ISSN: 2414-1895 DOI: 10.6919/ICJE.202108_7(8).0034

Study on the Lubrication Performance and Mechanism of a New-type of Cutting Fluid based on a Triethanolamine Borate Additive

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Abstract

Triethanolamine borate is a new type of green water-based synthetic cutting fluid additive, and its anti-friction and anti-wear properties in the cutting process have not been reported to date. Taking triethanolamine borate as the main research object and comparing it with glycerol, polyethylene glycol 400 (PEG400) and concentrated cutting fluids (MCFs) purchased from the market, a large number of milling experiments on titanium alloy materials were carried out. Based on the experimental data and a large number of comparative analyses, the lubrication effect of a cutting fluid based on a triethanolamine borate additive was systematically studied. Finally, the lubrication mechanism of the new cutting fluid based on a triethanolamine borate additive was studied by analysing the 3D molecular structure of triethanolamine borate and its reaction formula. The results show that among the four additives studied in this experiment, the properties of triethanolamine borate and glycerol are similar and superior to those of polyethylene glycol 400 and MCFs. Among the four cutting fluids with a 10% additive content, the cutting fluids with triethanolamine borate as the additive had the best comprehensive performance. By studying the reaction formula of triethanolamine borate and its 3D molecular structure, it is shown that triethanolamine borate is a cage-like heterocyclic compound. Triethanolamine borate contains nitrogen and boron elements with extreme pressure lubrication properties and can solve the problem of the easy hydrolysis of boric acid grease due to a lack of electrons of boron atoms by increasing steric hindrance.

Keywords

Triethanolamine Borate; Water-based Synthetic Cutting Fluid; Lubrication Additive; Titanium Alloy.

1. Introduction

With the development of the aviation industry, aircraft performance requirements are becoming increasingly rigorous [1]. Titanium alloys are widely used in the aviation industry [2-4] because of their high strength and good corrosion resistance. However, due to the poor thermal conductivity, low modulus of elasticity and high chemical activity of titanium alloy [5-7], tool wear is a very serious problem in the process of processing [8]. Tool wear phenomenon is an outstanding technological problem in the field of aviation manufacturing. Current practice shows that an excellent cutting fluid is an important means to improve the cutting performance of difficult-to-machine titanium alloy materials [9-10]. The cutting fluid can not only form a lubrication film between the tool, workpiece and chip but also reduce the cutting temperature by gasification and convective heat transfer to

ISSN: 2414-1895 DOI: 10.6919/ICJE.202108_7(8).0034

improve workpiece surface quality and tool durability [11-12]. It is well known that the use of water-based cutting fluids in the cutting process can effectively improve the processing efficiency, lubricant additives can reduce friction and wear, and a high water content be important for cooling [13].

In recent years, metal cutting fluids have been developing towards green and environmentally friendly water-based synthetic cutting fluids. While meeting the lubrication, cooling, cleaning and rust-proof functions, harm to the human body and environmental pollution caused by metal cutting fluids are decreasing [14-15]. Water-based synthetic cutting fluids rely on various additives to obtain excellent performance. The choice of additives includes surfactants, extreme pressure lubricants, rust inhibitors, etc. Among them, extreme pressure lubricants are related to the lubrication and wear resistance of cutting fluids [16]. Traditional extreme pressure lubricants contain elements such as sulphur, phosphorus and chlorine. Although they have excellent wear resistance, these lubricants do great harm to the human body and the environment [17]. With the progress of science and technology, boron extreme pressure lubricants, mainly organic borate esters, have attracted increasing attention. Organic borate esters have good antifriction and anti-wear properties and a high oil film strength, and they are non-toxic, harmless and degradable [18-19]. Triethanolamine borate has been extensively studied because of its excellent anti-rust properties [20], but its other properties have seldom been reported, especially when used as a lubricant for the metal cutting process.

In this paper, different water-based cutting fluids were prepared with triethanolamine borate as the main research object and with glycerol and polyethylene glycol as common lubricant additives, and the fluids were compared with green water-based cutting fluids purchased from the market. An in-depth study on triethanolamine-borate-based cutting fluids was carried out. The lubrication properties of the new cutting fluid with ester additives were studied, and the lubrication mechanism was determined.

2. Experiment

2.1 Experimental Materials

The test tool is a Swiss 68 degree 4 edge tungsten steel milling cutter. Its diameter, handle diameter, edge length and full length are 10 mm, 10 mm, 25 mm and 75 mm, respectively. The workpiece used in the test was TC4 titanium alloy with a density of 4.51 g/cm3 and a hardness of HRC31. The additives used in the test were triethanolamine borate, glycerol and polyethylene glycol 400, and a green water-based concentrate for the titanium alloy cutting fluid was purchased from the market (Dongguan Zetian lubricating Oil Co. LTD). The defoamer used in the experiment was a modified polyether, and the fungicide was isothiazolinone. Both were purchased from China Federal Fine Chemical Industry.

The test objects were cutting fluids composed of different lubricating additives and base fluids. The components of the base fluids included deionized water with a 99.5% volume ratio, fungicides with a 0.25% volume ratio and defoamers with a 0.25% volume ratio. The above three lubricating additives and market cutting fluid concentrates were mixed with a base fluid at a certain volume ratio, and they were allocated into cutting fluid samples with 5%, 10%, 15% and 20% contents, for a total of 16 groups. For example, 100 ml of a triethanolamine borate cutting fluid with a 5% triethanolamine borate content was obtained by mixing 5 ml of triethanolamine borate with 95 ml of the base fluid.

2.2 Experimental Equipment and Scheme.

The cutting test was carried out on a WINTEC MV-80 NC machining centre with a maximum speed of 5000 r/min. The dynamometer used was a YDX-III 9702 piezoelectric three-way milling dynamometer. The thermometer used was a THERMOVISION A20 infrared thermal imager. The cooling and lubrication modes of the cutting fluid were the spray type. Physical and schematic drawings of the experimental device are shown in Fig. 1. The dynamometer and the thermometer were installed before the experiment. The cutting fluid spray device was installed on the machine tool to ensure that the cutting fluid could be sprayed into the contact area during the test, and the position

ISSN: 2414-1895 DOI: 10.6919/ICJE.202108_7(8).0034

and spray volume of the cutting fluid spray device were ensured during the entire experiment. In the experiment, the processing parameters were applied by constant value. In this experiment, the spindle speed was 1200 r/min, the feed speed was 200 mm/min, the cutting depth was 0.2 mm and the cutting width was 10 mm. After installing the equipment and compiling the processing program, 16 groups of cutting fluids were tested in turn.

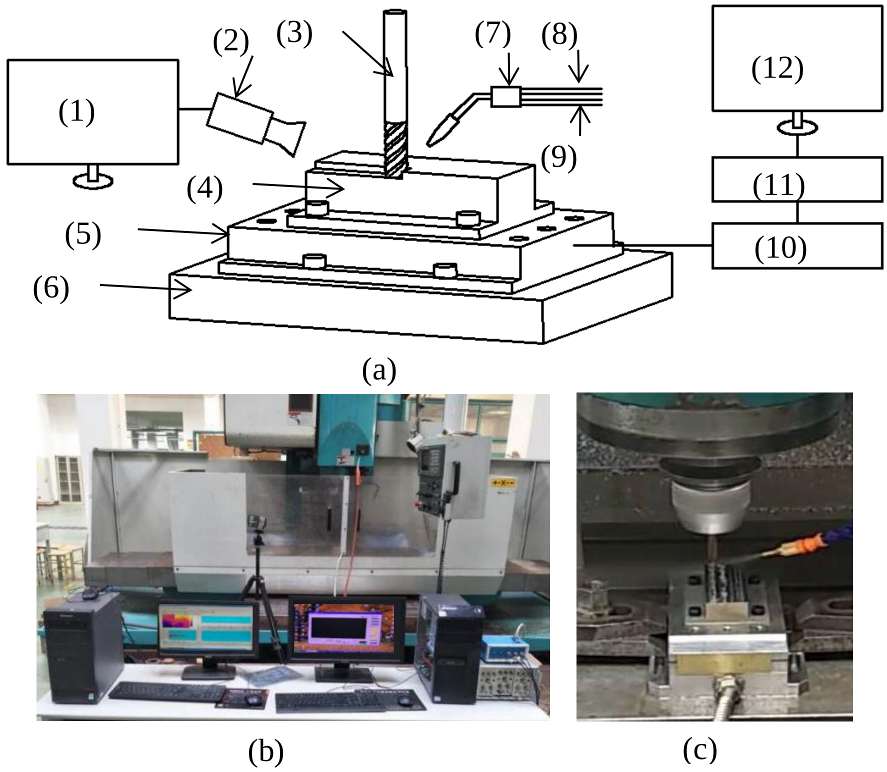

Fig. 1 Installation sketch of the milling test. b Installation physical drawing of the experimental measuring device. c Physical chart of the milling test process. (1) Milling temperature acquisition and analysis software; (2) infrared thermal imager; (3) milling cutter; (4) workpiece; (5) dynamometer; (6) machine tool workbench; (7) atomizer; (8) intake pipe; (9) cutting Fluid Pipe; (10) charge amplifier; (11) data acquisition instrument; (12) milling force acquisition and analysis software.

3. Study of the cutting performance and lubrication effect

3.1 Milling Force Analysis.

It is difficult to distinguish the performance of the cutting fluids by directly analysing the data obtained by the dynamometer. The experimental results need to be processed. Usually, the resultant milling force is used for characterisation and is calculated according to the resultant force calculation in Eq. (1). [21]. The resultant force calculation results are shown in Fig. 2, which compares the milling forces obtained from triethanolamine borate, glycerol, polyethylene glycol 400 and market cutting fluids at different contents. It can be seen from the figure that the resultant force of the market cutting fluid is the largest at any content, followed by polyethylene glycol 400. For cutting fluids prepared with glycerol and triethanolamine borate, the combined force of glycerol is greater than that of triethanolamine borate when the content is 5% and 10%, while the opposite is true when the content is 15% and 20%. According to the test results, triethanolamine borate is similar to glycerol in lubrication ability and superior to polyethylene glycol 400 and the market cutting fluid.

$$F=\sqrt{F_x^{\,2}+F_y^{\,2}+F_z^{\,2}} \tag{1}$$

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The variation of the resultant force measured by each cutting fluid with its content was analysed separately. The resultant force of the market cutting fluid gradually decreased when the content was 5% to 15% and then increased when the content was 20%. Similarly, the resultant force of triethanolamine borate obviously increased when the content was more than 10%. Polyethylene glycol 400 was the lowest at a 5% content, and the resultant force gradually increased before reaching a 15% content and slightly then decreased. For glycerol, the initial resultant force was basically unchanged, but the resultant force sharply decreased after the content of glycerol reached 20%. This situation was determined by the characteristics of each substance itself, in which the market cutting fluid and triethanolamine borate may increase their viscosity with an increasing additive content, resulting in a decrease in the permeability of the cutting fluid, which makes it difficult to enter the cutting zone and, ultimately, increases the resultant force. Although polyethylene glycol has good surface activity, it easily foams, so when the content of polyethylene glycol is low, the foaming resultant force is low. When the content reaches a certain value, the resultant force will suddenly increase. For glycerol, this increase may be because it is difficult to give full play to its lubrication performance at a low content, but at a high content, the lubrication ability will be significantly better than that of the other three fluids. Finally, considering the cost factors, the conclusion is that the 10% triethanolamine borate cutting fluid has the best cost performance ratio by analysing the milling resultant force.

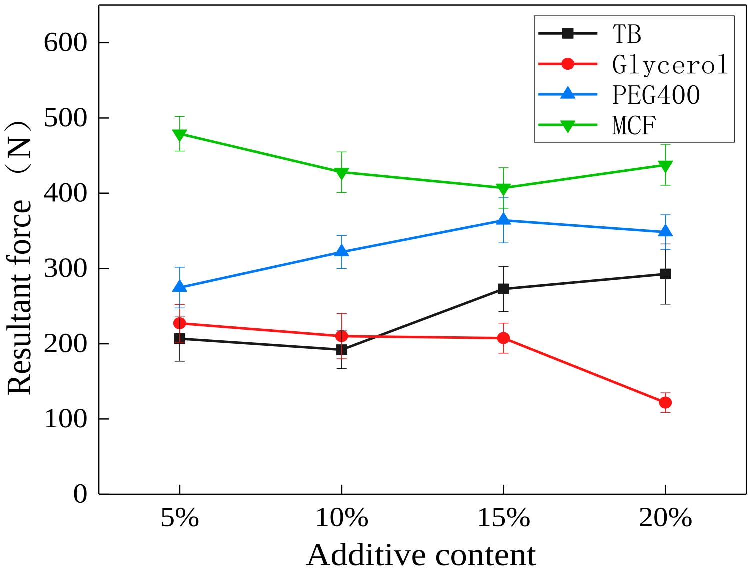

Fig. 2 Variation of the milling resultant force of the four cutting fluids with additive content

3.2 Milling Temperature Analysis.

The milling temperature can reflect the cooling performance of a cutting fluid. Temperature is particularly important for workpiece quality and tool wear. During the test, the position of the cutting fluid nozzle remains unchanged and the flow rate of the cutting fluid does not change. And the infrared thermal imager measures the temperature of the whole cutting area. At a room temperature of approximately 21℃, the milling temperatures of the four kinds of cutting fluids measured at different contents are shown in Fig. 3. It can be seen from the figure that the temperature of all the cutting fluids increases as the additive content increases due to the main cooling effect of deionized water in the cutting fluids, but the cooling performance of the material itself is also different. By contrast, the cooling performance of the four cutting fluids in the test are ordered from high to low as glycerol, triethanolamine borate, the market cutting fluids and polyethylene glycol 400. Among them, the temperatures of glycerol and triethanolamine borate slightly change with the content, while those of the other two undergo a relatively large change. According to the analysis of the milling temperature, glycerol has the best cooling performance.

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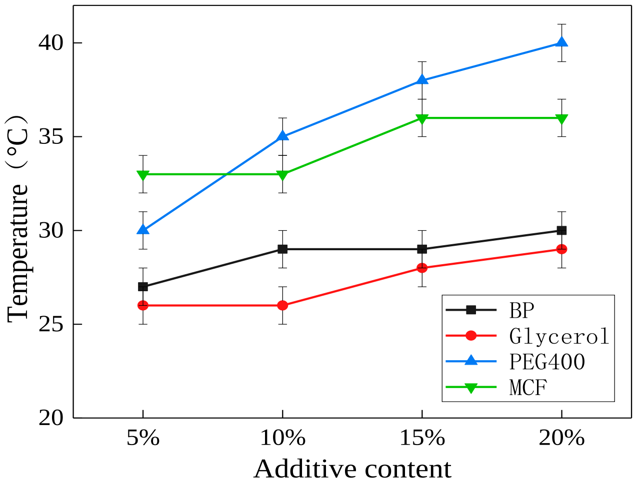

Fig. 3 Variation of the milling temperature of the four cutting fluids with the additive content

3.3 Surface Roughness Analysis

The roughness of a machined surface is measured by a roughness meter. The Ra and RSm values are taken from the measured roughness signals for analysis. The Ra value is a high characteristic parameter, which represents the average deviation of the contour arithmetic. The smaller the value, the smoother the measured surface. RSm is a spacing characteristic parameter that represents the average length of contour peaks and valleys on the midline. Fig. 4 shows the roughness Ra values of the machined surfaces measured with different cutting fluids. It can be seen from the figure that the corresponding Ra values of the different cutting fluids are between 0.3 and 0.4 microns. Among them, the Ra value of triethanolamine borate is the smallest when the additive content is 5% and 10%. After 15% and 20%, the Ra value of glycerol is the smallest, followed by triethanolamine borate, while the Ra values of polyethylene glycol 400 and the market cutting fluid are always relatively larger.

Fig. 5 shows the RSm value of the machined surface roughness measured with different cutting fluids. It can be seen from the figure that the RSm value corresponding to different cutting fluids ranges from 0.15 mm to 0.3 mm and that the difference between the RSm value and the Ra value is more obvious. The RSm value of glycerol is the smallest at any content. The RSm value of polyethylene glycol 400 is smaller than that of triethanolamine borate at 5% and 10%, and the reverse is true at 15% and 20%. The RSm value of the market cutting fluids is the largest when the content is 5% to 15%, but it is slightly smaller than that of PEG 400 when the content is 20%.

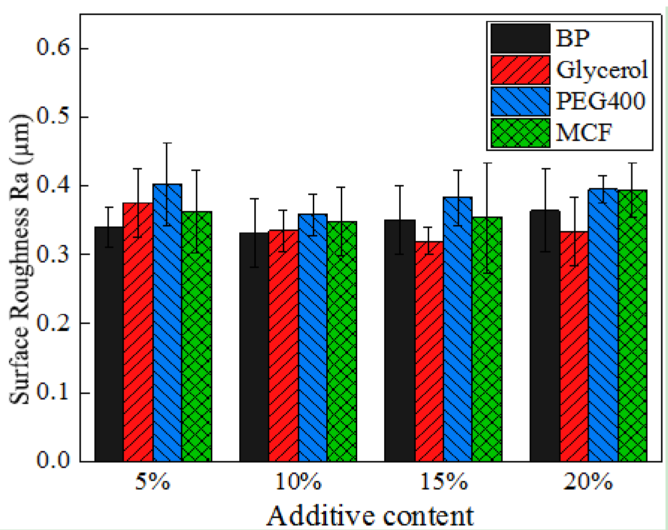

Fig. 4 Surface Roughness measured for the four kinds of cutting fluids at different contents

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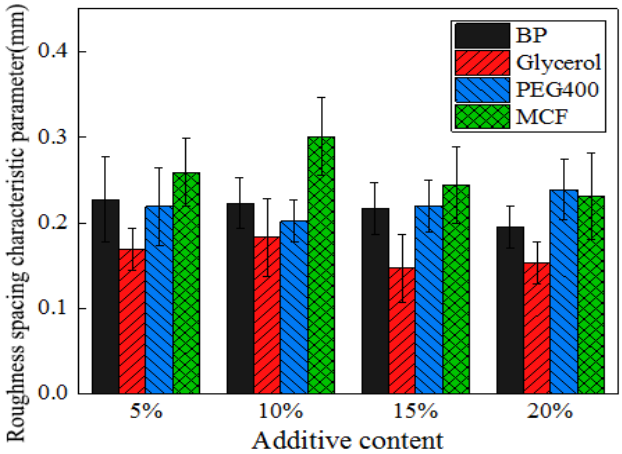

Fig. 5 RSm values of roughness measured for the four kinds of cutting fluids at different contents

According to Guo [22] et al., the quality of a machined surface cannot be fully characterized by the Ra value or the RSm value of roughness alone. The weights of the Ra value and the RSm value are 76% and 24%, respectively, in roughness parameters. Combining these two parameters, roughness ratio can be obtained. The roughness ratio is more comprehensive than single factor analysis. The calculated results of the roughness ratio values are shown in Fig. 6. It is obvious from the figure that when the content of glycerol exceeds 10%, the roughness ratio value of glycerol is the smallest, especially when the content is relatively high, and it is much smaller than the other three. When the content of triethanolamine borate is 5% and 10%, the roughness ratio value of triethanolamine borate is comparable to that of glycerol, while the roughness values of polyethylene glycol 400 and the market cutting fluids are always larger. According to the parameter of roughness, it is concluded that the surface quality of the workpiece using the glycerol cutting fluid is the best at a higher content.

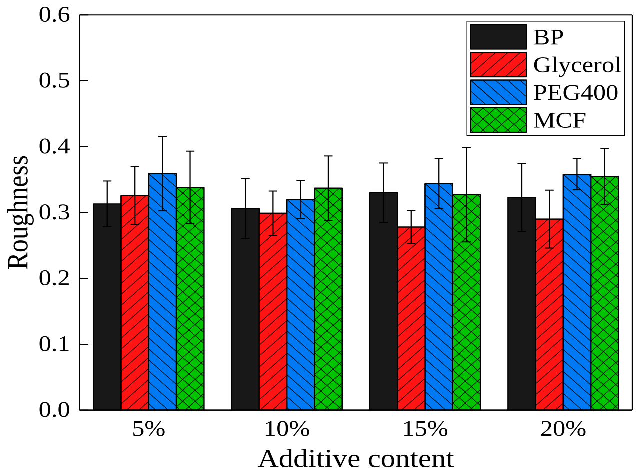

Fig. 6 Roughness synthetic figure of the four cutting fluids varying with content

3.4 Cutting Specific Energy

The cutting ratio can be used to represent the processing efficiency, which is defined as the energy consumed by removing material per unit volume. The smaller the cutting ratio energy, the higher the processing efficiency. The method to calculate the milling specific energy is given by Eq. (2) [23]. U denotes the specific cutting energy (J/mm3), P denotes the energy consumed (J), Qw denotes the volume removed by the workpiece, AP denotes the axial depth and AE denotes the radial depth.

$$U = \frac{P}{Q_w} = \frac{F}{a_p \cdot a_e} \tag{2}$$

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The specific energy of the different cutting fluids is calculated and shown in Fig. 7. It can be seen from the figure that when the additive content is 5% and 10%, the cutting ratios are ordered from small to large as triethanolamine borate, glycerol, polyethylene glycol 400 and the market cutting fluid, while the specific energy of glycerol is less than that of triethanolamine borate when the additive content is 15% or 20%. Eq. (2) shows that the cutting specific energy is affected by the resultant force value, so the change trend of the cutting specific energy is the same as that of the resultant force. Eq. (2) also shows that triethanolamine borate and glycerol are superior to polyethylene glycol 400 and the market cutting fluid in regard to processing efficiency. When the content of additives is low, triethanolamine borate has the highest efficiency, and glycerol has the highest efficiency when the content of additives is relatively high.

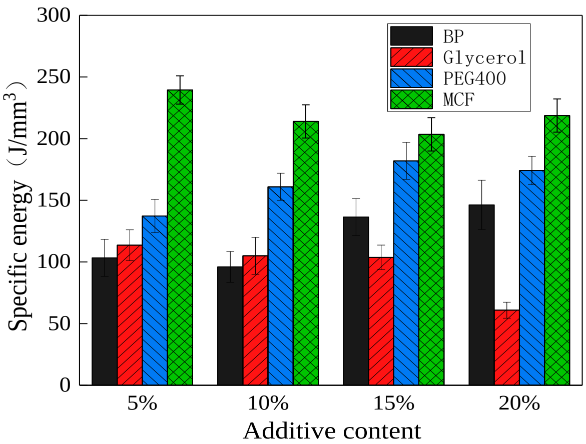

Fig. 7 Specific energy of the four cutting fluids with different additives

3.5 Friction Coefficient

Through analyses of the resultant force, temperature, roughness and other parameters, combined with the cutting fluid cost, we believe that when the additive content of cutting fluid is 10%, the cutting fluid not only has a good lubrication and cooling performance but also save costs. Therefore, in the following analysis, we only study an additive content of 10%.

The friction coefficient can reflect the lubrication ability of a cutting fluid. The smaller the friction coefficient, the better the lubrication effect of the cutting fluid. At present, the composite cutting force model mentioned by Milton C. Shaw [24] in Metal Cutting Principles is widely used in the analysis of cutting force, as shown in Fig. 8.

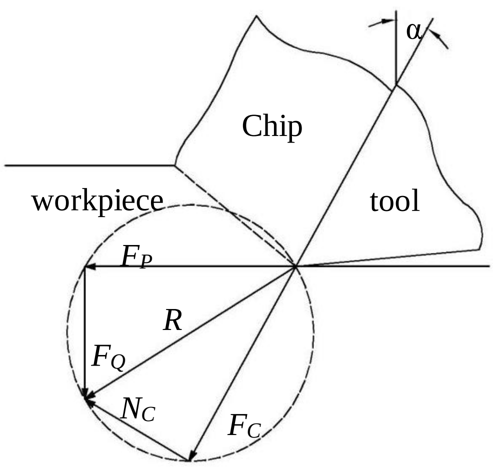

Fig. 8 Relation of forces in milling

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In Fig. 8, F_C represents the force along the tool surface, N_C represents the force perpendicular to the tool surface, F_P is the force in the horizontal direction, F_Q is the force in the vertical direction, and R is the force of F_C and N_C. The formulas for calculating the friction coefficient of the cutter-chip interface according to the force shown in the figure are as follows:

$$F_C = F_P \sin\alpha + F_Q \cos\alpha \tag{3}$$

$$N_C = F_P \cos\alpha - F_Q \sin\alpha \tag{4}$$

$$\mu = \frac{F_C}{N_C} = \frac{F_P \sin\alpha + F_Q \cos\alpha}{F_P \cos\alpha - F_Q \sin\alpha} = \frac{F_Q + F_P \tan\alpha}{F_P - F_Q \tan\alpha} \tag{5}$$

According to Eq. (5), the force in the Z direction measured by the dynamometer is brought into force F_Q, and the arithmetic square root of the sum of the forces in the X and Y directions is brought into force F_P to calculate the friction coefficient. Fig. 9 shows the friction coefficients of the four cutting fluids when the additive content is 10%. It can be seen that the lubrication ability of the four cutting fluids ordered from high to low is triethanolamine borate, glycerol, the market cutting fluids and polyethylene glycol 400. It can be seen that the lubrication effect of the cutting fluid prepared with triethanolamine borate as the additive is the best by analysing the friction coefficient of milling titanium alloy.

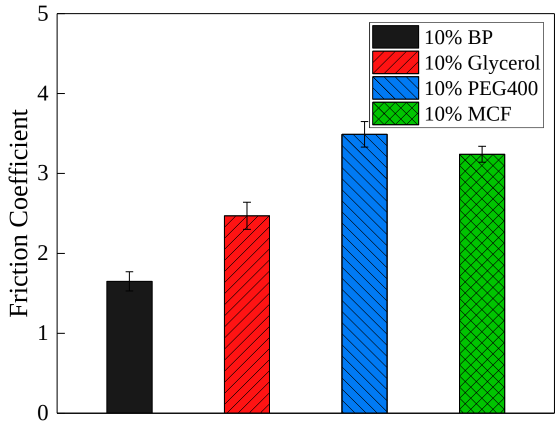

Fig. 9 Friction coefficients of the four cutting fluids at a 10% content

3.6 Spectrum Analysis

The time-domain signals of force and time are directly measured by the dynamometer. The dynamometer can directly measure the force magnitude, but this is only a preliminary analysis of the measurement results. The relevant literature [25-26] proposes that the time-domain signal can be converted into a frequency-domain signal through a Fourier transform, which can further analyse the processing conditions. The frequency domain signal is composed of an amplitude and a frequency. When analysing the amplitude-frequency curve of the milling force, the amplitude may be caused by tool tremor and the frequency of the special amplitude may be related to the processing parameters. Therefore, we use the magnitude to measure the stability of the working conditions. The smaller the magnitude at a certain frequency, the more stable the working condition and the smaller the tool tremor. In this experiment, the force change in the X direction is obvious, so the time domain signal in the X direction is converted into a frequency domain signal [1] through the FFT (Fast Fourier Transform) function of the MATLAB software, and the experimental results are shown in Fig. 10. It can be seen from the figure that when the four kinds of cutting fluids are used, the frequency of the resultant special amplitude is the same, so we focus on analysing the magnitude under the same frequency. When the frequency is close to zero, the corresponding amplitudes of the four cutting fluids are ordered as the market cutting fluids, polyethylene glycol 400, glycerol and triethanolamine borate. At a frequency of approximately 6 Hz, as shown in the figure, the amplitudes of the market cutting fluid and glycerol are higher, while those of triethanolamine borate and polyethylene glycol 400 are lower. The amplitude of triethanolamine borate is the smallest at frequencies greater than 10

ISSN: 2414-1895
DOI: 10.6919/ICJE.202108_7(8).0034

Hz, which indicates that the working condition is the most stable when the triethanolamine borate cutting fluid is used.

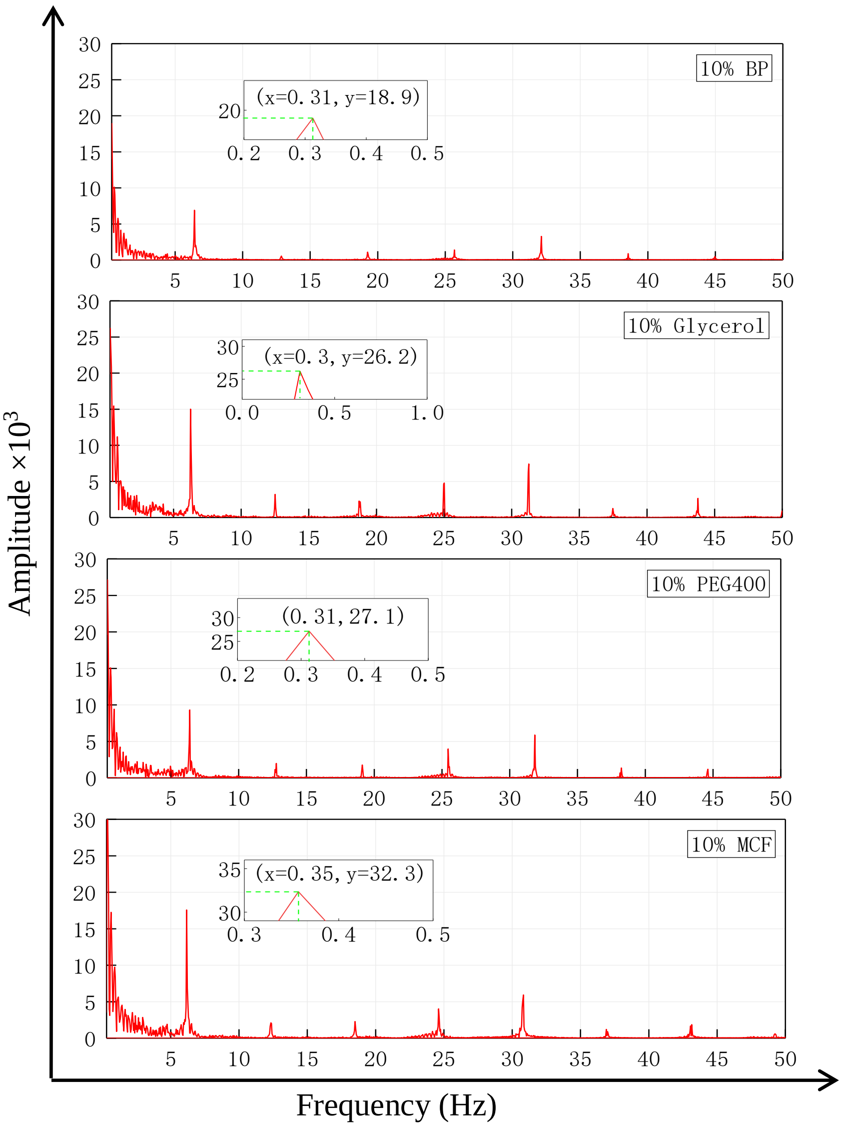

Fig. 10 Spectrum curves of the four cutting fluids at a 10% additive content

3.7 Surface Morphology Analysis

Scanning electron microscopy (SEM) was used to observe the machined surface of the workpiece. The surface morphology can reflect the wear resistance of the cutting fluid. As shown in Fig. 11, the morphology of the workpiece is observed 100 times, and then, an area is selected to observe 500 times. As seen from the figure, for 100 observations, all the pictures have arc-shaped scratches, which may be caused by the friction between the tool tip and the machined surface when cutting new materials, and all the pictures show a flaking or burning phenomenon. In addition to these obvious marks, we can see that the scratches of triethanolamine borate correspond to a meticulous shape and a regular arrangement from the 500-fold figure. The corresponding scratches of the market cutting fluids are similar to those of triethanolamine borate, but there are more exfoliation phenomena in the figure. A disordered arrangement appeared in the pictures corresponding to glycerol, and the disorder was more obvious in the pictures corresponding to polyethylene glycol 400. This finding shows that the wear resistance of triethanolamine borate is stronger and the surface quality of the corresponding workpiece is higher.

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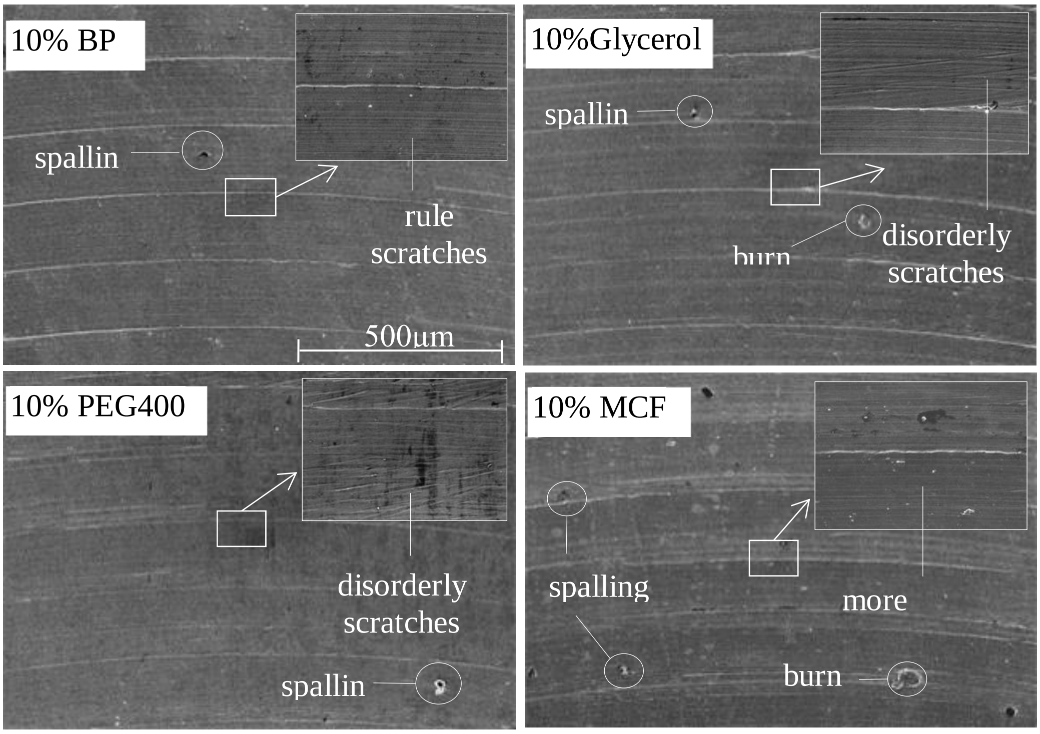
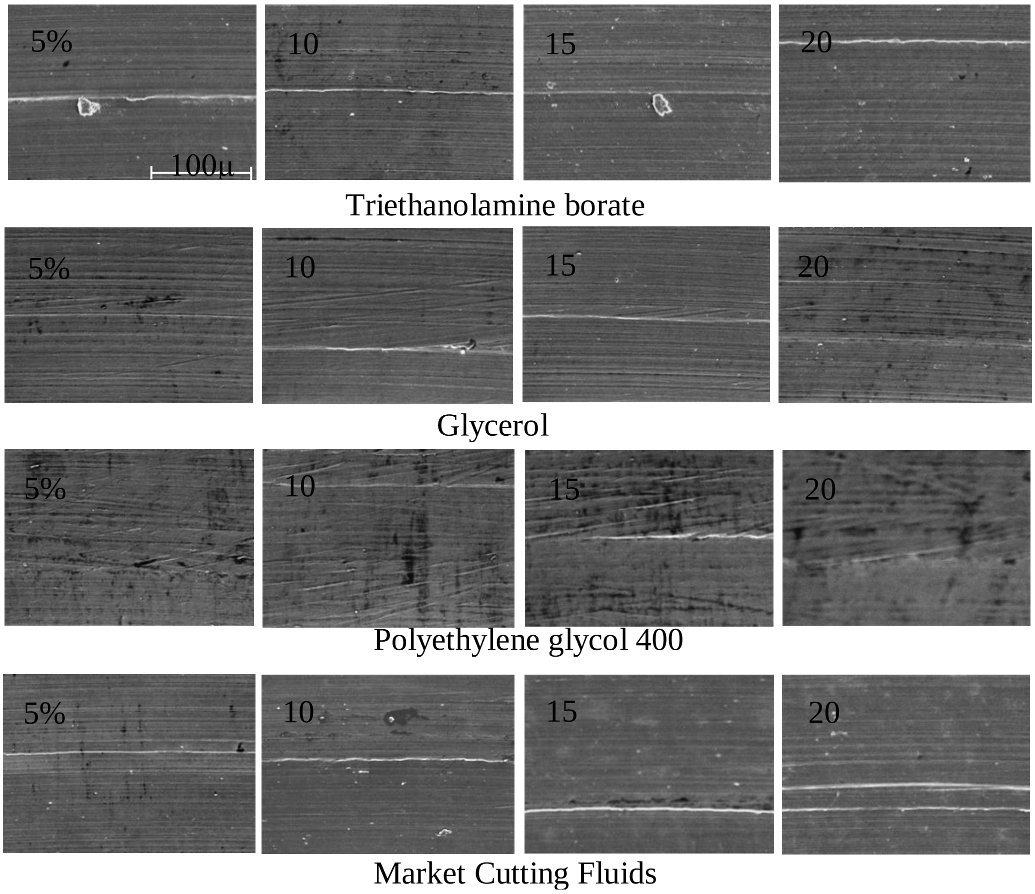


Note: All micrographs have the same scale bar

Fig. 11 Surface topography of a workpiece corresponding to various cutting fluids at a 10% additive content



Note: All micrographs have the same scale bar

Fig. 12 SEM charts of several cutting fluids at a 500-fold amplification

ISSN: 2414-1895 DOI: 10.6919/ICJE.202108_7(8).0034

In addition to the workpiece morphology corresponding to the four cutting fluids when the additive content is 10%, it is necessary to analyse the images of all the cutting fluids under a high power mirror. The images of all the test subjects at 500 times magnification are shown in Fig. 12, from which the relationship between the surface morphology of the workpiece and the additive content can be seen. The corresponding morphologies of glycerol and polyethylene glycol 400 at any content showed obvious disorder, and the corresponding morphologies of triethanolamine borate at 5% and 15% contents showed obvious exfoliation. For the four kinds of cutting fluids, the corresponding morphology does not greatly change with the increase of the additive content. This finding shows that it is reasonable for us to take the four cutting fluids with a 10% additive as main research objects.

4. Lubrication mechanism analysis

Summarizing the experimental results after analysing the four parameters of the resultant force (cutting force), temperature, roughness and specific energy, it can be seen that when the additive content is 5%, the performance trend of the four cutting fluids is quite different from that of the other additives. This result shows that the performance of the four additives cannot be correctly reflected when the additive content is 5%, possibly because of the low content of additives. However, the higher the content of additives does not lead to a better performance of the cutting fluid. For example, when analysing the temperature parameters, the higher the content, the worse the cooling performance because of the decrease of the water content. In addition, when the content of additives increases, the viscosity of the cutting fluid will increase, which will lead to a permeability decrease and affect the lubrication performance. In addition, the higher the content of additives, the higher the cost. At this time, it is necessary to consider the cost-performance ratio of improving the performance of the cutting fluid with the increase of the content of additives. Ultimately, we believe that the cutting fluid with a 10% content has the best cost performance ratio, so the performance of the four cutting fluids with a 10% content under each characterization parameter is arranged into four grades A, B, C and D from high to low. For example, in the analysis of the resultant force, the resultant force of triethanolamine borate with a 10% content is less than that of the other three, so it is grade A; the resultant force of the cutting fluid with a 10% content is the largest, so it is grade D.

Table 1. Performance of the four cutting fluids with a 10% content under various parameters

	10% BP	10% Glycerol	10% PEG400	10% MCF
Resultant force	A	B	C	D
Temperature	B	A	D	C
Roughness	B	A	C	D
Specific energy	A	B	C	D
Friction coefficient	A	B	D	C
Amplitude	A	C	B	D
Morphology	A	C	D	B

From Table 1, we can directly see the advantages and disadvantages of the four cutting fluids with a 10% content. Among them, the resultant force and the friction coefficient can reflect the friction reduction performance of the cutting fluids; the roughness and the surface morphology can reflect the anti-wear performance of the cutting fluids; the milling temperature corresponds to the cooling performance of the cutting fluids; the specific energy represents the processing efficiency, which is consistent with the trend of the resultant force; and the spectrum analysis can reflect the stability of the working conditions. As shown in Table 1, although glycerol is the best in terms of the milling temperature and roughness, triethanolamine borate is the best in other aspects, so we believe that the comprehensive performance of the triethanolamine borate cutting fluid with a 10% content is the best among the four cutting fluids studied in this experiment.

We also analysed triethanolamine borate itself. Triethanolamine borate is formed by the reaction of boric acid and triethanolamine under the action of a water-carrying agent [27]. During the reaction,

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the hydroxyl group in boric acid and the hydrogen atom in triethanolamine hydroxyl group form water. The boron atom directly combines with an oxygen atom in the triethanolamine hydroxyl group. The water-carrying agent continuously removes water and, finally, forms triethanolamine borate. The reaction formula is shown in Fig. 13. The stereo molecular structure is shown in Fig. 14. Triethanolamine borate is a cage-like heterocyclic compound. Triethanolamine borate contains a coordination bond between nitrogen and boron, which can increase steric hindrance, thus solving the problem of the easy hydrolysis of the boric acid ester due to the lack of electrons in boron atoms. Boron and nitrogen have extreme pressure lubrication properties, which are further enhanced by linking alkyl groups as carriers.

Under cutting conditions, some triethanolamine borate molecules are squeezed to break the molecular chain. In this case, nitrogen atoms and boron atoms may produce tiny hexagonal boron nitride particles [28]. Hexagonal boron nitride particles, known as "white graphite", have good lubrication and cooling abilities. The relevant literature suggests that hexagonal boron nitride can achieve super-slip under certain conditions [29]. If such tiny particles are generated, the lubrication ability of the cutting fluid will be enhanced to a certain extent. The analysis of the lubrication properties of triethanolamine borate is only a theoretical speculation, and the specific reasons need to be further explored from other fields.

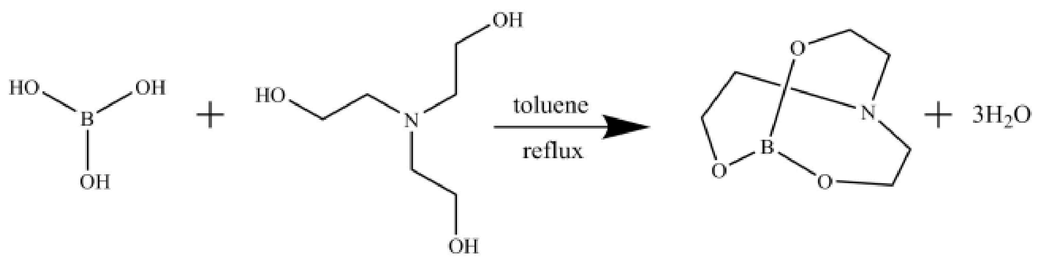

Fig. 13 Reaction formula of triethanolamine borate

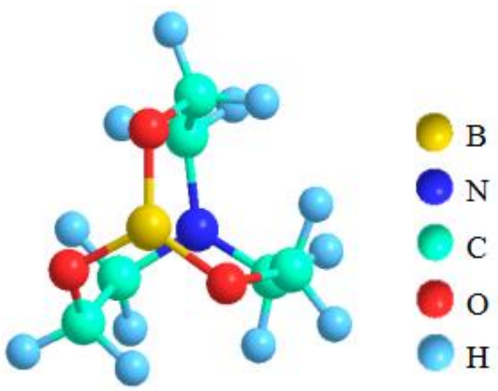

Fig. 14 Three-dimensional molecular structure of triethanolamine borate

5. Conclusion

(1) The experimental results show that when the additive content is 10%, the cutting fluids have excellent lubrication and cooling performances. In the four cutting fluids with a 10% additive content, the cutting fluid prepared with triethanolamine borate as the additive has the best comprehensive performance.

(2) By studying the reaction time and 3D molecular structure of triethanolamine borate ester, it is shown that triethanolamine borate ester is a cage-like heterocyclic compound. Triethanolamine borate contains a coordination bond of nitrogen and boron, which can increase steric hindrance and solve the problem of the easy hydrolysis of boric acid lipids due to the lack of electrons in boron atoms. In

ISSN: 2414-1895 DOI: 10.6919/ICJE.202108_7(8).0034

addition, boron and nitrogen have extreme pressure lubrication properties. The lubrication performance will be further enhanced by linking hydrocarbons as carriers.

(3) The lubrication performance and mechanism of the cutting fluid formed by triethanolamine borate as an additive are revealed for the first time in this paper, which provides a theoretical reference for the development of a new cutting fluid lubrication based on the triethanolamine borate additive.

Acknowledgments

This research was financially supported by the following Foundation items: Shandong Provincial Natural Science Foundation, China (ZR2017MEE077).

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