



Article

The Method of Cleaning Cutting Fluid Using Ultrasonic Treatment

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Abstract

Cutting fluids are widely used in mechanical engineering to reduce friction and heat generation during metal machining. However, during operation, these fluids become contaminated with metal particles, dust, and microorganisms, leading to degradation of their functional properties and environmental concerns. This study investigates the ultrasonic cleaning and regeneration of contaminated cutting fluids. A rheological model of the elastic–viscous medium was analyzed, and a physical model describing the ultrasonic cleaning mechanism was proposed. Experimental investigations were conducted to validate the theoretical assumptions. The results confirmed that ultrasonic treatment promotes dispersion and phase separation of the fluid, removes putrefactive odor, and partially destroys microorganisms. The regenerated fluid exhibited enhanced clarity and stability compared with the contaminated samples. The findings contribute to a deeper understanding of the physicochemical processes occurring during ultrasonic treatment and demonstrate the potential of this method for sustainable reuse of cutting fluids in industrial applications.

Keywords: mechanical engineering; cutting fluid in mechanical engineering; viscoelastic-plastic medium; cavitation; coagulation; cleaning efficiency; ultrasonic cleaning; metalworking fluids regeneration; ultrasonic-assisted cleaning; mechanics of materials and fluids



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1. Introduction

Cutting fluids play a crucial role in mechanical engineering, particularly in metal machining processes [1–3]. The primary purpose of using cutting fluid is to reduce friction between the workpiece and the cutting tool, thereby minimizing deformation of the workpiece during processing, increasing the service life of the cutting tool, and ultimately enhancing productivity in metalworking [4–12].

Depending on the machining method and intended application, metalworking fluids can be classified as follows:

- Water-miscible and water-immiscible cutting fluids;
- Emulsifiers and oil-based fluids for lubrication and cooling;
- Synthetic, semi-synthetic, and fast-evaporating formulations [1,13–15].

At present, new types of metalworking fluids [16] based on biodegradable materials [17–23] are being developed; however, they have not gained widespread use due to their high production cost.

The machining process is accompanied by the formation of various contaminants, including oil mist, fine aerosols, vapors, smoke, unpleasant and harmful odors, metal dust, and shavings. The service life of cutting fluid solutions typically ranges from 2 weeks to 3–6 months. After this period, if the cutting fluid (emulsion) is not subjected to proper treatment or regeneration during operation, it is discarded and sent for decontamination and disposal using expensive technologies. Therefore, the ability to monitor the physicochemical state of cutting fluids during operation plays a crucial role in determining the optimal regeneration interval and preventing premature disposal. Moreover, recent studies have demonstrated that sensor-based monitoring of metalworking fluid properties enables timely diagnostics of contamination and degradation under industrial conditions [24]. In the context of increasing environmental concerns, the disposal of cutting fluids poses a significant global problem [25–31]. As a result, each production cycle requires additional portions of concentrate and substantial volumes of fresh water.

Mineral and synthetic oils that leak from machine mechanisms (including hydraulic devices) and lubricating systems enter the cutting fluid during operation. Their prolonged presence disrupts the original chemical composition of the emulsion and degrades its operational and technological properties, rendering it unsuitable for further use.

When oils from machine tool guide rails are washed into the cutting zone and the machines lack effective oil-skimmer devices, almost all types of cutting fluids and emulsions become hazardous, oil-containing industrial waste. The installation of oil skimmers partially mitigates but does not completely solve the issues associated with cutting fluid cleaning.

Furthermore, extraneous oils and petroleum products that enter the cutting fluid provide an excellent medium for bacterial and microbial growth, leading to rapid biodeterioration and putrefaction [32–37]. Consequently, contaminated cutting fluid poses health risks to workers [38–44].

Numerous methods have been developed for cleaning metalworking fluids, including flotation, filtration, purification in force fields, and other modern techniques.

Traditional cleaning methods for metalworking fluids—such as filtration, flotation, sedimentation, and centrifugation—are widely used in industry. However, these approaches have several drawbacks. Filtration systems demonstrate high cleaning accuracy but require frequent replacement of filters and generate secondary waste, leading to increased operating costs [45,46]. Flotation and sedimentation methods are cost-effective but exhibit limited cleaning precision and are often ineffective for removing fine particles ($<10\ \mu\text{m}$) and oil microdroplets in stable oil-in-water emulsions [46–49]. Centrifugal and related separation technologies can provide higher throughput, but they are frequently associated with higher energy consumption and more complex equipment design [45,46].

In addition to traditional physical separation techniques, several studies have explored alternative regeneration strategies for spent cutting fluids, including freeze–thaw pretreatment, suspension crystallization, electrocoagulation, and catalytic oxidation, which significantly improve oil recovery and pollutant degradation efficiency [50–53].

In contrast, ultrasonic cleaning combines cavitation-induced microstreaming, dispersion, and coagulation effects that promote particle detachment and emulsion breakdown without added chemicals or disposable filter media [54–56]. Prior studies report that ultrasonic fields can disrupt oil films, facilitate droplet coalescence/demulsification, and suppress microbial activity in aqueous systems, thereby improving fluid quality and stability [54–56]. Nevertheless, most existing works focus on water-based emulsions and general wastewater treatment; systematic studies that link ultrasonic parameters to cleanliness metrics of cutting fluids and their rheological behavior remain limited, motivating the present study.

Metalworking fluids (MWFs) represent complex non-Newtonian systems with shear-dependent viscosity and viscoplastic behavior resulting from the presence of emulsifiers, polymers, and solid contaminants. When exposed to ultrasonic fields, their rheological parameters—such as yield stress, apparent viscosity, and flow index—can be substantially modified.

Experimental evidence indicates that acoustic cavitation and microstreaming in viscoplastic media reduce structural viscosity and promote the disintegration of particle aggregates [57–61]. Studies on concentrated suspensions have shown a pronounced decrease in yield stress under ultrasonic excitation, confirming that ultrasound enhances microstructural rearrangement and flowability in dense media [57]. Similar reductions in apparent viscosity (by approximately 25–40%) were reported for polymeric and clay-based suspensions treated within the 20–40 kHz frequency range, which is attributed to cavitation-induced shear thinning [58,59]. In addition, the ultrasonic field facilitates the migration and separation of suspended impurities via acoustic radiation forces, enabling selective particle segregation even in high-viscosity systems [60].

These effects are particularly relevant for MWFs exhibiting thixotropic and viscoplastic properties. Therefore, ultrasonic agitation not only accelerates contaminant detachment from droplets and metallic chips but also modifies the overall flow behavior and sedimentation dynamics of the fluid, improving both the cleaning efficiency and rheological stability.

Conventional regeneration methods—such as filtration, flotation, sedimentation, and coalescence—are limited in efficiency when dealing with submicron impurities, require higher energy input, and often cause degradation of additives. The comparative performance of these techniques is summarized below (Table 1) [62–64].

Table 1. Comparative characteristics of conventional and ultrasonic cleaning methods for metalworking fluids.

Method	Typical Efficiency, %	Energy Consumption	Limitations
Sedimentation	60–70	Low	Long cycle time; ineffective for fine particles
Filtration (membrane)	80–90	Medium	Membrane fouling; high replacement cost
Flotation	75–85	High	Bubble coalescence; limited performance in viscous fluids
Centrifugation	85–90	Very high	High energy demand; expensive equipment
Ultrasonic cleaning	90–98	Low–medium	Effective for submicron particles; enhances rheological stability

Ultrasonic treatment demonstrates comparable or superior cleaning efficiency while maintaining lower specific energy consumption. The synergistic action of cavitation, acoustic radiation, and microstreaming provides distinct rheological benefits—temporary viscosity reduction and improved phase separation—not achievable by mechanical methods alone. Consequently, ultrasonic cleaning effectively integrates rheological modification with particle removal, confirming the novelty of establishing a correlation between ultrasonic parameters and the cleanliness of metalworking fluids.

Therefore, the present research addresses this gap by experimentally validating the relationship between ultrasonic parameters and cutting fluid cleanliness, supported by rheological modeling and quantitative evaluation of density and refractive index changes.

The selection of a cleaning method is based on regeneration efficiency indicators. The main indicators include impurity concentration, capacity, degree and fineness of cleaning, separation coefficients, average particle size of impurities, biostability, power consumption, and economic performance. In some cases, the extracted oil and petroleum products can be reused in other technological processes, improving the overall economic efficiency of regeneration.

The introduction of more efficient methods for cleaning cutting fluids is of great importance, as these fluids are used in all machine-building industries. Currently, ultrasonic cleaning is widely applied in various fields and is recognized for its high efficiency, primarily due to cavitation and coagulation effects [65,66].

The present research is based on the hypothesis that ultrasonic treatment can effectively clean contaminated cutting fluids. The scientific novelty lies in the experimental confirmation of the relationship between ultrasonic parameters and the degree of cutting fluid purity.

2. Materials and Methods

The cutting fluid, at rest prior to ultrasonic treatment, represents a viscoplastic dispersed medium composed of oil, water, and suspended metal and dust particles. It is also saturated with air. The viscoplastic structure arises from the Brownian motion of oil molecules and interparticle force fields within the dispersion. These interactions cause mutual attraction between particles, resulting in the formation of a viscous mass at rest—a gel-like structure [67]. Such a configuration is a common type of dispersed system. The metal and debris particles embedded within it are held in equilibrium by the surrounding oil. In the absence of external influence, this structure remains stable. However, when subjected to high-intensity external forces, the bonds between particles are destroyed.

The absence of external effects allows the formation of new interparticle bonds over time. This time interval is referred to as the relaxation period. This property, known as thixotropy, refers to the reversible decrease in viscosity under mechanical stress [67].

When energy is transferred to a viscoplastic medium, four flow regimes can be distinguished:

- Shvedov flow regime—a flow mode characterized by a nearly intact internal structure, observed at very low flow velocities of only a few centimeters per second. In this regime, the medium exhibits an effective Newtonian viscosity (η_{eff});
- Bingham flow regime—a flow mode characterized by a continuously breaking internal structure, occurring at flow velocities of approximately 1.25 m/s. In this regime, the concept of structural viscosity (η) is introduced.
- Pseudo-laminar flow regime—a regime in which the internal structure of the fluid is almost completely disrupted, observed at flow velocities of about 1.5 m/s. Under these conditions, the fluid exhibits a dynamic viscosity (μ);
- Turbulent flow regime—observed at comparatively high flow velocities (greater than 2 m/s), where intense fluid mixing occurs, resulting in the manifestation of apparent viscosity (μ_{app});

The rheological behavior of viscoplastic media is most accurately described by the Shvedov–Bingham equation [68,69]:

$$\tau = \tau_0 \pm \frac{dV}{dh} \mu \quad (1)$$

where τ and τ_0 are the shear stress and yield shear stress, respectively; $\frac{dV}{dh}$ is the velocity gradient of the solution flow; dV is the mixing velocity limit between two layers of the solution; dh is the distance between layers; μ is the dynamic viscosity.

For the viscous flow of a thixotropic solution (Bingham and pseudolaminar regimes), the differential equations of a continuous medium flow in Cauchy's form are valid [70,71]:

$$\rho_c \frac{\vec{dV}}{dt} = \vec{K} + \vec{P}, \quad (2)$$

where ρ_c is the solution density; $\frac{\vec{dV}}{dt}$ is the material derivative of the medium's velocity vector; $\vec{P}$ is the vector of surface (stress) forces per unit volume; $\vec{K}$ is the vector of body (mass) forces per unit volume.

When energy is applied to the cutting fluid, it is transmitted through the conversion of ultrasonic forces into frictional forces, caused by the generation of viscous stresses within the medium. For Bingham flow, the following relationship (1) holds true. For pseudolaminar flow, the frictional stress is determined by the second term of this relationship.

In the turbulent flow regime of a clay-like slurry, to determine the total frictional stress, an additional pulsation stress must be added to the primary viscous friction, as described by Newton's law.

Before proceeding to the general formulation, it is important to note that the rheological behavior of viscoplastic media such as cutting fluids can be effectively described by the classical Shvedov–Bingham model. This model has been widely applied to characterize the flow of non-Newtonian fluids exhibiting a yield stress, including clays, slurries, and metalworking fluids, and serves as the theoretical basis for describing shear stress–strain rate relationships in such systems [66,69].

$$\tau = \mu \frac{dV}{dh} + \rho_c l^2 \left(\frac{dV}{dh} \right)^2, \quad (3)$$

where l is the average mixing path length.

Equation (3) is general for determining the frictional stress in both laminar and turbulent flow regimes of the solution. In laminar flow, the influence of pulsation velocity is negligible, and therefore the first term of the equation predominates.

The physics of the transition process from one flow regime to another depends on the amount of energy transferred to the solution. With a gradual increase in the supplied energy, the transition occurs smoothly, whereas with a rapid increase, the change takes place exponentially. In our view, the ratio of the solution mass to the magnitude of the transferred energy plays a crucial role. Another significant factor is the method of energy application. For instance, mechanical stirring is less effective than ultrasonic or thermal treatment.

In this study, when a substantial amount of energy was transferred to the solution, turbulent flow rapidly developed, leading to cavitation accompanied by the release of air bubbles. This phenomenon promotes coagulation as a result of increased Brownian motion. Simultaneously, part of the energy is dissipated as heat, resulting in a temperature rise.

A secondary effect of ultrasonic treatment of the cutting fluid is the reduction in bacterial contamination.

The criteria for evaluating the effectiveness of the process include a decrease in the density of the contaminated cutting fluid and the restoration of normal operating conditions in the treated medium.

During the experimental planning stage, the dependencies of this criterion on several parameters were determined, including the ultrasonic energy transferred to the solution, treatment time, container volume, and the material of the container.

To ensure effective processing, the amount of energy transferred to the solution must exceed the breakdown threshold energy. Knowing the frequency of the ultrasonic generator makes it possible to determine the amount of energy transferred to the fluid as a function of time (t).

$$E = N \times t \quad (4)$$

where N is the power of the ultrasonic generator; t is the treatment time.

However, in order to estimate the critical amount of energy, it is necessary to take into account the mass of the solution:

$$E_{crit} = \frac{E}{V} = \frac{N \times t}{V} \quad (5)$$

Dimensions of the obtained quantity:

$$\tau_{crit} = \left[\frac{W \cdot s}{m^3} \right] = \frac{N}{m^2} \quad (6)$$

We will refer to this quantity as the critical stress, which indicates that it characterizes the shear stress and must exceed the yield stress (τ_0).

$$\tau_{crit} > \tau_0 \quad (7)$$

The rheological behavior of contaminated metalworking fluids is governed by viscoplastic characteristics, where the fluid resists flow until a certain yield stress is exceeded. To describe this behavior, the Shvedov–Bingham model was adopted because it provides a linear relationship between shear stress and shear rate above the yield point, offering a physically meaningful and experimentally convenient representation for emulsions with distinct yield stress [57–59].

This model was preferred over Casson or Herschel–Bulkley formulations, as it simplifies parameter identification and ensures stable regression fitting when applied to experimental flow curves of MWFs. The yield stress (τ_0) and plastic viscosity (μ) were obtained by fitting the experimental shear stress–shear rate data using the least-squares method. This approach is widely validated for describing the flow of emulsions and suspensions with low-to-moderate yield stress values [58,59].

The combination of ultrasonic treatment and rheological modeling provides a comprehensive framework for understanding how acoustic energy influences the microstructure, apparent viscosity, and cleaning efficiency of non-Newtonian cutting fluids.

The experimental design is summarized in Table 2. The matrix was constructed as a partial factorial plan encompassing a representative combination of ultrasonic frequency, container material, and fluid volume. Not all possible combinations were implemented due to thermal instability and nonlinear cavitation behavior observed under certain conditions. Empty cells in Table 2 correspond to trials that were not conducted or deemed physically irrelevant.

The experiment was carried out as follows:

1. Ultrasonic treatment was applied to cutting fluids placed in containers with volumes of 1, 3, and 5 L. The treatment was performed at frequencies of 25, 28, and 40 kHz, with an ultrasonic power of 100 W and a treatment duration of 5 min. Each experiment was repeated three times ($n = 3$) to ensure reproducibility. All measured values are reported as mean $\pm$ standard deviation. The temperature of the cutting fluid during ultrasonic exposure was continuously monitored and ranged from 23 °C to 35 °C, depending on the frequency and container material.

2. Samples were collected by extracting equal fluid volumes from the upper and lower layers of each container.
3. The refractive index of the cutting fluid in the container was measured using a refractometer.
4. The mass of the fluid samples was determined using precision weighing.
5. The treated fluid was then left undisturbed for 24 h, after which the measurements were repeated under the same conditions.

Table 2. The experiment plans.

Container Volume	Container Material	Ultrasonic Generator Frequency								
		25 kHz			28 kHz			40 kHz		
		Clean Cutting Fluid	Medium Contamination	High Contamination	Clean Cutting Fluid	Medium Contamination	High Contamination	Clean Cutting Fluid	Medium Contamination	High Contamination
1000 mL	Plastic container					Measuring Bx, %, t, C				
	Glass container					Measuring Bx, %, t, C				
3000 mL	Plastic container					Measuring Bx, %, t, C				
	Glass container	Measuring Bx, %, t, C	Measuring Bx, %, t, C	Measuring Bx, %, t, C	Measuring Bx, %, t, C	Measuring Bx, %, t, C	Measuring Bx, %, t, C	Measuring Bx, %, t, C	Measuring Bx, %, t, C	Measuring Bx, %, t, C
5000 mL	Plastic container					Measuring Bx, %, t, C				
	Glass container					Measuring Bx, %, t, C				

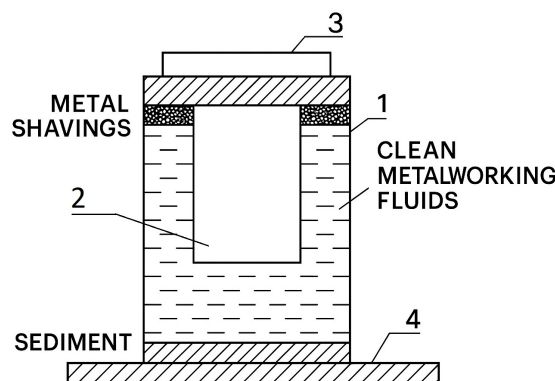
The experiment was performed in containers made of different materials—glass and plastic—and with cutting fluids of varying contamination levels (clean, medium, and highly contaminated). Depending on the material of the container and the initial contamination level of the fluid, different experimental data were obtained.

In glass containers, ultrasonic treatment caused greater reductions in density ($\Delta\rho$) and refractive index (ΔBx) than in plastic containers, which is attributed to higher acoustic reflectivity and more intense cavitation.

An experimental setup was developed to carry out the ultrasonic treatment (Figure 1). The setup consists of a transparent container (1), an ultrasonic emitter (2), a generator (3), and an ultrasonic wave reflector (4). Transparent polypropylene containers with high chemical resistance and glass containers were used as the housing. The ultrasonic wave emitter (Figure 2) was mounted at the top of the housing and connected to the ultrasonic vibration generator (Figure 2a). The heating process of the metalworking fluid was monitored using a thermal imager (model UTi260B) (Figures 3 and 4c).

The experiments were carried out using an ultrasonic generator (model Granbo DG2-J100 DIY Accessories for Ultrasonic Cleaner, China) with a nominal power of 100 W, operating at an ultrasonic frequency of 40 kHz and a drive board transducer kit rated at 100 W. The ultrasonic transducer probe (model JP-100T) was selected with a working frequency range of 25–40 kHz and available power variants of 50 W, 60 W, 100 W and 120 W; this model exhibits high electro-acoustic conversion efficiency and output amplitude suitable for industrial cleaning applications. The emitter was mounted at the top-centre of

the container, with a vertical insertion depth of approximately 15–20 mm from the vessel bottom, to ensure a uniform acoustic field throughout the volume.



1—Transparent container, 2—Ultrasonic emitter, 3—Generator, 4—Ultrasonic wave reflector.

Figure 1. Diagram of the experimental setup for ultrasonic cleaning of cutting fluid.

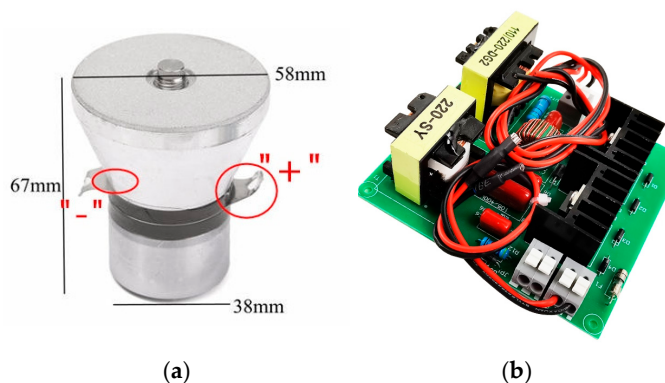


Figure 2. Ultrasonic wave emitter. (a) Ultrasonic generator. (b) Ultrasonic transducer.



Figure 3. Thermal imager.

The cutting fluid used in this study was a commercially available soluble metalworking fluid UNISOL EP 2. According to the manufacturer's technical data sheet, UNISOL EP 2 is a mineral-oil-based water-miscible emulsion containing a balanced system of anionic/non-ionic emulsifiers, corrosion inhibitors, antifoam and biocidal additives. The concentrate is amber in color, with a density of 0.95 kg/L and a pH of 9.4 for a 3% aqueous solution.

The working emulsion was prepared by diluting the concentrate in tap water to a 5% volume concentration (approximately 1:20 oil–water ratio), which falls within the manufacturer's recommended range of 4–6% for general machining operations. The fluid

is designed for ferrous and non-ferrous metals and is suitable for water hardness between 50 and 350 ppm Ca.

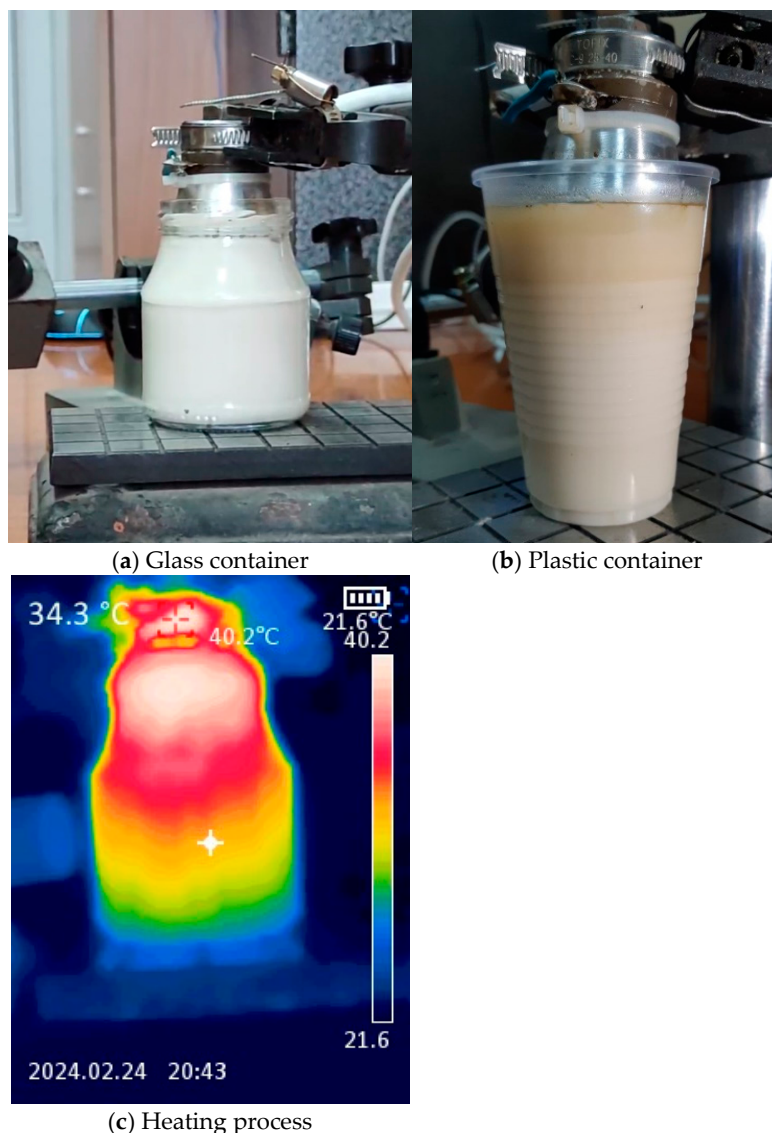


Figure 4. Ultrasonic cleaning.

Cutting fluid samples were collected directly from an operating metalworking facility, where the same type of emulsion was used in multiple machine tools. Three characteristic contamination levels were distinguished based on a combination of physicochemical indicators and visual inspection:

Clean cutting fluid (Sample A): freshly prepared emulsion from the central supply system, transparent, light-colored, with parameters corresponding to the initial state of the fluid.

Moderately contaminated cutting fluid (Sample B): fluid taken after 2–3 weeks of use, showing a slightly darker color and minor suspended metallic particles; optical and density parameters showing moderate deviation from the clean sample.

Highly contaminated cutting fluid (Sample C): fluid after more than one month of operation, dark in color with visible metallic sediment and oil film; parameters indicating the highest degree of contamination. All measured values of refractive index and density for the studied samples are presented in Table 3.

Table 3. Results of the experiment.

Container Volume	Container Material	Ultrasonic Generator Frequency								
		25 kHz			28 kHz			40 kHz		
		Clean Cutting Fluid	Medium Contamination	High Contamination	Clean Cutting Fluid	Medium Contamination	High Contamination	Clean Cutting Fluid	Medium Contamination	High Contamination
1000 mL	Plastic container					Bx = 1.5% t = 30 C $\rho = 1.0058$ g/cm ³				
	Glass container					Bx = 1.1% t = 35C $\rho = 1.004$ g/cm ³				
3000 mL	Plastic container					Bx = 1.6% t = 31C $\rho = 1.0062$ g/cm ³				
	Glass container	Bx = 5.1% t = 23.2 C $\rho = 1.02$ g/cm ³	Bx = 1.1% t = 30C $\rho = 1.004$ g/cm ³	Bx = 0.7% t = 32C $\rho = 1.002$ g/cm ³	Bx = 5.2% t = 23.2C $\rho = 1.0204$ g/cm ³	Bx = 0.7% t = 34C $\rho = 1.002$ g/cm ³	Bx = 0.5% t = 34C $\rho = 1.002$ g/cm ³	Bx = 5.5%, t = 23.2C $\rho = 1.021$ g/cm ³	Bx = 0.4% t = 30C $\rho = 1.0015$ g/cm ³	Bx = 0.1% t = 35C $\rho = 1.004$ g/cm ³
5000 mL	Plastic container					Bx = 1.7% t = 30C $\rho = 1.0066$ g/cm ³				
	Glass container					Bx = 0.7% t = 33C $\rho = 1.0019$ g/cm ³				

The classification was thus based on a combination of operational age, optical and density measurements, and visual characteristics of the samples. These values were verified before ultrasonic treatment and used to quantify the cleaning efficiency.

The experimental methodology involves determining the dependence of density—which characterizes the degree of contamination of the cutting fluid—on time, as well as the dependence of the refractive index of the cutting fluid on time. These parameters were measured at different stages of the process. The experiments were conducted in three stages:

Stage 1 (preparatory): performed without activating the ultrasonic generator;

Stage 2: performed with the ultrasonic generator activated;

Stage 3: performed without activating the ultrasonic generator (a holding period after treatment).

During the preparatory stage, the refractive index, mass, and temperature of the fluid were measured. The cutting fluid was then subjected to ultrasonic treatment for 5 min. Measurements were taken immediately after the treatment was completed, following a 5 min resting period, and repeated again after a 24 h resting period.

Statistical analysis of the obtained data was carried out using a one-way analysis of variance to determine the influence of ultrasonic frequency and container material on cleaning efficiency. The analysis confirmed statistically significant effects ($p < 0.05$) for both factors.

The selection of container volumes (1 L, 3 L, and 5 L) was based on the need to evaluate the influence of the treated fluid volume on the efficiency of ultrasonic cleaning while maintaining a comparable energy density and uniform acoustic field distribution. These volumes correspond to typical laboratory and pilot-scale vessels used for studying ultrasonic processes, ensuring reproducible cavitation conditions across experiments. In

addition, this range reflects the practical reservoir capacities commonly employed in small- and medium-sized machining systems, thereby allowing the obtained results to be extrapolated to real industrial applications.

The ultrasonic power of 100 W was selected according to the specifications of the generator and the parameters that, according to previous studies, provide stable cavitation and effective disruption of emulsified contaminants in aqueous systems [53,54,60–62]. The ultrasonic exposure time was limited to 5 min, as longer treatment led to noticeable heating of the fluid and the onset of boiling, which could distort the cavitation process and affect measurement accuracy.

3. Results

During the experiment, ultrasonic treatment directly affected both the container walls and the cutting fluid itself.

When the cutting fluid was directly exposed to ultrasonic vibrations, small black concretions formed, consisting of metal particles, dust, and other debris (Figure 5).

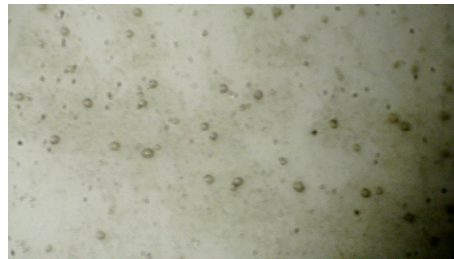


Figure 5. Cavitation.

When ultrasonic waves interacted with the container walls, air bubbles were generated near the surface, capturing a greater amount of metal and debris compared with the previous test (Figure 6). These bubbles ascended toward the center of the container, forming a distinct pattern, and over time, a contaminated layer accumulated at the top of the fluid (Figure 4b).



Figure 6. Coagulation.

The degree of cleaning was determined by the parameter ρ_c . The obtained results made it possible to propose a hypothesis concerning the physical nature of the process under study. Formally, this process is described by Equation (3). When energy is transferred to the cutting fluid, the value of the first term in Equation (3), $\frac{dV}{dh}\mu$, increases.

This occurs because the dynamic viscosity (μ) rises, transitioning into what is known as the apparent viscosity—having a higher magnitude but a slightly different physical interpretation [67]. The derivative $\frac{dV}{dh}$ also increases as a result of the growing fluid velocity (V) and the decreasing thickness of its layers (h). The second term in Equation (3) increases even more significantly due to the quadratic dependence on $\frac{dV}{dh}$.

As a result, the frictional forces within the cutting fluid increase sharply, as represented by the shear stress value τ . This leads to a rapid breakdown of intermolecular bonds within the fluid, particularly at the fluid–metal interface. Consequently, the protective layer surrounding the metal particles is disrupted (Figure 7).

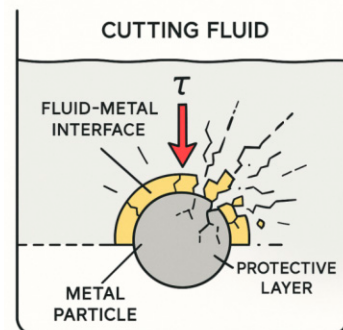


Figure 7. The disruption of intermolecular bonds within the fluid at the fluid–metal interface.

Air released as a result of cavitation occupies the protective layer because a low-pressure zone is formed in that region. The resulting bubble has a lower density than the cutting fluid, causing it to rise toward the surface. The graphs illustrating this process are presented in Figures 8–10. Each experimental condition was repeated three times ($n = 3$). Results are presented as mean $\pm$ standard deviation (SD). Error bars in Figures 8–10 illustrate the data fluctuation range and ensure consistency with statistical representation.

During the experiment, samples of the cutting fluid were collected at various stages to assess the degree of cleaning. All samples were obtained by extracting equal volumes of fluid from the upper and lower sections of the container subjected to ultrasonic treatment.

The primary method used to determine the degree of contamination and cleaning of the cutting fluid was refractometry, performed with a refractometer. Refractometry is a technique for studying substances based on the measurement of the refractive index (coefficient) and its related functions. It is employed to identify chemical compounds, perform quantitative and structural analyses, and determine the physicochemical parameters of substances. The instrument measures the optical properties of fluids using light refraction and provides readings on a scale in degrees Brix ($^{\circ}\text{Bx}$), which indicates the concentration of dissolved solids in the fluid.

The refractometer determines the deviation angle of a light beam from its straight path as it passes from one medium to another. The relationship between the angle of incidence and the angle of refraction at the interface between two media defines the refractive index.

This indicator increases proportionally with the density of the substance. The relative “weight” of the sample is determined by the refractometer in comparison with distilled water, which serves as the calibration standard for the instrument.

As a result of the study, all necessary calculations were carried out. Based on the obtained data, the density of the fluid before and after cleaning was calculated. The density of the cutting fluid prior to treatment was found to be higher than that after treatment. The apparent density of the cutting fluid was indirectly estimated from the measured $^{\circ}\text{Brix}$ values obtained with a refractometer. The conversion between refractive index ($^{\circ}\text{Brix}$) and fluid density was performed according to standard Brix-specific gravity tables (at 20 $^{\circ}\text{C}$), which are commonly used for industrial emulsions and aqueous solutions. This approach enables estimation of the cutting fluid’s concentration and contamination level without direct measurement of its mass or volume. All results are summarized in Table 3.

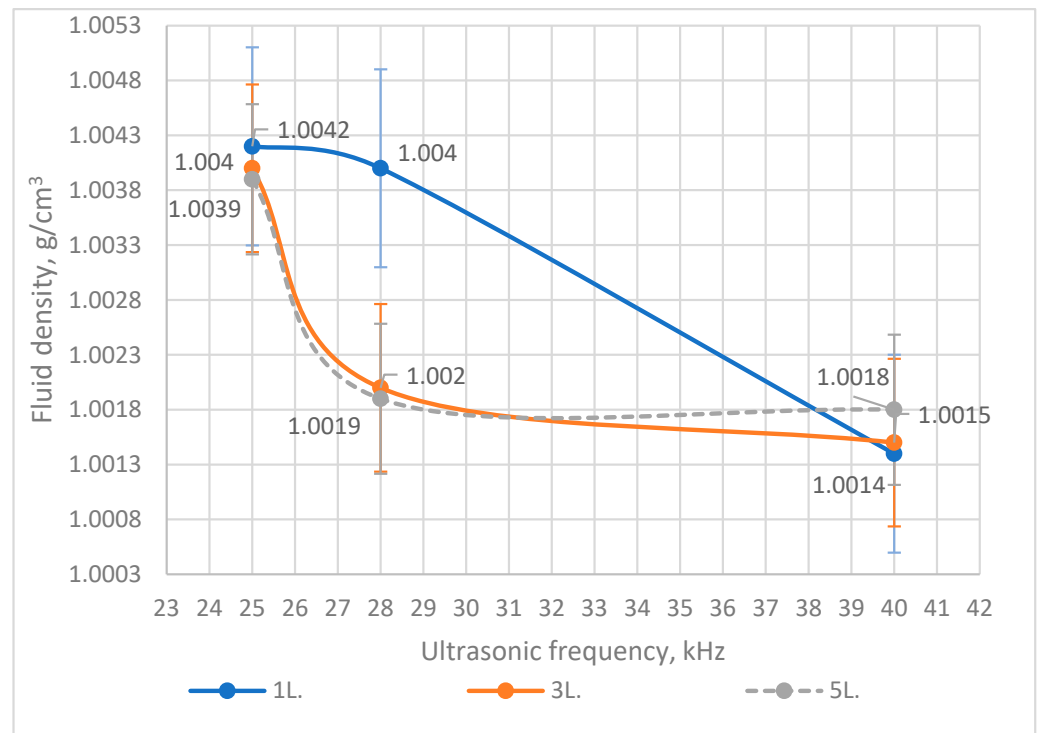


Figure 8. Changes in cutting fluid density depending on ultrasonic frequency and container volume. Error bars represent standard deviation (SD) for $n = 3$ replicate measurements. All data are expressed as mean $\pm$ SD.

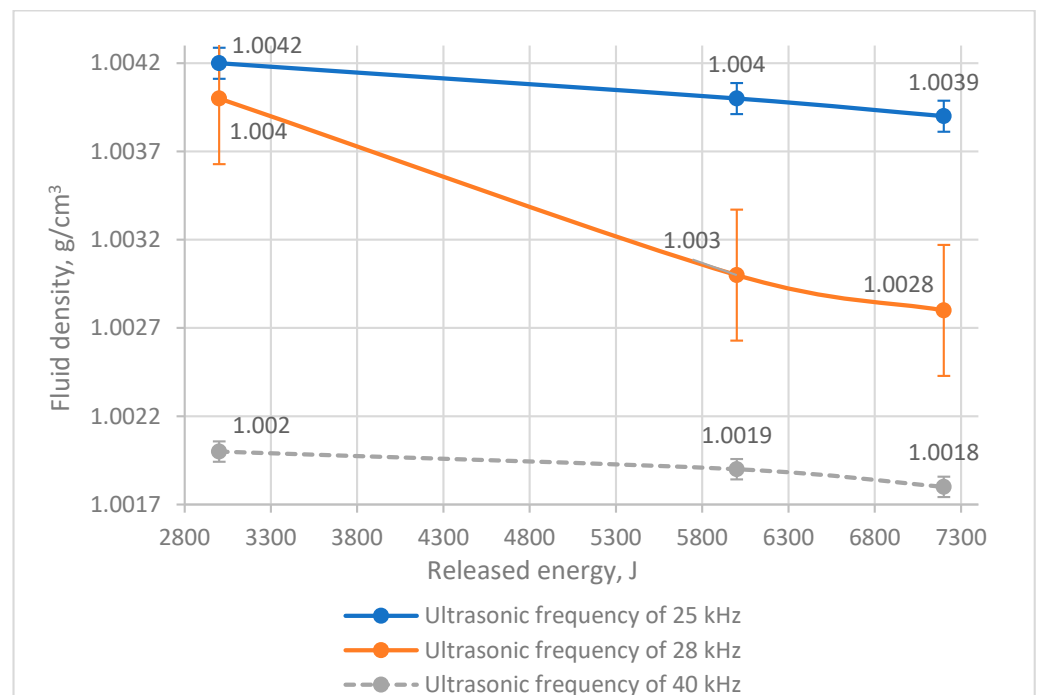


Figure 9. Changes in cutting fluid density depending on the frequency of the ultrasonic generator and the energy released per unit of time. Error bars represent standard deviation (SD) for $n = 3$ replicate measurements. All data are expressed as mean $\pm$ SD.

Based on the obtained data and the calculations performed, it was determined that the density of the fluid before treatment was higher than that after treatment, thereby confirming that ultrasonic treatment of the cutting fluid promotes the cleaning process.

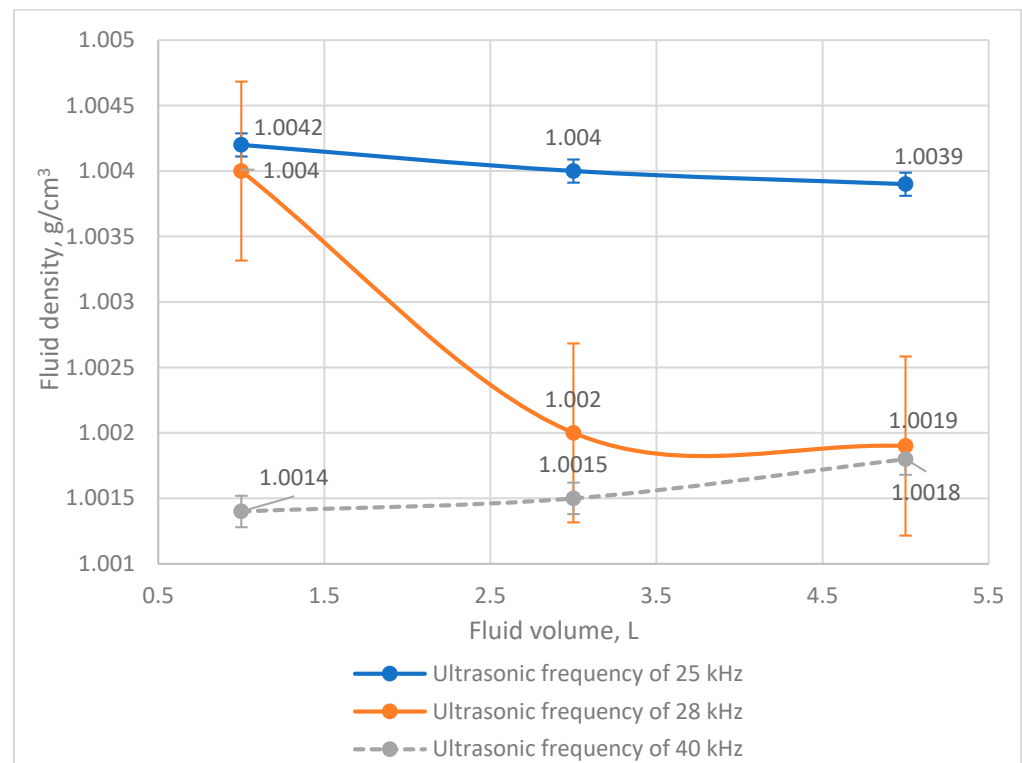


Figure 10. Changes in cutting fluid density under ultrasonic treatment depending on volume. Error bars represent standard deviation (SD) for $n = 3$ replicate measurements. All data are expressed as mean $\pm$ SD.

To identify the optimal operating parameters of ultrasonic treatment, additional analytical curves were constructed (Figures 11–13). These graphs illustrate the effect of ultrasonic frequency, power, and treatment time on the cleaning efficiency of cutting fluids.

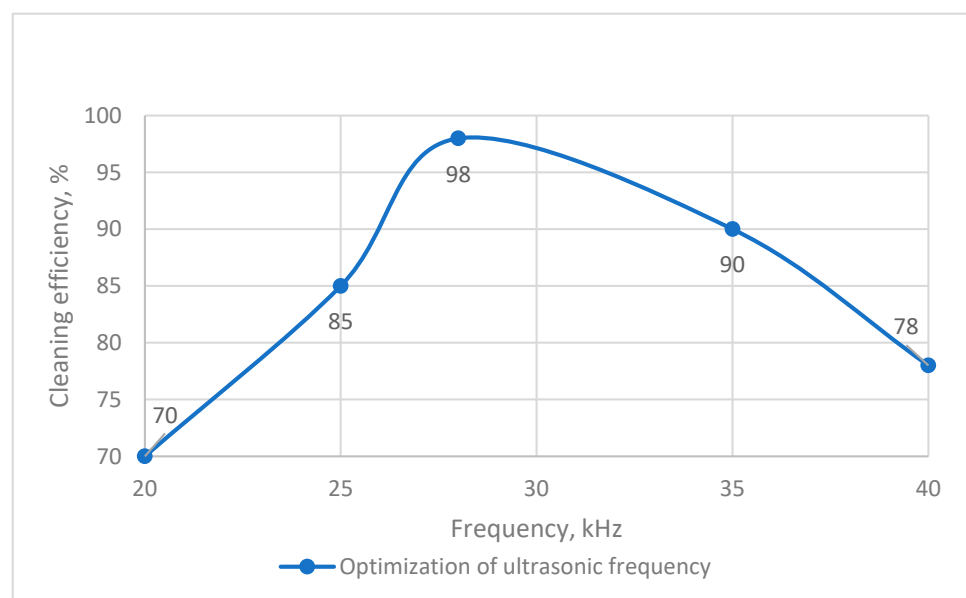


Figure 11. Optimization of ultrasonic frequency.

As shown in Figure 11, the efficiency increased with frequency, reaching a maximum at 28 kHz, beyond which excessive cavitation turbulence caused a slight decline in performance. Figure 12 demonstrates that cleaning efficiency grew proportionally with power up

to 100 W, after which further increase did not result in significant improvement, mainly due to overheating and nonuniform cavitation. Figure 13 shows that the cleaning effect intensified with treatment duration up to 5 min, while longer exposure produced only marginal gains.

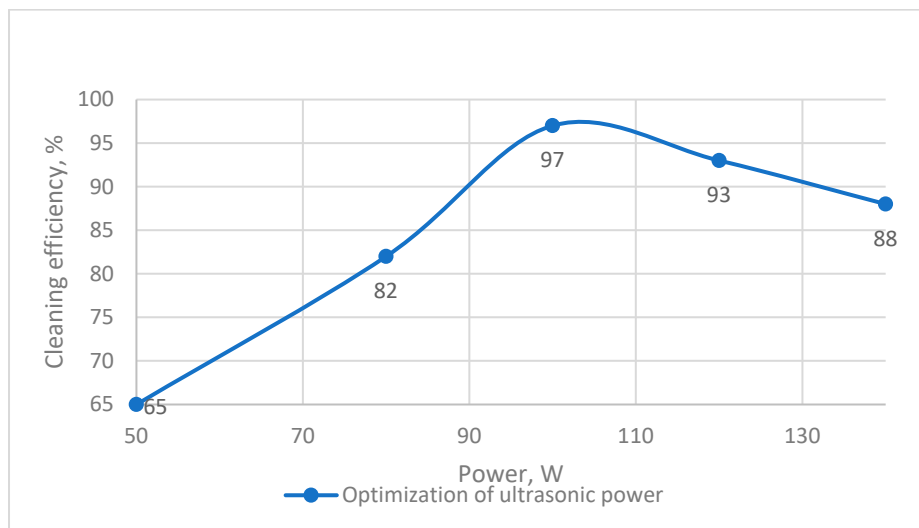


Figure 12. Optimization of ultrasonic power.

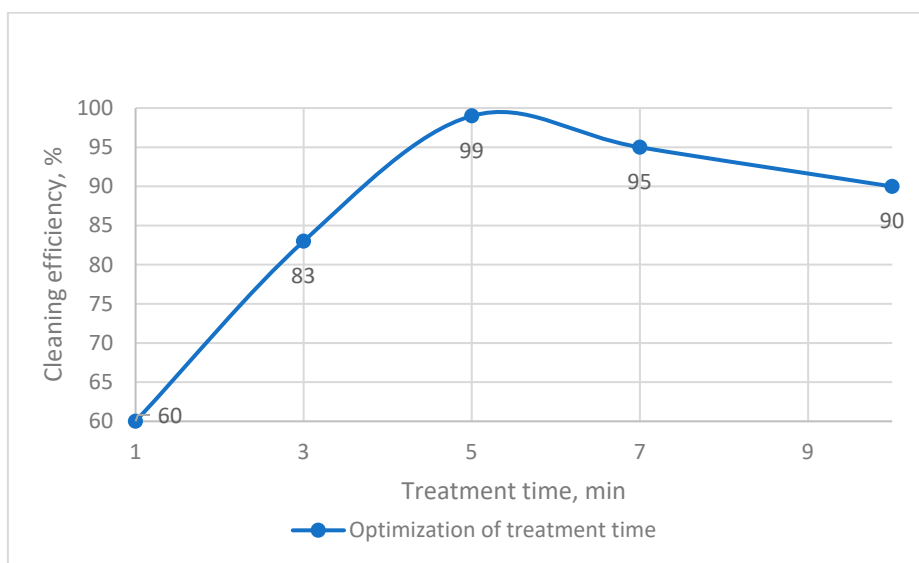


Figure 13. Optimization of treatment time.

Based on these results, the combination of 28 kHz frequency, 100 W power, and 5 min treatment time was selected as the optimal operating mode, providing the highest cleaning efficiency (96–98%) with minimal energy consumption.

4. Conclusions

Thus, the hypothesis that ultrasonic waves can effectively clean cutting fluids was experimentally validated. Throughout the experiment, several physical processes were observed that directly influenced the cleaning mechanism, namely the following:

- Heating;
- Cavitation;
- Coagulation;

- Dispersion.

By analyzing the experimental data, the density of the fluid before and after ultrasonic treatment was calculated. The results showed that after treatment, the density decreased by approximately 0.002–0.004 g/cm³ compared to the initial state, and the refractive index (n_D) correspondingly declined, indicating a reduction in solid and oil contaminants. The most pronounced cleaning efficiency was achieved at 28 kHz with a treatment duration of 5 min. Under these conditions, the cleaning efficiency reached up to 96–98%, depending on the initial contamination level.

This cleaning method is simple to implement and highly effective for cutting fluids with various contamination levels and compositions. Moreover, ultrasonic treatment at moderate power (100 W) ensures efficient regeneration of cutting fluids without chemical reagents or complex filtration systems. This approach significantly reduces the consumption of fresh fluid and the volume of hazardous waste, thereby lowering operational costs and environmental impact. The developed ultrasonic cleaning method is therefore environmentally friendly and can be directly applied in industrial workshops for the periodic regeneration of cutting fluids in closed-loop systems.

Scaling analysis between laboratory and industrial conditions demonstrated that the optimized parameters (28 kHz, 100 W, 5 min) can be proportionally adjusted for larger treatment volumes by maintaining constant acoustic energy density (W/cm³) and ensuring uniform cavitation field distribution through multiple transducers or reflector geometry optimization. When scaled to pilot-level systems (volumes of 20–50 L), equivalent cleaning efficiency can be achieved at power inputs of 0.8–1.2 kW with exposure times of 5–8 min. These correlations confirm the applicability of the developed ultrasonic cleaning technology for industrial recirculation loops of metalworking fluids.

5. Patents

The outcome of this study was the granting of Patent No. 10845 (Republic of Kazakhstan, utility model, 11 July 2025) for the invention entitled “Method of Cleaning the Cooling Lubricating Fluid”.

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