantage is the environmental threat that may arise when cutting oils leak into soil or water. Additionally, management of used oils is difficult.

Emulsions and microemulsions are a compromise between the beneficial tribological properties of oils and the good conductivity of water. Emulsions of the o/w type that are stabilized by appropriate emulsifiers are used in practice. They also contain improvers, such as corrosion and oxidation inhibitors, biocides and biostatics, antifoam agents, antiwear additives (AW), and extreme pressure additives (EP). Emulsions are treated as hazardous waste and the cost of their management is much higher than their production cost. They have an adverse effect on human health in the workplace. They may form toxic aerosols that cause irritation of the workers' skin and respiratory systems.

1. Solutions of chemical substances as new generation cutting fluids

Solutions of chemical substances do not contain oils and are a new kind of cutting fluids. They have been undergoing intensive scientific research. Therefore, our research is up-to-date and, apart from its cognitive character, it has a significant applicational "load," and the solutions are meant to be used directly in industry. The main aim of the study is to develop compositions of the solutions. Due to the innovative approach, it was necessary to select a wide spectrum of compounds that would be used as components of the solutions tested. They should also determine essential beneficial properties of cutting fluids in the form of solutions, such as long operation time, biostability, a low health hazard level, lubricity, and antiseizure properties. The effect of individual components on physicochemical, tribological, and functional properties of "model" cutting fluids was examined. The results obtained formed a basis for the optimisation of the composition and developing formulations that were tested on real systems (machine tools) in industry.

1.1. The composition of model cutting fluids

As a result of a wide range of investigations, the compositions of a number of cutting fluids were developed, and four of them became the subjects of patent applications [7–10]. The characteristics of cutting fluids containing water, surface-active compounds, anticorrosion and antifoam additives, and biocides will be presented.

- Water has the highest percentage share in the fluids (from 95 to 97%). Water with 10°n hardness was used in this study. It was prepared according to the procedure described in the PN-92/M 55789 standard. Hardness of this kind of water is close to the commonly used tap water in Poland.
- The components of cutting fluids are surface-active compounds at the concentrations of the order of several percent. Their aim is mainly to improve the tribological properties of water (reductions in resistance to motion and wear as well as better antiseizure properties). The paper presents results for two compounds: vinylpyrrolidone with a polymerization degree of 90 (PVP90) and sodium lauroyl sarcosinate (SLS) (PVP 90 + SLS).
- Anticorrosion additives (boric acid esters) were used in order to protect the machines as well as tools and machined elements against corrosion.
- During machine tool operation, there may occur very high pressures of coolants that may result in foam formation. Too much foam may be harmful to the life of the machine. Hydrophobic compounds with a low HLB present in silicone emulsions were used as antifoam additives.
- Bacteriostatic and bactericidal substances were included. Although there are no oils in the proposed cutting fluids, there still exists a possibility of microbiological contamination, though to a lesser extent than in emulsions. As a result, the fluids lose their functional properties and the compounds formed in biochemical reactions may pose a hazard to human health. Therefore, biocides were added to the formulations of the fluids.

1.2. Results of physicochemical studies

Cutting fluids were characterized by the following physicochemical properties: stability, surface tension, wettability, viscosity, foamability, and corrosion.

Stability assessment was made of the appearance, colour, consistency, clarity and homogeneity of the fluids stored at room temperature (storage test), reduced (5^{o}C) and increased (60^{o}C) temperatures (temperature tests), and exposed to centrifugal force (mechanical load tests). The PVP and SLS solutions were unstable at the concentration of 0.1%, whereas they were stable at the concentrations of 0.001, 0.01 and 1–5%.

Surface tension (σ) was based on the “ring tear” test. The method consists in measuring the force needed to tear a platinum ring off the surface of the solution tested. The measurements were made on a Lauda TD1C tensiometer. The surface tension of distilled water is about 72 mN/m. For 1% aqueous solutions of polyvinylpyrrolidone the σ value equals 52 N/m. A decrease in the σ value with an increase in concentration was observed for solutions containing sodium lauroyl sarcosinate (SLS) (Fig. 1).

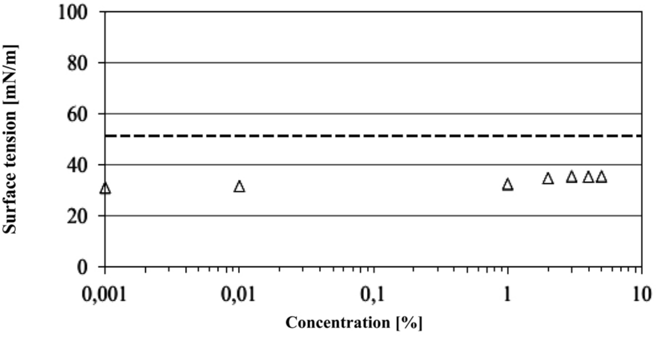

Fig.1. Dependence of surface tension on concentration of sodium lauroyl sarcosinate (SLS) in 1% aqueous solution of polyvinylpyrrolidone with a polymerization degree of 90 (PVP90). Dashed line – surface tension value for 1% aqueous solution of PVP90 is 51.6 mN/m. Surface tension value for water is about 72 mN/m

Reduced surface tension with an addition of an anionic surfactant is beneficial, because the additives exhibit higher surface activity, which should result in higher stability of the lubricant film being produced as a result of the formation of the surface phase.

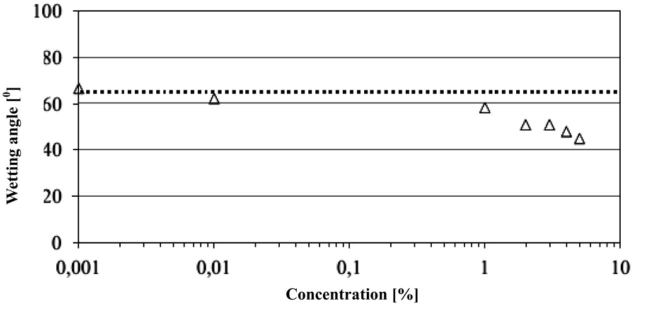

Fig. 2. Dependence of wetting angle on concentration of sodium lauroyl sarcosinate (SLS) in 1% aqueous solution of polyvinylpyrrolidone with a polymerization degree of 90 (PVP90). Dotted line – value of wetting angle for 1% aqueous solution of PVP90 is 66.7°. Value of wetting angle for water is about 89°

Wetting angle (Θ) of a steel surface was determined using the sitting drop method. The measuring unit used consisted of a microscope, a camera and a computer with a MultiScanBase system for visualization and image processing. The measurements were carried out at 25°C. Fig. 2 shows the dependence of wetting angle on SLS concentration.

A measured wetting angle (θ) is a measure of wettability. An increase in the value of wetting angle corresponds to a drop in wettability, while a decrease in the value of wetting angle corresponds to an increase in wettability. The wetting angle of a bearing steel surface for water is 89° and for 1% aqueous solutions of polyethylene glycols (PEG) equals 81° (PEG-4), 81° (PEG-100) and 80° (PEG-180). The wetting angle decreases with an increase in SLS concentration and its values are in the 45–50° range (Fig. 2a). In the case of 1% aqueous solutions of polyvinylpyrrolidones (PVP), the wetting angle values were 67° (PVP_90), 69° (PVP_450) and 69° (PVP_14400). The wetting angle decreases to 25–30° with an increase in concentration of SLS (Fig. 2).

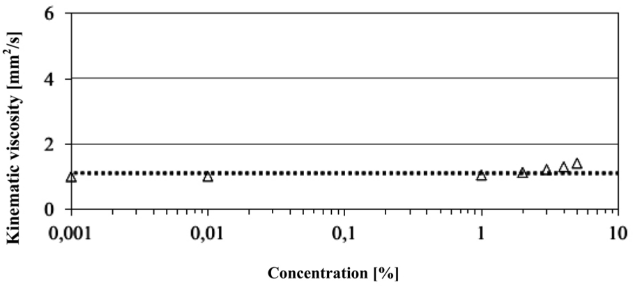

Fig. 3. Dependence of kinematic viscosity on concentration of sodium lauroyl sarcosinate (SLS) in 1% aqueous solution of polyvinylpyrrolidone with a polymerization degree of 90 (PVP90). Dotted line – value of kinematic viscosity of 1% aqueous solution of PVP90 is 0.99 mm^2/s. Kinematic viscosity value for water – 1 mm^2/s

Kinematic viscosity (ν) was determined according to the PN-81/C-04011 standard using an Ubbelohde capillary viscometer. The measurement consists in determining the time of flow of a given volume of the fluid tested through a viscometer capillary under the influence of gravity forces at 25°C. The dependence of viscosity on SLS concentration is presented in Fig. 3.

While analysing the results for solutions of the polymer with the surfactant, it can be said that an addition of an anionic surface-active compound affects the kinematic viscosity value to a small degree within the concentration range used (Fig. 3).

Foamability: The assessment of foamability and foam stability was carried out according to the PN-C-04055:1985 standard. The method consists in measuring the volume of foam produced when the air flows through a given volume of fluid. 190 ml of fluid was placed in a clean measuring cylinder

(1000 ml) wetted with the fluid studied. The fluid satisfies the standard requirements if the volume of foam does not exceed 300 cm^3 directly after formation and 10 cm^3 after 10 minutes.

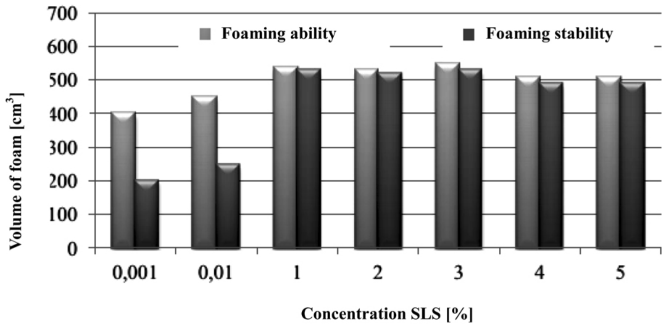

Fig. 4. The effect of concentration of sodium lauroyl sarcosinate (SLS) on foamability of 1% aqueous solution of polyvinylpyrrolidone with a polymerization degree of 90 (PVP90)

Figure 4 shows examples of the results of foamability tests for representative solutions of polymers with anionic surfactants.

Corrosion was assessed according to the PN-92/M-55789 standard (Ford Test). The method consists in the test fluid reacting with cast iron turnings placed on a Petri dish. The test lasts two hours. The test result is given in the form: F3/ 4, where F3 -symbol of FORD-TEST, 4- degree of corrosion according to the Table 1.

Table 1. Point estimation of degree of corrosion according to the PN-92/M-55789 standard

Degree of corrosion	Descriptive term	Stained surface [%]
0	no corrosion	no traces of corrosion
1	traces of corrosion	max. 3 corrosion stains up to 1 mm in diameter
2	light corrosion	not more than 1%, but stains are larger than for 1
3	moderate corrosion	above 1% up to 5%
4	significant corrosion	above 5% up to 20 %
5	heavy corrosion	above 20% up to 50%
6	very heavy corrosion	above 50%

The cutting fluids used in field tests did not cause corrosion (F3/0).

1.3. Results of tribological studies

Two types of tests were carried out – at a constant load and at a linearly increasing load using a four-ball machine (Tester T-02) produced at the Institute of Sustainable Technology in Radom (the device conforms to PN-76/C-04147).

Tests at a constant load: The measurements were carried out in order to determine resistance to motion and wear for individual kinds of fluids. The load was 4 kN. The test duration was 900 seconds, and the rotational speed was 200 rpm. The coefficient of friction (μ) was calculated based on measurements of the moment of friction force (M_T). Wear scar diameter (d) after the test was a measure of wear. The results of measurements of coefficients of friction and wear scar diameter are given in Figs 5a and 5b.

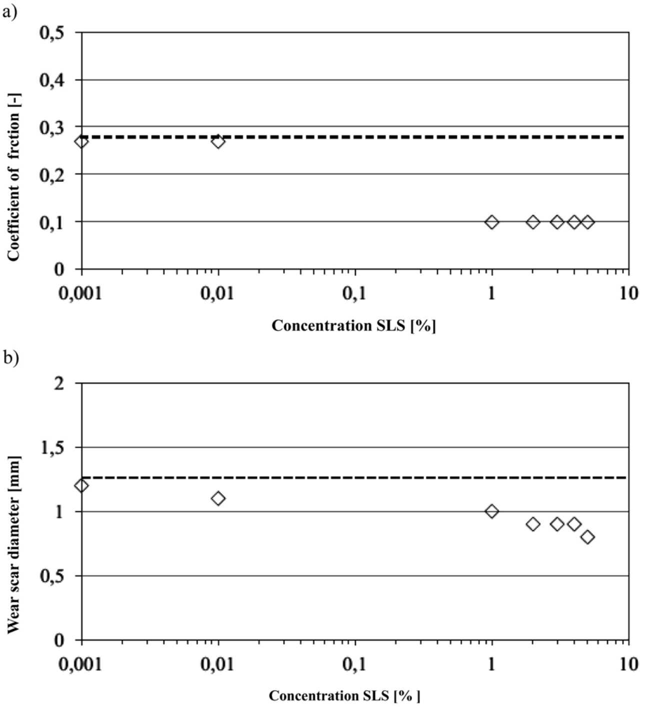

Fig. 5. Dependence of coefficient of friction (a) and wear scar diameter (b) on concentration of sodium lauroyl sarcosinate (SLS) in 1% aqueous solution of polyvinylpyrrolidone with a polymerization degree of 90 (PVP90).Values of coefficient of friction and wear scar diameter for 1% aqueous solution of PVP90 equal 0.29 and 1.3 mm, respectively (dashed line). Values of coefficient of friction and wear scar diameter for water are, respectively, 0.47 and 1.8 mm. Tribological test at constant load, T-02 apparatus, rotational speed of spindle 200 rpm, test duration 900 s, and load 2kN

The analysis of the results points to an important effect of anionic surfactants on the tribological properties of aqueous solutions of the polymer. A threefold decrease in the value of the coefficient of friction was observed in comparison with the values obtained for 1% solutions of PVP without any anionic surfactant.

Seizure tests were carried out at a linearly increasing (409 N/s) load, a load range from 0 to 7.2 kN, and the rotational speed of the spindle of 500 rpm.

The following quantities were determined [11, 12]:

- Seizing load (P_t) – the pressure above which there occurs a rupture of boundary layer manifesting itself in a sudden increment in the moment of friction forces (Fig. 6),
- Seizure load (P_{oz}) – the load at which the moment of friction force (M_T) increased to above 10 N·m (Fig. 7), and
- Limiting pressure of seizure (p_{oz}) (Fig. 8).

Additionally, measurements were made of wear scar diameter parallel and perpendicular to the direction of sliding. The d value was an average of the two measurements. A reflection microscope Polar produced by PZO-Warszawa (Poland) was used.

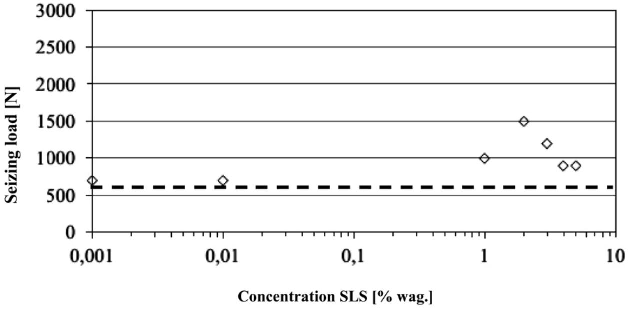

Fig. 6. Dependence of seizing load on the concentration of sodium lauroyl sarcosinate (SLS) in 1% aqueous solution of polyvinylpyrrolidone with a polymerization degree of 90 (PVP90). Dashed line – value of seizing load for 1% aqueous solution of PVP90 is 600 N. Value of seizing load for water is 200 N. Tribological test, load increment 409 N/s, test duration 18 s, and rotational speed of spindle 500 rpm

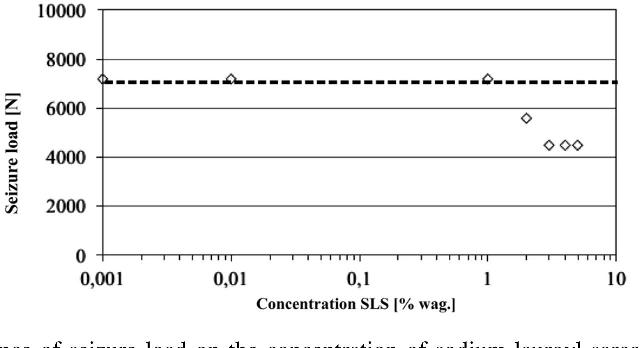

Fig. 7. Dependence of seizure load on the concentration of sodium lauroyl sarcosinate (SLS) in 1% aqueous solution of polyvinylpyrrolidone with a polymerization degree of 90 (PVP90). Dashed line – value of seizure load for 1% aqueous solution of PVP_90 is 7200 N. Value of seizure load for water is 4000 N. Tribological test, load increment 409 N/s, test duration 18 s, and rotational speed of spindle 500 rpm

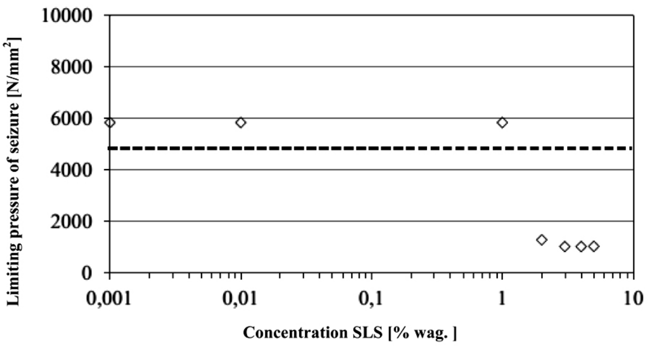

Fig. 8. Dependence of limiting pressure of seizure on the concentration of sodium lauroyl sarcosinate (SLS) in 1% aqueous solution of polyvinylpyrrolidone with a polymerization degree of 90 (PVP90). Dashed line – value of limiting pressure of seizure for 1% aqueous solution of PVP_90 is 4620 N/mm^2. Value of limiting pressure of seizure for water is 200 N/mm^2. Tribological test, load increment 409 N/s, test duration 18 s, and rotational speed of spindle 500 rpm

The results shown are representative for the other solutions, and they indicate that adding an anionic surface-active compound to a solution brings about a significant improvement in tribological properties.

1.4 Bench and field tests

As a result of the studies on physicochemical and tribological properties, formulations of stable, non-foaming solutions (foamability and foam stability equalled zero) were developed. They did not cause corrosion (F3/0), and their viscosity was comparable with water. The solutions underwent bench and field-testing.

Bench tests

Bench tests were carried out at The Institute of Advanced Manufacturing Technologies (formerly The Institute of Metal Cutting).

- *Tool life of cutting tools made of sintered carbides used for straight turning of standard steel C45:* Tool life of cutting tools of sintered carbides used for straight turning of standard steel C45 was tested on a machine tool. The stock was constructional carbon steel of higher quality C45 according to PN – EN 10083 – 8: 2008 in the standard state in the form of rollers with an initial diameter of _k. Φ180 mm and a length of _k. 600 mm and hardness of 167-179 HB. The reference fluid was a Castrol Hysol R coolant.
- *Tool life and cutting resistance by means of a WBS device:* A comparative method was used to assess machining properties of materials. It was based

on reboring at a constant feeding force. Indicators of machining properties of materials relative to the intensity of blunting of the cutting tool and cutting resistance were determined on a special test bench WBS. The machined material was constructional carbon steel of higher quality C45 (PN – EN 10083 – 2: 2008) in the standard state and hardness HB 174 ± 7. The cutting tool material was high-speed steel HS6 – 5 – 2 according to PN – EN 750 4957: 2004 with hardness HRC 64± 0.5.

Field tests in enterprises

Field tests were carried out in the P.P.H. RADMOT Jan Stańczyk Company and in Radom Arms Factory "Łucznik" LLC.

P.P.H. RADMOT Jan Stańczyk: The fluids were tested on an automatic SPRINT 65 Linear lathe used for machining bars. The lathe is used to produce medium to highly complex parts. The parts were made under production conditions in a continuous way. The reference fluid was a Castrol coolant.

Radom Arms Factory "Łucznik" LLC: The tests were carried out on four-numeric milling centres BROTHER and AVIA and on a WAGNER numerical lathe during regular production of parts of small arms. The fluid was tested during 120 hours on machines processing carbon steel and aluminium. The cutting tools used were of the WIDIA monolithic type, coated and non-coated, and multi-point cutting tools with replaceable tools.

2. Summary

Based on the field tests, the following results can be listed:

- All of the fluids showed good cooling and lubricating properties. No differences were observed in comparison to commercial cutting fluids, such as Castrol, Blaser, or Cimcool.
- Neither excessive tool wear nor a worse quality of element surfaces after machining were observed.
- No corrosion occurred on element surfaces and machine tool elements.
- There occurred a phenomenon of stickiness of elements of the machining centre and an impression of stickiness of the cutting fluid, but those can be eliminated by reducing the concentration of an active substance in the composition of the model fluid.

Based on the bench and field tests as well as physicochemical studies, it can be said that the cutting fluids developed satisfy the required assessment criteria allowing for the assumed applications.

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Ekologiczne ciecze obróbkowe

Słowa kluczowe

Ciecze obróbkowe, wodne roztwory surfaktantów, tribologiczne i eksploatacyjne właściwości.

Streszczenie

Stosowane w praktyce przemysłowej ciecze obróbkowe występują w formie emulsji i mikroemulsji typu o/w. Stanowią one zagrożenie dla środowiska naturalnego oraz ludzi na stanowiskach pracy. W przedstawionym artykule zaprezentowano nowy rodzaj bezpiecznych w stosowaniu cieczy chłodząco--smarujących. Są nimi wodne roztwory aktywne powierzchniowo. Dla zoptymalizowanych składów cieczy obróbkowych przeprowadzono badania fizykochemiczne, tribologiczne oraz eksploatacyjne. Ciecz obróbkowa o zoptymalizowanym składzie ma porównywalne a nawet korzystniejsze właściwości fizykochemiczne i użytkowe w porównaniu z ich najlepszymi odpowiednikami rynkowymi.