ABSTRACT

of the dissertation for the degree of Doctor of Philosophy (PhD)
in the field of study: 8D071 – Engineering and Engineering affairs,
educational program: 8D07101 – Mechanical Engineering

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DEVELOPMENT OF A METHOD OF ULTRASONIC REGENERATION OF A CUTTING FLUID FOR ITS REUSE

Relevance of the research. The dissertation is carried out in accordance with the priority area of scientific development "Energy, Advanced Materials and Transport", sub-priority "Mechanical Engineering and Transport", approved by the Higher Scientific and Technical Commission under the Government of the Republic of Kazakhstan, and is submitted for the degree of Doctor of Philosophy (PhD) in the field of study 8D071 – Engineering and Engineering affairs, educational program 8D07101 – Mechanical Engineering.

The linkage of the dissertation research with state scientific and technical programs confirms its practical orientation and applied significance. The topic of the dissertation formed the basis for grant funding of research conducted by young scientists within the "Zhas Galym" project for 2025–2027 (AP25794035), entitled "Development and research of a method for cleaning cutting fluid with ultrasound for its reuse," which indicates the demand for the obtained scientific results.

In mechanical engineering, metal cutting processes widely employ metalworking fluids (MWFs). The purpose of using MWFs is to reduce friction forces between the workpiece and the cutting tool, decrease workpiece deformation during machining, increase tool life, and enhance productivity in metalworking operations.

The service life of working MWF solutions typically ranges from two weeks to three–six months. After this period, if the fluids are not subjected to appropriate regeneration, they are rejected and sent for costly neutralization and disposal processes. Under conditions of unfavorable environmental impact, the disposal of MWFs represents a significant ecological problem in modern mechanical engineering. At the same time, new portions of MWF concentrate and large volumes of fresh water are introduced into the technological process, and the cycle is repeated.

The washing-off of lubricating oils from machine tool guideways during the supply of MWFs to the cutting zone transforms virtually all types of used MWFs into hazardous technogenic oil-containing waste.

Foreign oils and petroleum products entering MWFs form a favorable environment for the development of bacteria and microorganisms, accelerating biological degradation and putrefaction. Contaminated MWFs pose a significant health risk to operating personnel.

Several methods for MWF purification are currently applied, including flotation, filtration, and purification in force fields. The selection of a purification

method is based on regeneration efficiency indicators such as impurity density, productivity, degree and fineness of purification, separation coefficients, average particle size of impurities, cell biostability, energy consumption, and economic performance. However, all existing regeneration methods exhibit a number of disadvantages, including low productivity and purification efficiency, labor intensity, and structural complexity. Therefore, the development of a new method free from these limitations is required. At present, there is a lack of analytical relationships describing the purification process and experimental results on MWF regeneration. In this regard, substantiating the effectiveness of ultrasonic purification of MWFs and determining the key characteristics and parameters of the process for practical implementation is a relevant scientific and engineering task.

The research hypothesis assumes that optimally selected parameters of ultrasonic exposure are capable of providing effective regeneration of metalworking fluids through the occurrence of cavitation, coagulation, and dispersion processes within the fluid.

The objective of the research is to develop a method for ultrasonic purification of metalworking fluids and to establish relationships describing this process.

To achieve the stated objective, the following **tasks** were solved:

- analytical review of the composition and application of metalworking fluids;
- critical analysis of existing MWF purification methods, patents, and inventions in this field;
- development of an operating principle and design, and experimental investigation of a sensor for determining the degree of MWF contamination;
- experimental studies on ultrasonic purification of MWFs;
- mathematical modeling of the ultrasonic regeneration process and description of its physical mechanisms;
- experimental determination of the dependence of purification efficiency on the volume and material of the purification vessel;
- experimental verification of the effectiveness of ultrasonic purification;
- implementation of research results in industrial practice;
- development of recommendations for industrial implementation, taking into account quality control, occupational safety, environmental requirements, operating conditions, and equipment;
- assessment of the economic efficiency of ultrasonic MWF regeneration.

The following research **methods** were employed:

- analytical review of research results;
- patent analysis;
- mathematical modeling;
- experimental design and processing of experimental data.

The scientific novelty of the research consists of the following:

- for the first time, the effectiveness and necessity of ultrasonic purification of metalworking fluids have been substantiated;
- the physical mechanism of ultrasonic wave interaction with a viscoplastic

MWF medium has been described;

- relationships linking the electrical conductivity of MWFs with their degree of contamination have been obtained;
- experimental dependences of MWF purification efficiency on ultrasonic frequency, power, exposure time, fluid volume, and vessel material have been established;
- effective ultrasonic treatment regimes for MWFs have been determined depending on purification quality.

Scientific statements submitted for defense

1. The physical mechanism of MWF regeneration under ultrasonic wave action due to cavitation and coagulation processes.

2. The regeneration efficiency is directly proportional to ultrasonic power and exposure time and inversely proportional to the volume of the fluid container.

3. A sensor has been developed that enables determination of the degree of MWF contamination based on electrical resistance measurements.

4. Relationships determining MWF purification efficiency as a function of vessel material and volume, ultrasonic parameters, and exposure time.

5. Recommendations on the applicability of regenerated metalworking fluids in the development of technological processes for industrial production conditions.

The author defends:

- a method for ultrasonic purification of metalworking fluids;
- a description of the physical process of ultrasonic воздействие on a viscoplastic MWF medium;
- experimental results on determining MWF purity using a sensor based on electrical resistance;
- experimental results of ultrasonic purification of metalworking fluids.

The object of the research is the process of ultrasonic purification of metalworking fluids.

The subject of the research is ultrasonic exposure applied to metalworking fluids.

The practical significance of the research lies in the development of recommendations and calculated relationships for designing technological processes for ultrasonic purification of metalworking fluids.

The main results of the dissertation have been implemented in the production process of LLP “Maker (Мэйкер)” and in the educational process of the course “Theory of Metal Cutting” for second-year undergraduate students of the educational program 6B07104 – Mechanical Engineering at the Abylkas Saginov Karaganda Technical University.

The reliability of the dissertation results is ensured by correct problem formulation, application of appropriate research methods, and consistency between experimental and analytical data. The main provisions of the dissertation have been published in scientific articles and conference proceedings, and the author holds a utility model patent and a certificate of state registration of copyright objects.

Summary of the dissertation content.

The first chapter analyzes the current state of the problem of purification and

regeneration of metalworking fluids used in metal cutting operations. The causes of MWF degradation during operation are considered, and a review and comparative analysis of existing purification methods are presented.

The second chapter addresses issues of monitoring and control of MWF condition. Traditional methods for assessing MWF quality are analyzed. A sensor is developed, and a methodology for evaluating MWF contamination based on electrical resistance measurements using a two-electrode system and a digital multimeter is experimentally validated. The dependence of electrical resistance on the concentration of metallic contaminants is experimentally established.

The third chapter is devoted to the development and theoretical justification of the ultrasonic regeneration method for metalworking fluids. The physical nature of ultrasonic wave interaction with a viscoplastic MWF medium is considered, including cavitation, coagulation, dispersion, and separation of contaminants. Mechanisms of ultrasonic energy transfer into the liquid medium and their influence on flow regimes are described. It is shown that purification efficiency is determined by the ratio of transmitted energy, fluid volume, and ultrasonic exposure conditions.

An experimental setup for ultrasonic MWF purification is developed, and experiments are conducted at various values of frequency, power, exposure time, fluid volume, and vessel material. Experimental dependences characterizing MWF purification efficiency under these conditions are obtained.

The fourth chapter presents recommendations for implementing the research results in industrial practice and develops the necessary documentation. The economic efficiency of introducing an ultrasonic MWF purification system at a mechanical engineering enterprise is assessed. The annual economic effect is calculated due to reduced costs for purchasing fresh MWFs, disposal of waste fluids, and operating expenses. It is shown that the application of the developed method provides a significant economic benefit in the operation of machine tool fleets.

Personal contribution of the author

The work was carried out personally by the author. The author performed an analysis of existing purification methods and conducted a patent review. The research objectives were formulated and the research methodology was developed. A methodology for monitoring the degree of MWF contamination based on electrical resistance measurements was developed, experiments were conducted, and a sensor was designed. Experimental studies on ultrasonic regeneration of metalworking fluids were carried out, and an experimental ultrasonic purification setup was developed.

Publication and approbation. The main results of the dissertation are published in 11 scientific works in Russian and English, including 2 articles indexed in Scopus (Journal of Measurements in Engineering – 28%, Applied Mechanics – 61%), 3 articles recommended by the Committee for Quality Assurance in Science and Higher Education of the Ministry of Science and Higher Education of the Republic of Kazakhstan, 1 utility model patent of the Republic of Kazakhstan, 1 certificate of state registration of copyright objects, and 4 papers in international scientific and practical conferences.

The main research results were presented and discussed at international

scientific and practical conferences and scientific seminars:

- the International Scientific and Practical Conference “XV Saginov Readings. Integration of Education, Science, and Industry”, Karaganda, 2023;
- the International Scientific and Practical Conference “XVI Saginov Readings. Integration of Education, Science, and Industry”, Karaganda, 2024;

- the International Scientific and Practical Conference “Development of the Mechanical Engineering Industry and Training of Highly Qualified Specialists of a New Formation (State, Problems, and Solutions)”, Astana, 2005;
- scientific seminars of the Department of Technological Equipment, Mechanical Engineering and Standardization (2021–2026);
- scientific seminars of the Dissertation Council (2024–2026) for the defense of doctoral dissertations in the specialties 8D07101 “Mechanical Engineering” and 8D07102 “Transport, Transport Engineering and Technology” at Abylkas Saginov Karaganda Technical University.

Dissertation structure and volume.

The dissertation comprises 125 pages of typewritten text and includes a list of symbols and abbreviations, an introduction, four chapters, conclusions, 38 figures, 6 tables, a list of references, and appendices.

The dissertation contains new scientifically substantiated theoretical and experimental results, the combination of which is aimed at solving a relevant scientific and practical problem in mechanical engineering — the development of a method for ultrasonic regeneration of metalworking fluids for their reuse in metal cutting processes.

As a result of the conducted research, an important applied scientific and practical problem has been solved, which allows the following conclusions to be drawn:

1. Based on an analytical review of the composition, operating conditions, and functions of metalworking fluids, as well as a critical analysis of existing purification methods, it has been established that traditional regeneration techniques (flotation, filtration, purification in force fields, etc.) are characterized by limited efficiency, high energy consumption, and structural complexity, and do not ensure comprehensive removal of contaminants during prolonged MWF operation.

2. Analysis of patents and technical solutions in the field of metalworking fluid purification has shown that modern developments are mainly focused on multistage and combined regeneration schemes using mechanical, chemical, and magnetic effects. At the same time, the absence of methods based on the targeted use of ultrasonic exposure as an independent and primary method of MWF regeneration has been identified.

3. An analysis of existing methods for monitoring the condition of metalworking fluids demonstrated that visual, laboratory, and instrumental techniques do not provide universal and prompt assessment of contamination levels under industrial conditions. In this regard, the expediency of developing a simple and accessible express method for MWF quality control adapted to real operating conditions has been substantiated.

4. A sensor for indirect monitoring of the degree of metalworking fluid contamination based on electrical resistance measurements has been developed, and the feasibility of using this parameter for assessing the operational state of MWFs has been experimentally confirmed.

5. Experimental dependences of the electrical resistance of metalworking fluids on the degree of their contamination have been established, confirming the applicability of the proposed method for operational quality control and decision-making regarding the need for MWF regeneration.

6. A method for ultrasonic regeneration of metalworking fluids has been developed and an experimental setup for its implementation has been created. It has been established that ultrasonic exposure provides effective purification of MWFs due to the combined manifestation of cavitation, coagulation, and dispersion processes of contaminant particles.

7. Experimental dependences of metalworking fluid purification efficiency on ultrasonic frequency, power, and exposure time, as well as on fluid volume and vessel material, have been obtained, which made it possible to determine optimal ultrasonic treatment regimes ensuring maximum purification efficiency with rational energy consumption.

8. A mathematical model of the ultrasonic regeneration process of metalworking fluids has been developed, describing the physical mechanisms of purification of a viscoplastic medium under ultrasonic oscillations and allowing prediction of process efficiency when operating parameters change.

9. The possibility of repeated use of regenerated metalworking fluids in metal cutting technological processes has been experimentally confirmed, indicating the feasibility of implementing the developed method in industrial practice.

10. Recommendations have been developed for the implementation of the ultrasonic regeneration method of metalworking fluids under production conditions, taking into account quality control requirements, occupational safety, industrial safety, and environmental regulations.

11. The practical significance of the research results is confirmed by their implementation in the production process of LLP “ Maker (Мэйкер ”, as well as their use in the educational process of Abylkas Saginov Karaganda Technical University in the training of specialists in the field of Mechanical Engineering.

Thus, all the objectives set in the dissertation have been accomplished, the research goal has been achieved, and the obtained results demonstrate scientific novelty and practical significance.