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Design of Real-Time Monitoring System for Cutting Fluids

Frantisek Jurina, Jozef Peterka *, Marek Vozar, Boris Patoprsty and Tomas Vopat

Institute of Production Technologies, Faculty of Materials Science and Technology in Trnava, Slovak University of Technology in Bratislava, 812 43 Bratislava, Slovakia
* Correspondence: jozef.peterka@stuba.sk; Tel.: +421-905-930-245

Abstract: The paper describes the design and implementation of a cutting fluid monitoring system, as well as the design and development of an algorithm to increase the life of the cutting fluid in the machine tool reservoir. Cutting fluids are the most common type of coolant in machining. During its use, it becomes contaminated and gradually degrades until it needs to be replaced with fresh fluid. To increase its effective service life, its parameters should be monitored at regular intervals, and corrective measures such as topping up the fluid quantity and adding inhibitors and additives should be taken if necessary. For this purpose, a conceptual design of a monitoring device was developed, and a prototype device was subsequently manufactured. The device is designed as a floating probe in the storage tank. Therefore, its shape had to be designed to accommodate multiple sensors, batteries, and electronic components while remaining floating and watertight. The designed prototype was made by additive manufacturing and placed in a cutting fluid while being measured at regular intervals. In the event of non-compliant parameters, the algorithm generated corrective actions, and the machine operator could take the required steps to significantly increase the lifetime of the cutting fluid.

Keywords: cutting fluids; monitoring system; probe design; machining technology

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1. Introduction

Processes of metal cutting, such as milling [1,2], boring and drilling [3], and turning [4], can be characterized as a sequence of gradual deformation and separation of material, with the removed material layer exiting the process in the form of a chip sliding on the rake face of the cutting tool. Due to the mechanical nature of this process, high pressure, friction, and deformation cause the transformation of energy into heat [5].

Since the heat generated during machining is a serious problem, it is important to select suitable lubrication/cooling conditions to improve the machinability of the material [6,7] and also to increase the tool life. The trend is to develop systems to monitor selected properties of elements of the cutting process, namely: cutting tools [8], workpieces, and also cutting fluids [9].

Today, a wide variety of cutting fluids are commercially available [10–12]. Generally, there are considered to be four different types of cutting fluids: neat oils, soluble oils, semisynthetic fluids, and synthetic fluids [13].

Depending on the machining operations, the properties of the cutting fluid required may be oriented either toward cooling (typical processes are turning and milling) or lubricating (typical processes are tapping [14] and broaching [15]), or both. The effectiveness of cutting fluid depends on a number of factors, such as types of machining operations, cutting parameters, and methods of cutting fluid application. Cutting fluids, specifically the water-soluble types, are all formulated to operate within a certain range of conditions in areas such as concentration, pH, dirt levels, tramp oil, bacteria, and mold. When fluid conditions exceed this range in one or more of these areas, performance problems can develop. It is therefore necessary to control the following factors to keep cutting fluids in optimal conditions [16].

Although there are various other approaches to removing heat from the cutting process—by cooling or reducing friction—via lubrication, such as machining approaches with minimum use of cutting fluids [17], cooling with cold or cryogen air fluids [18], etc., these problems are not addressed within the scope of our paper.

1.1. The Concentration of Cutting Fluid

Water-soluble cutting fluids are typically formulated to operate within a certain concentration range. The concentration value is one of the most important parameters for water-soluble cutting fluids. It indicates the ratio of basic components—cutting oil with additives—dissolved in the water. The concentration should be kept within the levels specified by the manufacturer of the cutting oil. However, during the machining operations, the concentration value can change considerably due to water evaporation. An increase in oil concentration can cause issues with the foaming of cutting fluid. The toxicity of the cutting fluid also increases, which leads to worsening work conditions for machine operators [19]. A decrease in concentration occurs when the oil component gets removed by the chips exiting the machining process. A low concentration of cutting oil increases the cooling effect of the fluid as well as the risk of corrosion and contamination by microorganisms [20].

The emulsion-based cutting fluids are designed to perform within the concentration range of 3 to 12%, depending on the specific type of cutting fluid and its application. The need to regularly check the value of cutting fluid concentration is apparent [16].

Concentration control is critical for the overall performance of water-miscible metalworking fluids. Low concentrations can result in poor machinability, increased corrosion, and poor product stability. High concentrations can lead to foaming, misting, smoking, and increased dermal and respiratory irritation, especially in the metalworking industry. It is recommended that the concentration of the emulsion be tested at least once a week and even daily if the emulsion volume is small and/or it is used in highly stressed machining centers with high drag-out [21].

1.2. pH Value

pH values of water-soluble cutting fluids are typically in the range of 8.5 to 9.5. Most cutting fluids degrade if the pH value gets lower than 8. At these values, the risk of corrosion occurring on both the workpiece and the machine gets higher, destabilization of the emulsion also occurs, and carcinogenic agents get released. Values of pH higher than 9.5 are usually caused by the contamination of the cutting fluid and can cause skin irritation for the machine operators [16].

A pH value measurement must be performed at least once a week (TRGS 611). An important point for pH value measurements and the corresponding documentation is the development of the pH value over the course of the emulsion's service life. The continuous monitoring of pH values allows countermeasures to be taken in good time [21].

1.3. Debris

During the machining process, various types of dirt can get into the cutting fluid, such as dust particles, fine chips, particles from the seals, etc. Even though there are usually multiple filtration systems in place, some particles of debris can re-enter circulation. They can clog the cutting liquid distribution system or cause an insufficient quality of the machined surface; it is therefore important to monitor the cutting fluid in order to avoid an excessive amount of debris in the liquid volume [22].

1.4. Temperature

Cutting fluid temperature is an important factor when machining materials that generate large quantities of heat or when dealing with precise machining where thermal expansion can significantly influence the workpiece's dimensional accuracy [3].

If the cutting fluid is overheated for prolonged periods of time, its water component evaporates faster and the fluid depreciates faster as well, leading to reduced effectiveness. The temperature of 60 degrees Celsius is not to be exceeded.

When a cutting fluid management program is in place, the fluctuation in the aforementioned variables is substantially reduced, and a more consistent quality of parts can be achieved. Properly monitored and controlled fluids do not need to be replaced as often [23]. This reduces the costs associated with machine downtime, disposal, and new fluid purchase [24].

Generally, diagnostic or monitoring of cutting fluids can be divided into the following categories: manual monitoring, laboratory monitoring, and real-time monitoring [25].

1.5. Manual Monitoring

The basis of manual monitoring is the use of handheld devices and tools by the operators of the machining center. Handheld devices such as refractometers, pH paper indicators, thermometers, and so on are utilized. The advantages of using this method are that it's simple, fast, and not very expensive.

In the forefront are two important checks that should be performed daily. The first is a basic prerequisite for keeping cutting fluids in good condition and involves checking the cutting fluid level in the tank. In machine tools with insufficient cutting fluid in the tank, the circulation pump can draw air, and this can lead to cutting emulsion foaming. This, in turn, can lead to other problems such as inadequate heat dissipation from the tool and component and thus reduced performance, such as grinding burns or reduced tool life. The second visual evaluation of the emulsion concerns the emulsion color and degree of dispersion. If optical changes to the cutting fluid occur, this is usually an indication of a change in the condition of the cutting fluid. This requires specific counter-measures, which must be accompanied by a comprehensive review of the causes. Normally, an emulsion does not have floating or creamy oil on its surface [21].

1.6. Laboratory Monitoring

When using this method of cutting fluid monitoring, a sample of the fluid needs to be taken from the machine shop and transported to a specialized laboratory for subsequent analysis. The laboratory can be located within the company, but external laboratories are used more often. The advantage of using this method is that it's possible to obtain a wide range of cutting fluid characteristics with high precision.

1.7. Real-Time Monitoring

Online monitoring systems are utilized. They can either be external devices or are integrated into in-line sensors in the structure of the machine tool. With regard to the modification of the unsuitable cutting fluid properties, there are systems with or without direct feedback. For systems without feedback, the modification of the cutting fluid, such as refilling or additive application, is carried out manually by the machine tool operators. Systems with direct feedback automatically modify the cutting fluid based on the measured data. The advantage of this type of monitoring is that the measured parameters of the cutting fluid are always up-to-date, and for the systems with feedback, the entire process is automated.

The authors [26] proposed a system based on the input of additives into the cutting fluid circulation in order to extend its effective lifetime. Avoiding frequent refilling of the fluid is viable from the standpoint of eco-friendly manufacturing processes. The authors [9] proposed a system based on the input of additives into the cutting fluid circulation in order to extend its effective lifetime. Avoiding frequent refilling of the fluid is viable from the standpoint of eco-friendly manufacturing processes. Authors [27] conduct a review on multiple aspects of cutting fluid systems used in machining processes.

2. Materials and Methods

A monitoring system for automatic data collection of cutting fluid properties is designed. Based on the previous research (Refs. [23,28,29], chapter 6. Patents), the most important characteristics to be monitored were selected. The system records properties such as pH, coolant concentration, temperature, and the amount of cutting fluid in the machine sump. Based on this information, the machine operator or the person responsible for fluid management can effectively and simply monitor the conditions of the cutting fluid. It is also possible to top up the lacking volume of cutting fluid or decide to replace the fluid completely based on this information. This way, errors caused by manual fluid control are eliminated (for example, a wrong reading of concentration). The design of the monitoring system includes both hardware and software hardware and software components. Our proposed design of the monitoring system includes both hardware and software parts Figure 1.

The hardware part consists of a probe placed in the machine sump, which automatically reads the selected properties using built-in sensors.

The software part consists of an application that collects and displays the measured properties of the cutting fluid. Communication between the hardware and software parts is established via an internet network.

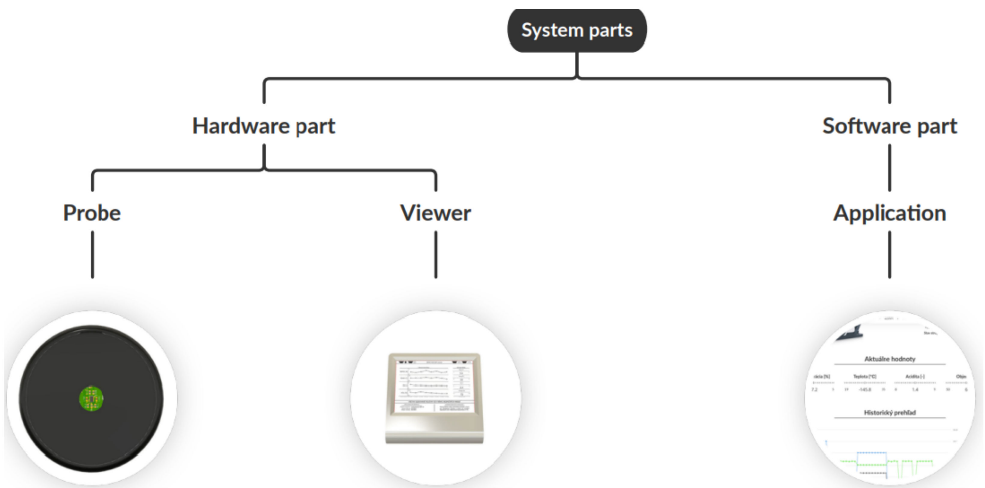

Figure 1. Scheme of monitoring system design overview.

The shape of the probe had to be designed to perform its intended task without any issues. It also had to be compact enough to fit into the machine sump and manipulated easily. Three main requirements had to be taken into consideration.

- method of manufacturing,
- placement of the sensors and components, dimensions,
- and shape of the probe ensuring adequate buoyancy.

2.1. Probe Design

Many prototype productions are nowadays realized by modern additive 3D printing technologies [30,31]. The probe body in our case was fabricated by FDP (Fused Deposition Modeling) 3D (3-Dimensional) printing. ABS material was used to produce the probe, which is the standard material supplied for the 3D printing method. The dimensions of the probe are as follows: diameter D = 140 mm, height 90 mm. The advantage of using this manufacturing technology is the ability to make complex shapes from free-form surfaces, which are present both on the outer shell and inner cavity. A charging coil for contactless recharging could be incorporated into the lower part of the probe beneath all other components, so that it can be placed on the charging pad without the need to connect any cables or replace the battery. Sensors and other components in the probe were placed so that the resulting center of gravity would not be offset and the probe could remain floating in the fluid. For this reason, the combined sensor for measurement of concentration and temperature was also placed at the bottom of the probe, since this part of the probe was the heaviest one. Another reason for this placement was to reduce the amount of accumulated sediment on the sensor. On the side of the probe, there is a sensor for measuring the pH value of the cutting fluid. A sensor for measurement of the level of cutting fluid in the machine sump is placed on the top of the probe alongside notification LED diodes. Enclosed inside the probe is the custom-printed circuit board as well as the battery powering the probe. All sensors are shown in Figure 2.

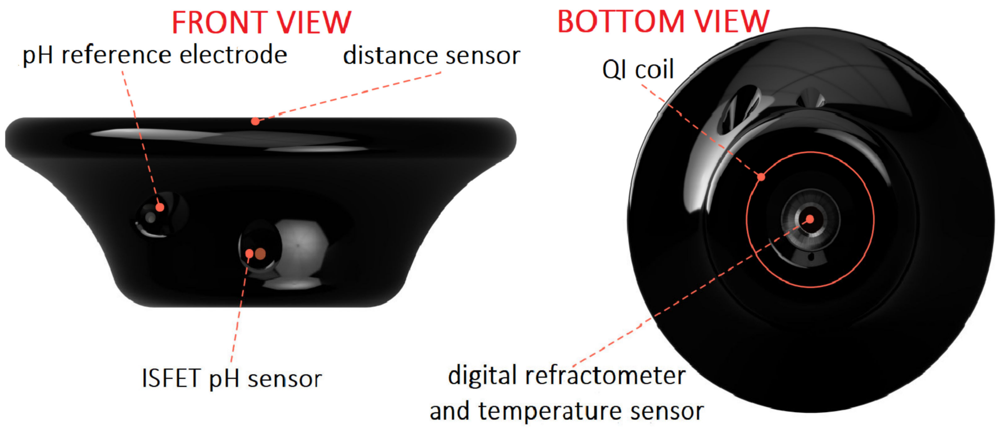

Figure 2. Probe for collecting information on selected cutting fluid properties.

The circuit board is the most important part of the probe, and it was designed in Autodesk Eagle. The basic component of the circuit board is the ESP 32 microcontroller. This chip combines a double-core ARM processor and an A/D converter for communication with peripheral devices—sensors, wi-fi, Bluetooth connectivity, and memory for performing the program instructions. This component makes it possible to collect the measured data and broadcast them to the server, where these data are further processed. Besides the mentioned component, there are other sections on the circuit board, such as power management, voltage references for each of the sensors, an antenna for connecting to the wireless network, and the distance sensor with the LEDs. The control program—firmware that is loaded on the ESP 32 microcontroller was created in the Wiring programming language. The structure of the firmware consists of loading up constants, initializing the measurement sequence, transmitting the measured values on the web server, and putting the probe in energy-saving standby mode until the next measurement run. The complementary part of the measurement system is the standalone viewer, which is running on the same hardware as the probe—an ESP 32 microcontroller—with the addition of peripheries needed to connect and utilize a low power e-ink display. This can be used for the non-stop display of up-to-date measurement data of the cutting fluid in close proximity to the machine with the active probe in the sump.

The probe is placed in the coolant tank, where it floats on the surface of the cutting fluid while measuring and recording the following data. Concentration ratio—a built-in digital refractometer is utilized. The refractometer's measuring range is from 0 to 70% cutting emulsion concentration. The measurement accuracy of the refractometer is 0.2% with automatic temperature compensation. This sensor is located on the bottom face of the device. pH—with a built-in, non-glass ISFET (Ion-Sensitive Field-Effect Transistor) pH probe. The measuring range is from 2 to 12. Accuracy is $\pm$ 0.1 pH units. This sensor is located on the side of the device. Temperature—for temperature reading an NTC (Negative Temperature Coefficient) thermistor is used. Cutting fluid level—Cutting fluid level with a built-in distance optical sensor RFD (Remote Flammable Detector) 77402 with a wide measuring range from 5 to 200 cm. This sensor is located at the top of the device. The sensor measures the distance from the probe to the top of the machine reservoir. This way, it can determine the amount of liquid in the tank by defining the total tank height.

The probe uses a built-in 1450 mAh battery as a power source. The most important part of the probe is an electrical circuit containing an energy-efficient 'soc esp 32', components needed for power management, and I/O (Input/Output) peripherals to the individual sensors. The ESP32 is made in Espressif and it is a programmable chip. A prototype of the control program was written in the Arduino IDE (Integrated Development Environment) console. The program manages the collection and evaluation of data and ensures communication between the probe and the application. The MQTT (Message Queuing Telemetry Transport) protocol for IoT (Internet of Things) devices is used for communication between the probe and the application. Wireless charging technology is used to charge the device. The QI coil for charging is located at the bottom of the probe. PCB (Printed Circuit Board) used in the probe is shown in Figure 3.

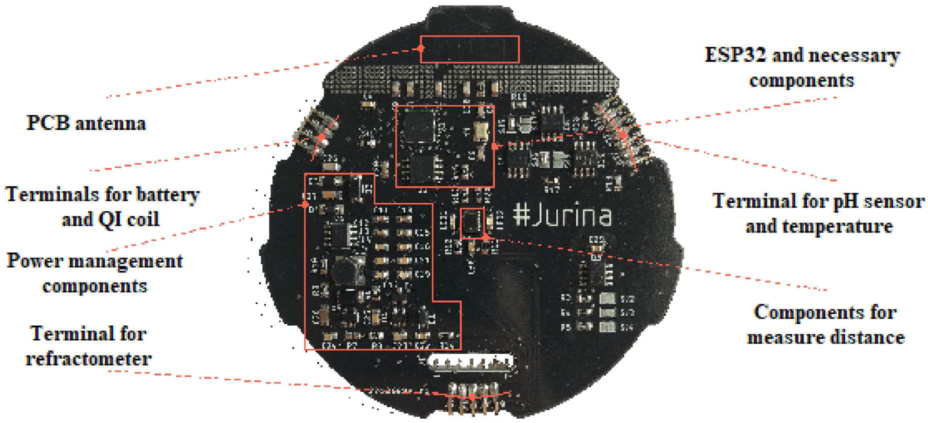

Figure 3. PCB used in the probe.

A detailed electrical schematic design is shown in Figure 4. The schematic and circuit board were created using Eagle software.

Figure 4. The part of the scheme of an electrical schematic design.

2.2. Software Design

The software developed for use with the probe is a simple tool for managing, viewing, and evaluating measured data. It is essentially a web application that can run on any device connected to the internet, be it a phone, tablet, or computer, via a web browser. The application interface shows information about the machine tool where the monitoring system is running. The application itself consists of multiple sections. The first section contains basic information about the machine tool, its description, type, and current state. The section labeled "current values" contains information about the up-to-date measurement of selected parameters (concentration, temperature, pH, volume) and set limits. Another section labeled "historical overview" contains a tool for viewing past measured data for selected parameters. Selected data can be summarized and exported as an image or a graph. Graph tools can be used to further select and specify the desired information shown in the export. The most important section, labeled "pending tasks" shows what maintenance actions need to be taken. If there is a need to carry out corrective actions, the machine operator gets a notification about what maintenance is required and what to do to maintain the fluid parameters within the optimal range. For example, if there is a notification regarding the low level of cutting fluid in the sump, based on the measured level of concentration and fluid volume, the software provides instructions to the machine operator on how and what amount of missing fluid components are needed to be added. When the maintenance task is completed, the operator confirms it in the monitoring system, which connects to the probe in the sump to carry out the new measurement. If the measured values are within the specified range, the task is considered to be successfully accomplished, and the notification gets moved to another section called "event overview". In cases where the task cannot be carried out or is not carried out properly, it is possible to postpone it for later. The "event overview" section contains a list of all previous maintenance actions as well as measurements of the probe and probe maintenance such as charging or sensor calibration. The event table has three main rows with the date, type, and description of the events. There are customizable viewing options and also a search function. Figure 5 shows the application interface, for the machine tool.

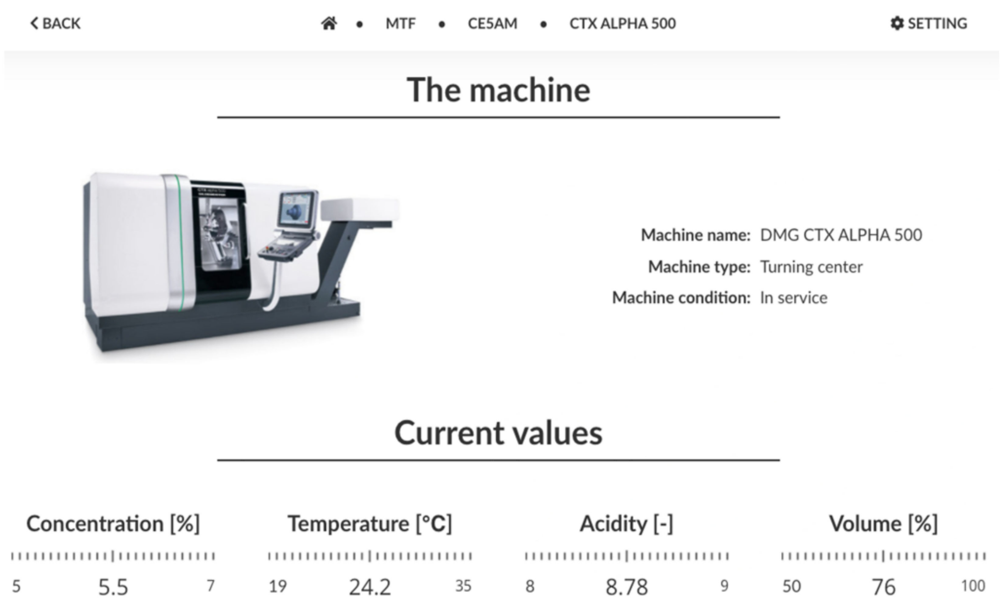

Figure 5. Software—Application interface.

For each event, a protocol document is generated, depending on the type of event. If there is a measurement action, the protocol contains the measured values of all parameters, machine tool information, deviations of measured data, and information about specified limits as well. This protocol can be exported in PDF format or printed. The last section of the application is called "fluid info", which contains basic information about the cutting fluid type, name, and manufacturer, as well as the date of initial filling. There is also a short description of the specific fluid, guidelines, and safety information.

3. Results

A successful test run of the cutting fluid monitoring system has been accomplished. Before placing the probe in the machine sump, all the sensors were tested and calibrated to ensure full functionality. Subsequently, the probe was inserted into the machine sump of a 5-axis turning machine, the DMG CTX Alpha 500. The cutting fluid used in the machine was 'Alusol ABF10′, which is a semi-synthetic water-based fluid.

Its basic selected cutting fluid characteristic is [32]: It is boron (and no amine, chlorine; formaldehyde releasing agent) free. It provides product stability and improves bio-resistance properties. The selected advantages:

- Formaldehyde releasing free to comply with health and safety regulations,
- Boron-free for environmental compliance and improved residue characteristics,
- Chlorine and nitrite free to fulfill your local legislation, waste treatment, and environmental requirements,
- Resists fungal attacks to extend fluid life and reduce maintenance and machine downtime,
- Excellent wetting properties reduce coolant drag out and deliver clean machine tools and components.

The selected typical characteristics
Concentrate:
Appearance—Test Method (Visual), Value (Amber)
Mineral oil content—Test Method (Calculated), Value (Wt% 40)
Emulsion:
Appearance—Test Method (Visual), Value (Milky)
Mineral oil content—Test Method (DIN 51369, ASTM E70-97), Value (8.9)
Additives: EP-Ester.
Recommended Concentrations:

Grinding 4–5%, General Machining 5–7%, Drilling 5–7%, Reaming and tapping 6–9%, Broaching 8–10%. Water range 100–400 ppm $CaCO_3$.

The capacity of the tank is 1 m^3 and the concentration of the fluid was 5%. The probe remained in the sump for the duration of three days, with the measurement interval being 12 h. Measured data can be seen in Table 1.

Table 1. An example of possibilities of results of a testing run of the probe.

Measurement Time		Measured Parameters		
Day	**Time**	**Concentration [%]**	**Amount of CF in the Sump [%]**	**Temperature [°C]**
1	8.00	5.4	76	21.2
	20:00	5.8	54	22.4
2	8.00	5.5	75	22.0
	20:00	5.9	77	21.8
3	8.00	6.0	73	21.6
	20:00	6.3	74	22.0

CF—Cutting Fluid.

As the machine tool specified in the article was a 5-axis turning machine, the DMG CTX Alpha 500, machining operations were both turning and milling. Over the duration of the days that were monitored, multiple different materials, such as aluminum, brass, and stainless steel, were machined using a multitude of different tools. Listing all of the materials, tools, and cutting conditions is outside the scope of the article, as it has no significant influence on the condition of the cutting fluid. Since the cutting fluid state does not rapidly change over the course of 48 h during standard machining operations, the purpose of the testing run was to merely verify the functionality of the probe, not to determine the influence of machining operations and conditions on the condition of the cutting fluid.

The software part—the application—allows different interpretations of the data measured from the probe. Graphical interpretation of the data from the web application is shown in Figure 6.

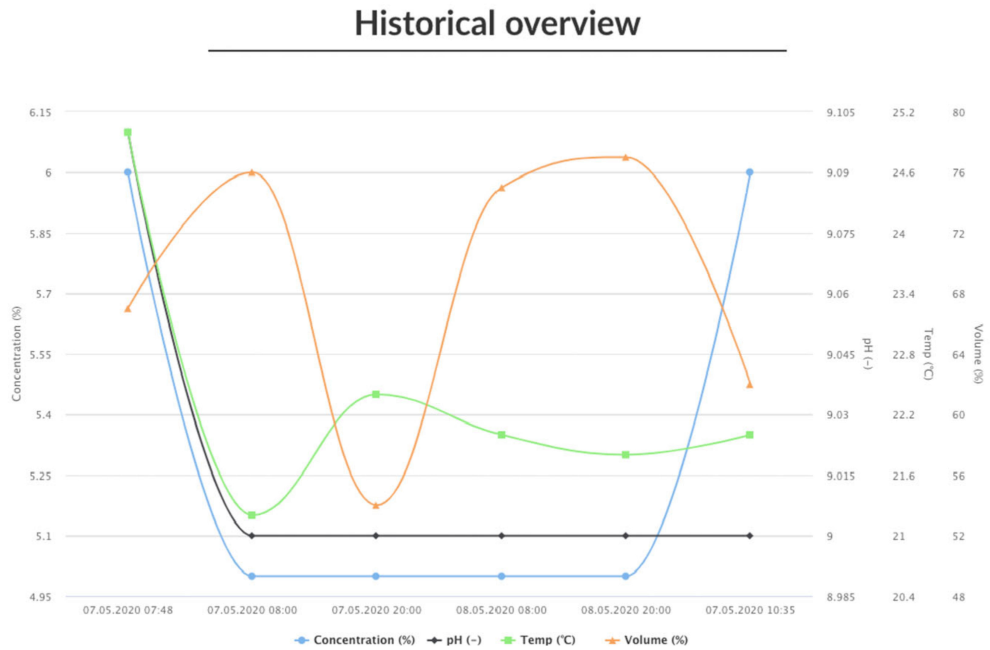

Figure 6. An example of a graphical representation of measured parameters in the web application.

Figure 6 in question is no more than an illustrative screen capture of the web application, as showing the entire application would not be suitable for the scope of the paper. For this reason, only the most important part of the monitoring web application was chosen to be shown. The figure contains a graph that shows how the selected cutting fluid parameters are monitored and what time range can be selected. Hovering the mouse cursor over the graph areas shows detailed information. It is also possible to export the graphs into .cvs files and then proceed to evaluate them in tools such as MS Excel or other data software.

The site has been created for testing purposes and is not currently accessible via a browser over www. It is only available locally on one computer without being able to connect to it from outside. The front-end of the site was created using html, css, and JavaScript technology, and the back-end was created using PHP+ database and the chart.js tool was used to display the charts.

During the testing run, the cutting fluid was also measured with handheld tools to provide reference values. The only parameter that was differing significantly was pH value, as the sensor stopped functioning due to prolonged exposure to the cutting fluid environment. The deviations for the temperature values were in the range of ± 0.4 °C, fluid amount deviation was 2%, and the concentration value deviation was ± 0.5%. Although the pH sensor damage was not expected, the testing run was considered a success, and the design of both the measuring probe and data collection system was proven to be effective and accurate.

4. Discussion

On the basis of the trial operation, which will gradually move into pilot operation, we can already state that deviations for measured parameters were:

- the temperature values were in the range of ±0.4 °C,
- fluid amount deviation was 2%,
- and concentration value deviation was ±0.5%.

Although the pH sensor damage was not expected, the testing run was considered a success, and the design of both the measuring probe and data collection system was proven to be effective and accurate. The article describes the advantages and disadvantages and methods of cutting fluid maintenance. Regular maintenance of cutting fluids is important because it extends their effective life. The maintenance process can be divided into the monitoring of selected properties (concentration, pH, dirt level, etc.) and the treatment of cutting fluids (top-up emulsion, cleaning the machine sump, etc.). So far, in most cases, diagnostics have been performed manually using a handheld refractometer, test pH strips, and such.

The automatic measurement system design was described in this article. The system consists of hardware and software parts. The hardware part is placed in the probe, which is floating in the coolant tank. In contrast to other cutting fluid control systems (manual or laboratory), the presented design of the system is simple to implement and use.

The probe's shape is designed:

- to float in the cutting fluid,
- and keep the sensors clean so they can function properly.

The software part consists of a simple application running in the browser that is designed to be user-friendly and easy to use as well. The use of this system prevents inaccuracies in data acquisition, and it can work continuously.

In the future, we will focus on the following research and development directions and tasks:

1. the design and implementation of new shapes and probe configurations with the possibility of adding additional sensors to a single probe,
2. the search for smaller and miniature sensors for monitoring the properties of cutting fluids,
3. deployment of measurement probes in multiple CNC (Computer Numeric Control) machine tools simultaneously.

The proposed probe aims to memorize the selected properties of cutting emulsions in real-time. It currently includes the following sensors: temperature, distance, concentration to record, and pH sensor. From the perspective of medical device machining, where minimal to zero bacteria presence on the machined surface is required, it would be useful to add a subsystem to the system to monitor the number of bacteria. It is known that one indicator of bacterial growth in emulsions is temperature rise. This parameter is monitored and recorded in this case.

In the paper, there is information regarding the designed cutting fluid monitoring system. In general, it can be argued that similar systems are meant for simple analysis of a single parameter, and in most cases, these devices require difficult incorporation into the machine tool fluid system. Based on the patent literature research, it is apparent that there aren't many similar systems developed, since in the related documents there are mostly devices for mixing or distributing cutting fluid in the machine tool, such as an automatic device that adds cutting fluid, cutting fluid concentration monitoring, an automatic proportioning system, working method, monitoring of lathe cutter cutting temperature and cooling device, a cutting fluid regeneration system, a cutting liquid concentration automatic stabilizing device, and an intelligent adjustable cooling device for cutting fluid flow of numerically-controlled machine tool [33–38]. Likewise, these systems are rather difficult to operate, especially those designed in the past [39]. On the contrary, complex commercial systems are economically demanding and difficult to implement as well [40,41]. The designed monitoring system is very straightforward from the standpoint of implementation, very affordable, and easy to operate. Its biggest disadvantage is that it is merely a monitoring system, and there is still a need for personnel to carry out maintenance tasks.

Cutting fluids play a critical role in the performance of machining operations, and their effectiveness can be improved by real-time monitoring systems. Real-time monitoring systems for cutting fluids are designed to measure various parameters of the fluid, such as pH, concentration, temperature, and conductivity, among others. These systems provide data that can be used to optimize the performance of cutting fluids and ensure that they are functioning properly.

One of the main benefits of real-time monitoring systems is that they can detect problems with cutting fluids before they cause damage to machinery or products. For example, if the pH of the cutting fluid becomes too high or too low, it can cause corrosion or other issues with the machinery. Real-time monitoring systems can detect these changes in pH and alert operators to take corrective action before damage occurs.

Another benefit of real-time monitoring systems is that they can help optimize the use of cutting fluids. By measuring the concentration and other parameters of the fluid, operators can adjust the flow rate and other settings to ensure that the fluid is being used efficiently. This can help to reduce waste and improve the overall performance of the machining operation.

However, there are also some limitations to real-time monitoring systems for cutting fluids. One limitation is that they require specialized equipment and expertise to install and operate. This can be a significant investment for some companies and may not be feasible for smaller operations.

Additionally, real-time monitoring systems may not always provide accurate measurements of the cutting fluid parameters. For example, changes in the temperature or other environmental factors can affect the accuracy of the readings. This can lead to false alarms or other issues that can impact the performance of the machining operation.

In conclusion, real-time monitoring systems for cutting fluids can provide significant benefits for machining operations, including improved performance and reduced downtime. However, companies should carefully evaluate the costs and benefits of these systems before investing in them and should also be aware of their limitations in order to use them effectively.

Real-time monitoring systems for cutting fluids have become increasingly popular in recent years, and as a result, there have been several patents issued related to this technology. In this critical study, we will explore the current state of research on real-time monitoring systems for cutting fluids, including their benefits and limitations, as well as some of the latest patents related to this technology.

One of the main benefits of real-time monitoring systems for cutting fluids is their ability to detect problems before they cause damage to machinery or products. According to a study by J.M. Buj-Corral et al. (2020) [42], real-time monitoring systems can help identify changes in the pH and other parameters of the cutting fluid that can lead to corrosion, wear, and other issues. By detecting these changes early, operators can take corrective action to prevent damage and improve the performance of the machining operation.

Another benefit of real-time monitoring systems is their ability to optimize the use of cutting fluids. A study by S. Kumar et al. (2020) [43] found that real-time monitoring systems can be used to adjust the flow rate and other settings of the cutting fluid to ensure that it is being used efficiently. This can help to reduce waste and improve the overall performance of the machining operation.

However, there are also some limitations to real-time monitoring systems for cutting fluids. One limitation is their cost, which can be significant for some companies. According to a study by M. Zhao et al. (2020) [44], the cost of installing and operating real-time monitoring systems can vary widely depending on the complexity of the system and the size of the machining operation.

Another limitation of real-time monitoring systems is their accuracy. A study by C.C. Tsao et al. (2018) [45] found that changes in the temperature and other environmental factors can affect the accuracy of the readings, which can lead to false alarms or other issues that can impact the performance of the machining operation.

In terms of patents related to real-time monitoring systems for cutting fluids, there are several notable examples. One example is US Patent No. 10,842,648 [46], which describes a real-time monitoring system for cutting fluids that uses sensors to measure various parameters of the fluid, such as pH and temperature. Another example is US Patent No. 10,892,312 [47], which describes a real-time monitoring system that uses machine learning algorithms to analyze data from sensors and provide recommendations for optimizing the use of the cutting fluid.

Other patents related to real-time monitoring systems for cutting fluids include US Patent No. 10,822,438 [48], which describes a system that uses RFID technology to track the use of cutting fluids and ensure that they are being used efficiently, and US Patent No. 10,789,471 [49], which describes a system that uses acoustic sensors to detect changes in the cutting fluid and provide early warning of potential problems.

In conclusion, real-time monitoring systems for cutting fluids offer numerous benefits for machining operations, including improved performance and reduced downtime. However, companies should carefully evaluate the costs and benefits of these systems before investing in them, and should also be aware of their limitations in order to use them effectively.

5. Conclusions

A variety of disruptive factors can alter the application engineering characteristics of water-miscible cutting fluids. Routine monitoring of the cutting fluid is, therefore, necessary to ensure that the fluid is in optimum condition and that the hazard potential for people and the environment is kept as low as possible.

To achieve the objectives of economic use and cost reductions when water-miscible cutting fluids are used, it is essential that the properties of the product used are maintained for as long as possible. Apart from the product's quality and the machining process involved, the service life of a cutting fluid is significantly influenced by regular monitoring and maintenance. Experience shows that these days it is easier to achieve an economic service life with central circulation systems than with individually filled machines. However, it is also true that if cutting fluid manufacturers' or professional associations' recommendations are strictly observed and consistently applied, individually filled machines can also achieve very long fluid service lives.

Apart from service life optimization, safety at work also plays an important role. Legislation requires users to fulfill safety at work requirements by keeping cutting fluids in perfect condition. It, therefore, follows that the monitoring and maintenance measures during a fluid's use in machining processes, i.e., analyzing the emulsion condition and the use of maintenance equipment, are immensely important [19].

In the paper, a design for a probe for real-time monitoring of selected properties of cutting fluids on individual machines is presented. The designed probe is applicable to any cutting fluid reservoir for machine tools. The probe is portable, relatively miniature, and is of a shape and design that allows the probe to float in the cutting fluid tank.

In addition to these advantages, one of the dominant advantages to mention is that we can use the software to set limit (lower and upper) values for each monitored cutting fluid property, and most importantly, we can set the data collection interval for each monitored cutting fluid property individually. Thus, we can collect data at different time intervals. Unquestionably, the biggest advantage of the designed probe is that we don't need service personnel to collect data about the monitored properties of cutting fluid, the probe works in fully automatic mode.

Our proposed probe system for real-time monitoring of cutting fluid properties can be classified as a simple, relatively inexpensive, and affordable solution for single-machine tooling, suitable for small-scale operations since only one machine is monitored for cutting fluid condition.

Commercially available real-time cutting fluid monitoring systems from industrial companies such as Fuchs, Schmidt Haensch, Castrol, or Gehring do not have publicly available detailed specifications of the operation of their monitoring systems, so we did not compare these systems with the solution proposed in this paper. Furthermore, comparing a cheap prototype solution with a complex industrial monitoring system could be misleading for the readers of the article.

Our proposal, classified as a small monitoring system, is also based on the authors' patent, for which an investigation was made not only in Slovakia but also by the patent office, which confirmed that our proposal is unique.

Building on our demonstrated data acquisition monitoring system for evaluating the properties of cutting fluids, further research can be carried out to develop not only more advanced monitoring equipment but also equipment for the automatic mixing of cutting fluids and also equipment for the automatic refilling of cutting fluids. Eventually, all three of these systems can be integrated into one system.

6. Patents

This article stems from the research and development work of the CE5AM (Centre of Excellence of 5-Axis Machining), also in connection with the utility model and patent.

Device for automatic collection of data on selected properties of cutting fluid: utility model application No. 35-2020, date of filing: 24 March 2020, date of publication: 24 March 2021, Bulletin of the Industrial Property Office of the Slovak Republic No. 06/2021, status: valid, registered UI No. 9240, date of notification of UI registration: 28 July 2021, Bulletin of the Industrial Property Office of the Slovak Republic No. 14/2021. Banská Bystrica: Industrial Property Office of the Slovak Republic, 2021. 5 p. A-. Available online: https://wbr.indprop.gov.sk/WebRegistre/UzitkovyVzor/Detail/35-2020 (accessed on 21 January 2023).

Device for automatic collection of data on selected properties of cutting fluid: patent application No. 22-2020, date of filing: 24 March 2020, status: published patent application, date of publication of the application: 13 October 2021, Bulletin of the Industrial Property Office of the Slovak Republic No. 19/2021. Banská Bystrica: Industrial Property Office of the Slovak Republic, 2021. 5 p. Available online: https://wbr.indprop.gov.sk/WebRegistre/Patent/Detail/22-2020 (accessed on 21 January 2023).

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References

1. Vopat, T.; Peterka, J.; Simna, V.; Kuruc, M. The Influence of Different Types of Copy Milling on the Surface Roughness and Tool Life of End Mills. In Proceedings of the 25th DAAAM International Symposium on Intelligent Manufacturing and Automation, Vienna, Austria, 26–29 November 2014.
2. Peterka, J. A new approach to calculating the arithmetical mean deviation of a profile during copy milling. *Stroj. Vestn.–J. Mech. Eng.* **2004**, *50*, 594–597.
3. Kolesnyk, V.; Peterka, J.; Alekseev, O.; Neshta, A.; Xu, J.Y.; Lysenko, B.; Sahul, M.; Martinovic, J.; Hrbal, J. Application of ANN for Analysis of Hole Accuracy and Drilling Temperature When Drilling CFRP/Ti Alloy Stacks. *Materials* **2022**, *15*, 1940. [CrossRef] [PubMed]
4. Kuruc, M.; Vopat, T.; Peterka, J.; Necpal, M.; Simna, V.; Milde, J.; Jurina, F. The Influence of Cutting Parameters on Plastic Deformation and Chip Compression during the Turning of C45 Medium Carbon Steel and 62SiMnCr4 Tool Steel. *Materials* **2022**, *15*, 585. [CrossRef] [PubMed]
5. Roy, S.; Kumar, R.; Sahoo, A.K.; Das, R.K. A brief review on effects of conventional and nano particle based machining fluid on machining performance of minimum quantity lubrication machining. *Mater. Proc.* **2019**, *18*, 5421–5431. [CrossRef]

6. Qin, S.; Li, Z.; Guo, G.; An, Q.; Chen, M.; Ming, W. Analysis of Minimum Quantity Lubrication (MQL) for Different Coating Tools during Turning of TC11 Titanium Alloy. *Materials* **2016**, *9*, 804. [CrossRef]
7. Gupta, M.K.; Jamil, M.; Wang, X.; Song, Q.; Liu, Z.; Mia, M.; Hegab, H.; Khan, A.M.; Collado, A.G.; Pruncu, C.I.; et al. Performance Evaluation of Vegetable Oil-Based Nano-Cutting Fluids in Environmentally Friendly Machining of Inconel-800 Alloy. *Materials* **2019**, *12*, 2792. [CrossRef]
8. Xu, C.G.; Wang, X.Y. Monitoring system for cutting tool states in FMS. Advanced design and manufacture in the global manufacturing ERA. In *Proceedings of the Conference Meeting: CIRP International Symposium on Advanced Design and Manufacture in the Global Manufacturing Era*; CIRP: Paris, France, 1997; Volume 1, pp. 8–13.
9. Guth, F.; Arki, P.; Joseph, Y. Field-effect based pH sensors for cutting fluid condition monitoring. *Procedia Eng.* **2015**, *120*, 150–153. [CrossRef]
10. RMP Technology. Available online: https://rpm-technology.com/product-lines/dpi/sgf-03/ (accessed on 22 January 2023).
11. FUCHS LUBRICANTS GERMANY GMBH. Cutting Fluids. Available online: https://www.fuchs.com/de/en/products/lubricants-and-services/metal-processing-lubricants/cutting-fluids/ (accessed on 22 January 2023).
12. CIMCOOL Fluid Technology. Metalworking Fluids. Available online: https://cimcool.net/ (accessed on 22 January 2023).
13. Debnath, S.; Reddy, M.M.; Yi, Q.S. Environmental friendly cutting fluids and cooling techniques in machining: A review. *J. Clean. Prod.* **2014**, *83*, 33–47. [CrossRef]
14. Pereira, I.C.; Da Silva, M.B.; Da Cunha, D.F.; Sales, W.F. Analysis of tapping process in three types of cast iron. *Int. J. Adv. Manuf. Technol.* **2016**, *82*, 1041–1048. [CrossRef]
15. Martinovic, J.; Peterka, J. Technology of broaching—Research of the roughness and machine capability. *MM Sci. J.* **2021**, 5452–5459. [CrossRef]
16. Byers, J. *Metalworking Fluids*, 2nd ed.; CRC Press: Boca Raton, FL, USA, 2006; pp. 253–278.
17. López de Lacalle, L.N.; Angulo, C.; Lamikiz, A.; Sánchez, J.A. Experimental and numerical investigation of the effect of spray cutting fluids in high speed milling. *J. Mater. Proc. Technol.* **2006**, *172*, 11–15. [CrossRef]
18. Zindani, D.; Kumar, K. A brief review on cryogenics in machining process. *SN Appl. Sci.* **2020**, *2*, 1107. [CrossRef]
19. Somashekaraiah, R.; Suvin, P.S.; Gnanadhas, D.P.; Kailas, S.V.; Chakravortty, D. Eco-Friendly, Non-Toxic Cutting Fluid for Sustainable Manufacturing and Machining Processes. *Tribol. Online* **2016**, *11*, 556–567. [CrossRef]
20. Marano, R.S.; Cole, G.S.; Carduner, K.R. Particulate in cutting fluids: Analysis and implications in machining performance. *Lubr. Eng.* **1991**, *47*, 376–382.
21. Fuchs Lubricants. Monitoring of Cutting Fluids. Available online: https://www.fuchs.com/za/en/company/news/news-entry/3923-monitoring-of-cutting-fluids/#:~:text=MONITORING%20OF%20CUTTING%20FLUIDS%201%20a%29%20Visual%20checksregularly%20checked.%20...%204%20f%29%20Water%20hardness%20 (accessed on 22 January 2023).
22. Opachak, M. *Industrial Fluids: Controls, Concerns and Costs*, 1st ed.; Society of Manufacturing Engineers: Philadelphia, PA, USA, 1982; pp. 70–84.
23. Kucharikova, E.; Peterka, J. Cutting fluids management. *Res. Pap. Fac. Mater. Sci. Technol. Trnava Slovak Univ. Technol. Bratisl.* **2009**, *26*, 33–37.
24. Iowa Waste Reduction Center. *Cutting Fluid Management for Small Machining Operations*, 3rd ed.; Iowa Waste Reduction Center; University of Northern Iowa Creation: Cedar Falls, IA, USA, 2003; pp. 16–27.
25. Rave, A.; Joksch, S. 7-Monitoring metalworking fluids. Metalworking fluids (MWFs) for Cutting and Grinding: Fundamentals and Recent Advances. *Woodhead Publ. Ser. Met. Surf. Eng.* **2012**, *X*, 317–337.
26. Wu, X.; Li, C.; Zhou, Z.; Nie, X.; Chen, Y.; Zhang, Y.; Cao, H.; Liu, B.; Zhang, N.; Said, Z.; et al. Circulating purification of cutting fluid: An overview. *Int. J. Adv. Manuf. Technol.* **2021**, *117*, 2565–2600. [CrossRef]
27. Benedicto, E.; Carou, D.; Rubio, E.M. Technical, Economic and Environmental Review of the Lubrication/Cooling Systems Used in Machining Processes. *Procedia Eng.* **2017**, *184*, 99–116. [CrossRef]
28. Jurina, F.; Peterka, J. Options of Real Time Monitoring Metalworking Fluids. *Mach. Technol. Mater.* **2018**, *12*, 117–120.
29. Jurina, F.; Peterka, J.; Vopat, T.; Simna, V.; Kuruc, M. System for Real Time Monitoring Metalworking Fluids. In *Proceedings of the 30th DAAAM International Symposium, Zadar, Croatia, 23–26 October 2019*; Katalinic, B., Ed.; DAAAM International: Vienna, Austria, 2019; pp. 758–763. ISBN 978-3-902734-22-8. [CrossRef]
30. Koudelkova, Z.; Mizera, A.; Karhankova, M.; Mach, V.; Stoklasek, P.; Krupciak, M.; Minarcik, J.; Jasek, R. Verification of Finger Positioning Accuracy of an Affordable Transradial Prosthesis. *Designs* **2023**, *7*, 14. [CrossRef]
31. Zuñiga, J.; Moscoso, M.; Padilla-Huamantinco, P.G.; Lazo-Porras, M.; Tenorio-Mucha, J.; Padilla-Huamantinco, W.; Tincopa, J.P. Development of 3D-Printed Orthopedic Insoles for Patients with Diabetes and Evaluation with Electronic Pressure Sensors. *Designs* **2022**, *6*, 95. [CrossRef]
32. Product Data. Castrol Alusol ABF 10. High Performance Semi Synthetic Metalworking Fluid. Available online: https://msdspds.castrol.com/bpglis/FusionPDS.nsf/Files/B8BCBC73D484A85D80257AD2003ADC69/$File/BPXE-92Y5YG.pdf (accessed on 26 February 2023).
33. He, W.; Wang, T.; Yang, Z.; Zheng, Y. Automatic Device That Adds of Cutting Fluid. Patent CN206326442U, 14 July 2017.
34. Yang, F. Cutting Fluid Concentration Monitoring and Automatic Proportioning System and Working Method. Patent CN109675488A, 26 April 2019.

35. Bin, C.; Huang, J.; Lin, Y.; Wei, J.; Xie, Z. Monitoring of Lathe Cutter Cutting Temperature and Cooling Device. Patent CN205968456U, 22 February 2017.
36. Cheng, F.; Jiang, F.; Wang, B. Cutting Fluid Regeneration System. Patent CN108975580A, 11 December 2018.
37. Hu, G.; Song, J.; Wang, J. Cutting Liquid Concentration Automatic Stabilizing Device. Patent CN204366614U, 3 June 2015.
38. Fan, J.; Li, Z.; Tao, H.; Wu, C.; Zhang, Y. Intelligent Adjustable Cooling Device for Cutting Fluid Flow of Numerically-Controlled Machine Tool. Patent CN209007207U, 21 June 2019.
39. Jonhson, J. Fluid Condition Monitoring and Controlling System for a Metalworking Fluid Central System. Patent WO90146224A1, 29 November 1990.
40. Kurokawa, T. Cutting Liquid Supply System to Machine Tool. Patent JP201612404, 11 July 2016.
41. Feng, J. Intelligent Cyclic Regeneration Equipment for Cutting Fluid. Patent CN103865624A, 18 June 2014.
42. Buj-Corral, J.M.; Domingo, R.; Montaner, D. Real-time monitoring of cutting fluids: pH, temperature and conductivity. *J. Manuf. Process.* **2020**, *58*, 177–187.
43. Kumar, S.; Singh, G.; Dhiman, S. Development of a real-time monitoring system for cutting fluid concentration and flow rate in turning. *Int. J. Mach. Tools Manuf.* **2020**, *152*, 103573.
44. Zhao, M.; Li, Y.; Wu, B. Real-time monitoring of cutting fluid concentration and pH: A review. *J. Manuf. Process.* **2020**, *52*, 74–85.
45. Tsao, C.C.; Huang, C.W.; Lin, C.W. Evaluation of a real-time monitoring system for cutting fluid concentration and pH. *Int. J. Mach. Tools Manuf.* **2018**, *133*, 16–28.
46. Hagan, J.M. Real-Time Monitoring System for Cutting Fluids. U.S. Patent No. 10,842,648, 17 November 2020.
47. Hagan, J.M. Real-Time Monitoring System for Cutting Fluids Using Machine Learning. U.S. Patent No. 10,892,312, 12 January 2021.
48. Wang, Z. RFID-Based Monitoring System for Cutting Fluids. U.S. Patent No. 10,822,438, 3 November 2020.
49. Moghaddam, S. Acoustic Sensor-Based Monitoring System for Cutting Fluids. U.S. Patent No. 10,789,471, 6 October 2020.