ISSN: 2710-0588

Development and Physicochemical Properties of New Cutting Fluid for Titanium Alloy Machining

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Abstract

This article focuses on titanium alloy research, using triethanolamine oleate as the lubricating additive, the reaction product of triethanolamine, monoethanolamine and decanoic acid as a rust inhibitor, together with modified organosilicon antifoam agent and triazine fungicide, a new type of titanium alloy cutting fluid with excellent environmental protection and rust inhibition was prepared, and its physicochemical properties were systematically investigated through a large number of experiments. The results show that the prepared cutting fluid meets all specifications and demonstrates promising application prospects.

Keywords

Titanium Alloy; Cutting Fluid; Triethanolamine Oleate; Physicochemical Properties.

1. Introduction

Titanium alloys have been widely used in aerospace, biomedicine, and other fields due to their high strength and good corrosion resistance. However, their poor thermal conductivity and high chemical reactivity lead to severe tool wear and poor surface quality during machining, which hinders the improvement of processing efficiency and quality. Currently, solutions to issues such as tool wear and poor surface quality in titanium alloy machining mainly focus on improving tool materials and structures, adopting new cooling methods, utilizing auxiliary and composite energy fields for processing, employing finite element analysis for prediction, among other methods. These solutions typically have complex structures and to some extent increase costs. In comparison, the application of cutting fluids remains a common and effective approach. Currently, the development of cutting fluid additives is mostly based on common metals such as steel or aluminum alloys, with limited research on cutting fluid additives for titanium alloys. Therefore, the development of cutting fluids for titanium alloy machining is of great significance.

Cutting fluids can be divided into oil-based cutting fluids and water-based cutting fluids based on different base oil contents. Oil-based cutting fluids have a high base oil content, leading to excellent extreme pressure lubrication performance. However, oil-based cutting fluids suffer from poor cooling performance and environmental pollution issues [1]. Additionally, cleaning and disposal of oil-based cutting fluids can be challenging. Water-based cutting fluids can be further categorized into emulsions, semi-synthetic cutting fluids, and fully synthetic cutting fluids based on the base oil content. Fully synthetic water-based cutting fluids have the highest water content, typically offering better cooling properties than oil-based cutting fluids, and can achieve extreme pressure lubrication effects through the addition of suitable additives.

In conclusion, the development of environmentally friendly cutting fluids that are harmless to humans and comply with green development requirements is the future trend for cutting fluid development [2]. The development of green and environmentally friendly water-based fully synthetic cutting fluids is of significant importance.

ISSN: 2710-0588

2. Composition Design and Preparation of Cutting Fluid

2.1. Selection of Additives

During the machining of titanium alloys, the cutting zone experiences high temperatures and severe wear, leading to issues such as tool wear and poor surface quality. Therefore, in order to reduce the cutting temperature, reduce friction, wash off the chips at the same time, improve the cutting quality and cutting efficiency, it is necessary to use good cooling and lubrication performance, and have a certain cleaning and anti-rust cutting fluid.

2.1.1. Selection of Lubricating Additives

During the processing of difficult-to-machine materials such as titanium alloys, the mutual friction between the tool, chips, and workpiece can lead to tool wear, decreased tool lifespan, and reduced surface quality. Therefore, it is necessary to add extreme pressure anti-wear lubricants to the cutting fluid to effectively reduce tool wear and improve surface quality. The traditional extreme pressure antiwear lubricants are compounds containing chlorine, sulfur and phosphorus. However, due to the tendency of sulfur and phosphorus compounds to promote microbial growth in aqueous solutions and the toxicity of chlorides, the use of traditional extreme pressure anti-wear lubricants has gradually decreased. Currently, more and more researchers are focusing on developing new water-based lubricant additives for titanium alloys. Since triethanolamine oleate is a water-soluble lubricant with excellent lubrication effect, this study used triethanolamine oleate as a lubrication additive [3].

2.1.2. Selection of Surfactants

Surfactants in cutting fluids can be broadly divided into ionic, nonionic and other types. Commonly used anionic surfactants include carboxylates, sulfates, sulfonates and phosphates; cationic surfactants are generally divided into amine salts, quaternary ammonium salts and heterocyclic three types; nonionic surfactants according to hydrophilic groups to categorize, which can be divided into two major categories of polyoxyethylene and polyol type. Other types of surfactants include fluorinated surfactants, emulsifiers containing heterocyclic groups, quaternized glycerol phosphate, substituted phenol amine salts, siloxane sulfates, and polyamino acid type surfactants [4].

The lubricant additive chosen for this paper, triethanolamine oleate, is itself a nonionic surfactant, and thus serves a multi-purpose function here.

2.1.3. Selection of Rust Preventive Agent

Due to the high water content in fully synthetic cutting fluids, it is easy to cause rust and corrosion on machine tools, cutting tools, and workpieces. Some workpieces may stay between processes for a long time, so the requirement for rust prevention in fully synthetic cutting fluids is quite stringent. The rust prevention principle of rust inhibitors, as shown in Figure 1, is to form a protective layer on the metal surface to prevent contact between the metal surface and the corrosive medium.

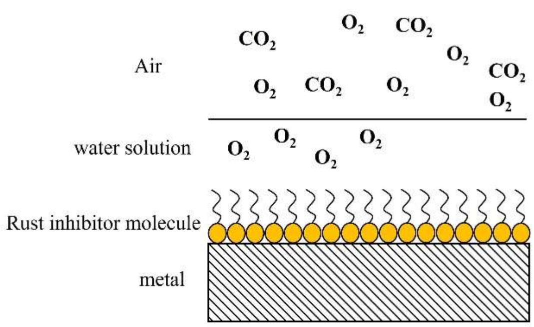

Figure 1. Mechanism of anti-rust agent

ISSN: 2710-0588

Rust inhibitors can be divided into organic series, inorganic series, and composite series. The organic series includes compounds such as benzoic acid, sulfonic acid, dicarboxylic acid, and amino acids; the inorganic series mainly consists of nitrites, molybdates, phosphates, silicates, etc.; while the composite series often involves multiple components. Traditional rust inhibitors like sodium nitrite can generate carcinogens under certain conditions, posing risks to human health, and are gradually being banned by various countries. In recent years, a large number of scholars have begun to develop environmentally friendly water-based rust inhibitors.

Research has shown that the reaction products of mixed alkanolamines with dicarboxylic acids and tricarboxylic acids exhibit excellent rust prevention and corrosion resistance [5]. In this study, triethanolamine, monoethanolamine and decanedioic acid were selected as novel rust inhibitors in cutting fluids, and they were formulated in certain proportions. The results indicate that this formulated rust inhibitor demonstrates excellent rust prevention properties.

2.1.4. Other Additives

In the process of metal processing, if too much foam is produced, it will not only affect the observation effect, but also make the flow of the working fluid complex, affecting the lubrication and cooling performance of the cutting fluid. Therefore, the additives of cutting fluid should use low-foam components as far as possible or add appropriate defoamer. According to the different components, the defoamer mainly includes non-silicon type, polyether type, silicone type and silo-ether compound type [6]. Because the silicone defoamer modified by special polyether has good water solubility and strong defoamer ability, this study selected the silicone defoamer modified by special polyether.

During the use of cutting fluids, various impurities can mix into them, and the water used to dilute the cutting fluid may contain ions such as potassium, calcium, magnesium, and others. These factors can promote the growth of microorganisms, leading to bacterial proliferation and causing the cutting fluid to deteriorate. Therefore, it is necessary to add appropriate bactericides to the cutting fluid. Taking into account both the bactericidal effectiveness and the impact on the environment and human health, this study selected highly efficient and low-toxicity triazine-type bactericides.

2.2. Preparation of Cutting Fluid

The preparation process of the cutting fluid is shown in Figure 2. The cutting fluid is prepared using the DF-101S thermostatic magnetic stirring device, and Figure 3 is the thermostatic magnetic stirring device. The deionized water comes from the laboratory reverse osmosis deionized pure water machine, as shown in Figure 4.

According to the proportions, start by adding 1/3 of deionized water, then sequentially add the additives into the deionized water, followed by adding the remaining deionized water. Heat the mixture (50°C to 70°C) and stir until the system is uniformly clear, resulting in the original cutting fluid. The composition and proportions of the cutting fluid are shown in Table 1. During the experiment, dilute the concentrated cutting fluid with deionized water to 5% (mass fraction).

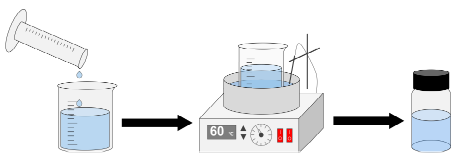

Figure 2. Cutting fluid preparation process

ISSN: 2710-0588

Figure 3. Heat collecting constant temperature magnetic stirrer

Figure 4. Reverse osmosis deionization water purifier

Table 1. Cutting fluid composition and proportion

Additives	Mass fraction w/%
Triethanolamine	10
Monoethanolamine	1.5
Triethanolamine oleate	5
Bactericides	0.5
Sebacic acid	1.5
Defoaming agent	0.1
Deionized water	Surplus

3. Study on Physical and Chemical Properties of Cutting Fluid

In the metal cutting process, cutting fluid mainly has four functions: cooling, lubrication, cleaning and rust prevention, and the study of the physicochemical properties of cutting fluid is not only an important guarantee of normal processing, but also an important basis for the use and management of cutting fluid [7]. Physical and chemical properties of cutting fluid research is closely related to its processing performance [8]. In this chapter, the physical and chemical properties of new cutting fluids are evaluated and analyzed by laboratory methods.

3.1. Experimental Reagents and Materials

Anhydrous ethanol (analytical pure), gray cast iron, copper sheet, aluminum alloy sheet, pH wide test paper.

3.2. Experimental Apparatus

Electrothermal constant temperature incubator, SDKZL-0904 type interfacial tension tester, electronic balance.

3.3. Development of Cutting Fluid Physical and Chemical Properties Test

3.3.1. Appearance of Cutting Fluid

According to the national standard GB/T 6144-2010 "Synthetic Cutting Fluids," the concentrated cutting fluid should appear as a homogeneous liquid without stratification or precipitation, while the diluted cutting fluid should be transparent or semi-transparent. The appearance of the newly developed cutting fluid concentrate and dilution at room temperature is shown in Figure 5.

ISSN: 2710-0588

(a) concentrated solution (b) diluent

Figure 5. Appearance of oleic acid triethanolamine cutting fluid

As can be seen from the Figure 5, the formulated cutting fluid is light yellow and transparent, and after dilution is colorless and transparent liquid, and there is no delamination, precipitation and other phenomena, the stability is good.

3.3.2. Storage Stability Test

The storage stability of cutting fluids refers to the ability of the cutting fluid to maintain its performance and quality during storage. To ensure the storage stability of cutting fluids, methods such as controlling storage conditions, regular inspections, adding antioxidants and corrosion inhibitors, periodic replacement, and maintenance are commonly employed.

In order to test the storage stability of the developed new cutting fluid, according to the requirements of the national standard GB/T6144-2010 "Synthetic Cutting Fluid", 50mL of the new cutting fluid concentrate was put into a 100mL stoppered cylinder, which was placed in a constant temperature drying oven and kept in 70±3℃ for 5h, and then the cylinder was taken out and placed in room temperature (15~35℃) for 3h, and then kept in a low temperature environment of -12±3℃ for 24h, and finally taken out and stood to room temperature for 1h. After that, the cylinder was kept in a low temperature environment at -12±3°C for 24h, and finally the cylinder was taken out and left to room temperature for 1h. The experimental test results are shown in Figure 6.

Figure 6. Storage stability test

As can be seen from Figure 6, the prepared new cutting fluid can be restored to its original state after the experiment without delamination, phase change and gelatinization. It can be considered that the storage stability of the new cutting fluid meets the requirements of the national standard.

3.3.3. pH Measurement

pH is also an important performance indicator of cutting fluid, too high or too low will affect the performance of the cutting fluid. A high pH value may lead to skin allergies in operators and corrosion of non-ferrous metals; whereas a low pH value can impact the rust prevention and antimicrobial properties of the cutting fluid [9].

According to the national standard GB/T6144-2010 "synthetic cutting fluid" requirements, the use of pH precision test paper measurement method is to be immersed in the liquid to be tested, quickly removed, and compared with the standard colorimetric plate, so as to get the pH value.

ISSN: 2710-0588

Use pH extensive test paper to measure the pH value of the test liquid, as shown in Figure 7. As can be seen from the above figure, the measured pH value of the new cutting fluid is about 9, which is in line with the pH requirements of the cutting fluid.

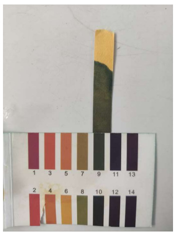

Figure 7. pH of cutting fluid compared with standard colorimetric card

3.3.4. Measurement of Surface Tension

The surface tension of a liquid refers to the tendency of the liquid surface to contract due to the intermolecular forces between molecules on the surface. The magnitude of the surface tension depends on the nature of the liquid and environmental conditions. Generally, the stronger the intermolecular forces, the greater the surface tension of the liquid. The surface tension of cutting fluids has a significant impact on lubrication and cooling effects during the cutting process.

According to GB/T 6144-2010, the surface tension is measured using a tensiometer (ring method). In this study, the surface tension of the cutting fluid was measured using the SDKZL-0904 type tensiometer, as shown in Figure 8. After testing, the platinum ring was heated and dried with an alcohol lamp, followed by multiple measurements.

Figure 8. Surface tension measurement of cutting fluid

The measured surface tension values were collected, as shown in Figure 9. It can be seen from the figure that the measured surface tension is lower than 40mN/m in the standard, indicating that the surface tension of the prepared cutting fluid meets the standard and has good surface activity.

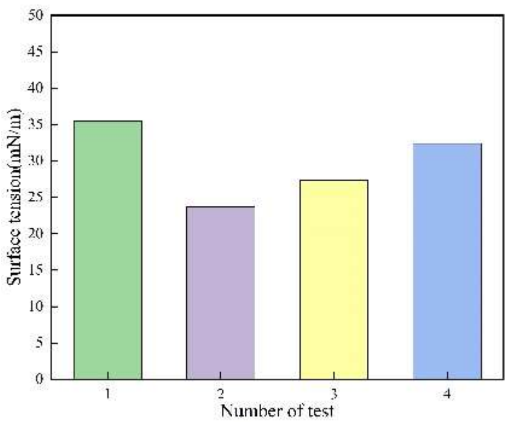

Figure 9. Cutting fluid surface tension test

ISSN: 2710-0588

3.3.5. Corrosion Test

The corrosivity experiment of the new cutting fluid was carried out in accordance with the requirements of the national standard GB/T6144-2010 "Synthetic Cutting Fluid". The test piece material is cast iron and copper, the test piece will be polished smooth before the experiment [10], the main chemical composition of the material is shown in the following Table 2, 3.

Table 2. Chemical Composition of cast iron (%)

Fe	C	Si	Mn	P	S
Substrate	3.0-3.3	1.8-2.2	0.6-0.9	<0.3	<0.12

Table 3. Chemical composition of copper (%)

Cu+Ag	Fe	Pb	S	Sb	As	Bi
99.90	0.005	0.005	0.005	0.002	0.002	0.001

The specimens of different materials are fully immersed in containers filled with diluted cutting fluid. Glass covers are placed on the containers of each specimen to prevent external contaminants from entering. The containers are then placed in a constant temperature chamber at 55±2℃ for a specified experimental time (24 hours for cast iron, 4 hours for copper). After the experiment, each specimen is removed and the surface condition is examined.

Figure 10. Appearance of cast iron before and after corrosion test

Figure 11. Appearance of copper before and after corrosion test

From the Figure 10,11, it can be observed that there is no corrosion on the surfaces of cast iron and copper, indicating that the prepared cutting fluid exhibits good corrosion inhibition for cast iron and copper.

3.3.6. Rust Resistance Test

During metal cutting processes, metal surfaces are prone to coming into contact with corrosion-inducing agents such as moisture in the air or cutting fluids, leading to oxidation or rusting of the metal. Therefore, cutting fluids are typically required to possess a certain level of rust prevention properties. In accordance with the national standard GB/T6144-2010 "Synthetic Cutting Fluids," rust prevention tests are conducted for new cutting fluids.

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Figure 12. Single sheet rust resistance test

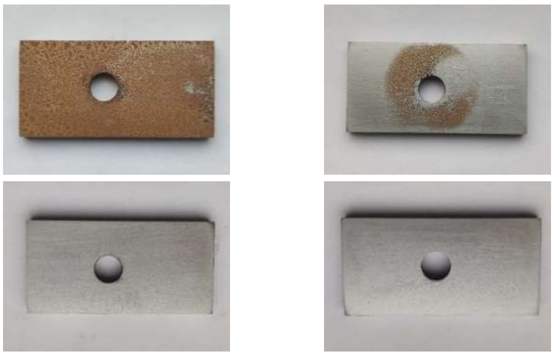

Figure 13. Laminated rust resistance test

The results of the rust prevention tests for single-piece and stacked-piece samples are shown in Figure 12, 13. It can be observed from the graph that in the single-piece rust prevention test, there is no corrosion observed in the area where the cutting fluid droplets were applied. In the stacked-piece rust prevention test, there is no corrosion observed on the overlapping surfaces of the samples where the cutting fluid was applied, indicating excellent rust prevention performance of the cutting fluid that meets the standard.

3.3.7. Anti-foaming Test

Foaming in cutting fluids can interfere with the cutting process, affecting processing efficiency and quality. Therefore, antifoaming properties are an important performance indicator of cutting fluids. In accordance with the national standard GB/T6144-2010 "Synthetic Cutting Fluids," antifoaming tests are conducted for new cutting fluids.

Figure 14. Foam condition of cutting fluid after experiment

Figure 14 shows the foam situation of the cutting fluid after standing still. It can be observed that the volume of foam on the liquid surface is less than 2 milliliters, indicating that the cutting fluid exhibits good antifoaming properties.

3.4. Comprehensive Performance Evaluation Results of Developed Cutting Fluids

Table 4 presents the comprehensive performance evaluation results of the prepared cutting fluid. This cutting fluid performs excellently in terms of harmlessness, appearance, rust prevention properties, etc. It is suitable for various cutting processing scenarios and exhibits good compatibility with both human health and the environment.

Table 4. Results of comprehensive performance evaluation of new cutting fluid

	Item	Test index	Developed cutting fluid	Experimental method
Concent-rated solution	Appearance	No stratification, no precipitation, uniform transparent liquid	Light yellow transparent liquid	Visual inspection
	Storage stability	No delamination, phase change and gelatinization, can be restored to the original state after the test	No stratification, no precipitate	GB/T6144-2010
5% diluent	Appearance	Transparent	Transparent	Visual inspection
	pH value	8.0~10.0	8~9	pH test paper
	Defoaming property/(mL·min)$^{-1}$	Not more than 2	0	GB/T6144
	Surface tension/(mN·m^{-1})	Not more than 40	23.72	GB/T6144
	Rust resistance test(35℃±2℃), Cast iron			
	Single sheet, 24h	Qualified	Qualified	
	Lamination, 4h	Qualified	Qualified	
	Corrosion test(55℃ ±2℃)			GB/T6144
	Cast iron, 24h	Level A	Level A	
	Copper, 4h	Level A	Level A	

4. Conclusion

(1) Firstly, an analysis and selection of additives for the cutting fluid were conducted. Oleic triethanolamine was chosen as the lubricant additive, while triethanolamine, monoethanolamine, and decanoic acid were used as reactants for the rust inhibitor. The antifoaming agent was a modified organic silicon compound, and the biocide was of the triazine class. A new green and highly rust-resistant cutting fluid for titanium alloys was prepared.

(2) According to GB/T6144-2010, the storage stability, surface tension, corrosion resistance, rust prevention properties, antifoaming properties, and other physicochemical performance indicators of the developed cutting fluid were studied. The results indicate excellent physicochemical properties across all aspects.

References

[1] L.D. Wang, G.B. Tao and J.L. Zhong: Current Research Situation and Developing Trend of Environmental Cutting Fluids, Journal of Chongqing University of Technology (Natural Science), 2015, 29(04): 44-47+96.

[2] H.Q. Xiong, G.X. Jiang and G.X. Chen: Development of Environmentally Friendly High Performance

[3] Semi-synthetic Cutting Fluid, Lubrication Engineering, 2016, 41(06): 106-112.

[4] X.L. Zhang, X.M. Jia: Triethanolamine and Its Application in Water Base Cutting Fluids, Lubricating Oil, 1999,(05):36-37.

[5] Y.L. Zhang: Preparation of Environment-friendly Water-based Nano-material Cutting Fluids and its Application (MA.Eng, Wuhan Institute of Technology, China 2016), p.9.

ISSN: 2710-0588

[6] W.J. Sun, H. Li and R.X. He: Development of a Total Synthetic Cutting Fluid for Nonferrous Metals, Journal of Southwest University (Natural Science Edition), 2018,40(01):157-164.

[7] X. Xu, W.Y. Xu and Y.F. Hu: Synthesis and Properties of A Novel Modified Polyether Defoamer, Guangzhou Chemical Industry, 2023,51(14):73-76.

[8] L.D. Wang: Research on Efficient Shaving Process And Environmental Protection Cutting Fluid (ME, Chongqing University, China 2014), p.23.

[9] J.Y. Zhu, Q.G. Jiang: Aqueous Cutting Fluid, Bearing, 1994,(12):35-39.

[10] S.F. Li: Study on New Green Water-based Cutting Fluid and its Mechanism (ME, Jiangnan University, China 2008), p.45.

[11] B. Yuan: Study on Preparation and Performance of Semi-synthetic Cutting Fluid (ME, Tianjin University of Science and Technology, China 2016), p.44.