

The Role of Tribology in Environmentally Friendly MQL Machining



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Minimal quantity lubrication (MQL) machining has been recognized as a representative and successful environmentally friendly cutting operation. Specific synthetic polyol esters are optimal cutting fluids for MQL machining because of their high biodegradability, excellent oxidation stability and satisfactory cutting performance and can effectively lubricate cutting zone vicinities in very small quantities. The cutting performance of these esters is closely connected with tribological behavior based on the adsorbing characteristics of the ester and atmospheric gases onto nascent clean metal surfaces. In particular, the presence of oxygen is preferable in the case of machining steel, whereas oxygen causes unfavorable cutting situations in the case of machining aluminum.

Key Words: MQL, machining, environment, ester, tribology

1. Introduction

Tribology has contributed greatly over the years to energy savings and resource conservation through reducing friction and suppressing wear. Tribological technology has significantly improved vehicle fuel efficiency, and we can expect that it will continue to do so. This directly contributes to the reduction of CO₂ emissions and is effective in preventing global warming. It is no exaggeration to say that tribology is a key technology to achieving a sustainable, low-carbon society.

Tribology plays a major role in cutting, a core technology within "monozukuri" excellent manufacturing. Regarding cutting tools, various surface coating methods and materials with superior friction and wear resistance characteristics have been developed and have enabled great strides recently in cutting tool performance¹⁾. In addition, technologies to improve workpiece machinability by the addition of certain elements, such as development of resulfurized free-cutting steels, have long been used to increase productivity at machining workplaces. Cutting oils are indispensable to proper cutting operations because their lubricating and cooling capabilities enable them to work effectively against shearing at the time of chip formation and against cutting vicinity friction, and also because they aid the chip removal by their flow.

However, in regard to efforts to prevent the advance of global warming, the review of all types of manufacturing technologies is being called for. As a result, in some cases, cutting oils have been criticized for the dirty

work environments caused by them and further for the harmful influence with their disposal on the global environment, and this has therefore led to a lot of R&D efforts to create dry cutting methods and introduce these at workplaces^{2),3)}. Of course dry cutting, which utilizes no cutting oil whatsoever, is one means of contributing to the solution of environmental problems, but inevitably it has disadvantages, such as sacrificing production efficiency or lowering production precision, and therefore has a limited range of application. On the other hand, if we make a system of using cutting oil effectively only in necessary amounts, preventing the contamination of surrounding areas, and lastly disposing of it properly, this will enable highly efficient manufacturing and high product precision and overall will be environmentally friendly manufacturing technology.

In that regard, herein Minimal Quantity Lubrication (MQL) is introduced as a representative example of environmentally friendly "eco-machining." Specifically, the role and importance of tribology in MQL machining are explained based on the results of research carried out by the authors who have so far investigated the cutting performance of cutting oil used in MQL machining particularly in connection with its adsorption characteristics onto nascent clean metal surfaces.

2. MQL Machining and Cutting Oil

2. 1 Near-Dry Machining by MQL Method

Machining methods that, while not completely dry, use a minimal amount of cutting oil are referred to as near-dry machining, one of which is MQL machining. Incidentally, in Japan this is commonly referred to as "semi-dry" machining, but I would like to use "near-dry" because it is the more proper term in English.

In MQL machining, cutting oil particles in mist form in extremely small quantities of several tens or less of mL per hour are delivered to the cutting vicinity by high quantities of compressed gas (carrier gas). This very small quantity of cutting oil performs the task of lubricating while the carrier gas (normally air) removes chips and cools the cutting area. This machining method, despite the fact that it uses several thousand or tens of thousands times less cutting oil than conventional wet machining, shows no disadvantage in reducing cutting resistance, suppressing cutting tool wear, improving workpiece precision, etc. and is steadily being adopted at actual manufacturing workplaces as an environmental machining method³⁾⁻⁷⁾.

2. 2 Cutting Oil for MQL Machining

2. 2. 1 Secondary Performance

Regarding the practical performance of cutting oil, there is primary performance, which refers to cutting performance, and secondary performance, which concerns safety-related and work-related performance features such as tendency to cause skin irritation, odor, and putrefaction resistance. Superior performance of both types is sought in cutting oils. Particularly in the case of cutting oils for MQL machining, in order to minimize the environmental load caused by oil mist particles that escape the plant, it is necessary for the cutting oil to have the secondary performance feature of biodegradability. Concerning cutting oils normally possible to obtain and having a high degree of biodegradability, there is vegetable oil, and some esters (mainly polyol esters derived from polyhydric alcohols) also display good biodegradability.

In the case of cutting oils, fine oil particles adhere little by little to machine tool inner walls, etc., accumulate, and form thin oil films. The influence of oxygen causes these thin oil films to deteriorate easily, and often they change into gluey substances that worsen the work environment. Because of this, it is essential that oils for MQL machining have high oxidation stability⁸⁾. In order to confirm this experimentally, we placed thin films of various oil types on aluminum plates and heated them for 168 hours at 70°C, and then investigated molecular weight after oil oxidative degradation (weighted average molecular weight Mw and number average molecular weight Mn) to determine the change ratios from molecular weights

prior to heating. Results are shown in **Fig. 1**⁹⁾. Normally, the generation of a gluey degradation substance becomes conspicuous when this change of ratio exceeds 10%. The three oil types A, B and C selected this time were all developed using as a base synthetic polyol ester, which possesses biodegradability, and show almost no change compared with the significant change of ratio obtained for vegetable oil. In other words, because they possess a high degree of oxidation stability, they can be expected to be suitable as cutting oils for MQL machining.

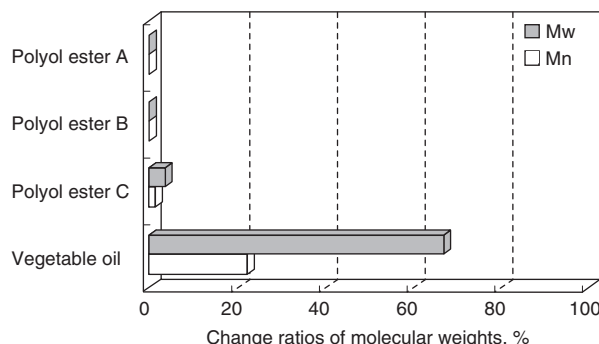
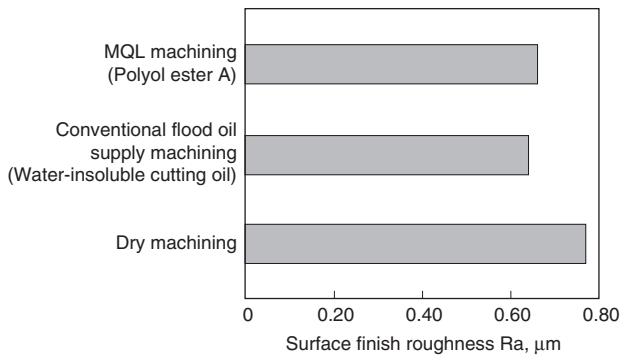


Fig. 1 Changes of molecular weight by oxidative degradation

2. 2. 2 Cutting Performance

In the selection of suitable cutting oils for MQL machining, while the secondary performance features biodegradability and oxidation stability are even more important than in the case of conventional cutting oils, there is no change to the importance of the primary feature cutting performance as a selection criterion. For example, **Fig. 2**, which compares surface finish roughness after MQL machining, conventional flood oil-supplied machining, and dry machining, shows that the finish obtained by MQL machining has surface roughness almost equivalent to that obtained by conventional machining. Shown in **Fig. 3** is a comparison of cutting forces during end milling in the cases of MQL, dry operation, and conventional oil supply. Cutting force in the case of MQL machining using polyol esters is clearly lower than such force not only in the case of dry machining but also in the case of conventional machining using cutting oil with extreme-pressure-additive sulfuric compounds excelling in cutting performance improvement. In regard to end milling, which involves intermittent cutting, results show that MQL actually is the preferable method.

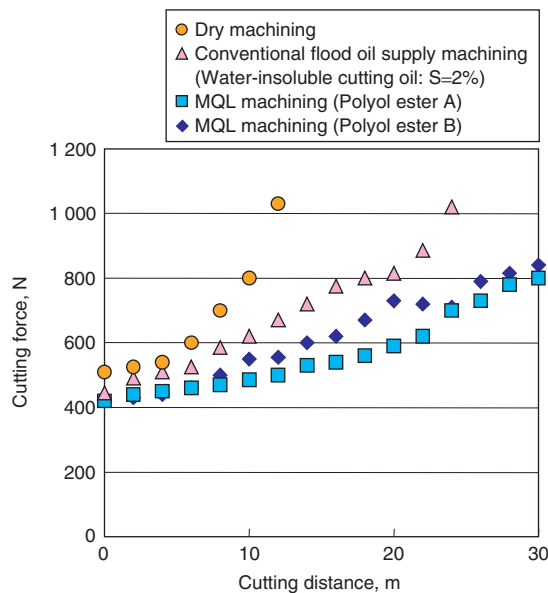
Needless to say, the success of product manufacturing by MQL machining depends largely on the effectiveness of the cutting oil in lubricating the cutting vicinity with a minimal amount of oil. Put differently, the influence on machining of the tribological behavior brought about by the cutting oil is much greater in the case of MQL than in the case of conventional oil supply. The study below was carried out for the purpose of clarifying this behavior.



[Cutting conditions]

Cutting tool: WC (TiCN-Al₂O₃-TiN coating)
Workpiece material: JIS S45C, Cutting speed: 200 m/min
Depth of cut: 1.0mm, Feed: 0.1 mm/rev
MQL: Air=0.3 MPa, Oil=25 ml/h, Outside supply

Fig. 2 Surface finish roughness after turning



[Cutting conditions]

Workpiece material: JIS S55C steel,
Cutting tool: Cemented carbide ($\phi 10$ mm)
Cutting speed: 60 m/min, Feed: 0.1 mm/tooth
Axial depth of cut: 4.0mm, Radial depth of cut: 1.0mm
MQL: Air=0.2 MPa, oil=15 ml/h, Outside supply

Fig. 3 Cutting force during end milling

3. Action Mechanism of Ester Cutting Oil in MQL Machining

3. 1 Controlled Atmosphere Machining Experiment

It is known that ester performs effectively as a lubricant through its adsorption as a film onto the metal surface¹⁰⁾. The adsorption behavior of ester, etc. was investigated using the controlled atmosphere machining apparatus of **Fig. 4**, and results herein are introduced¹¹⁾. Experimental conditions were shown in **Table 1**. In this experiment, after a vacuum level down to 10^{-4} Pa was created in the machining chamber, the

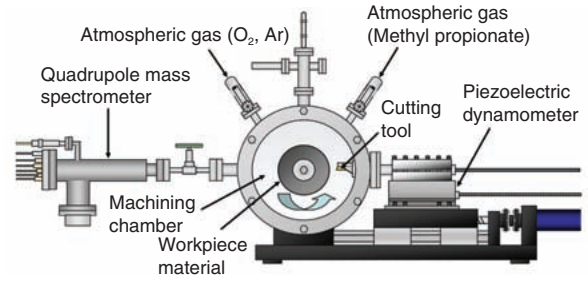
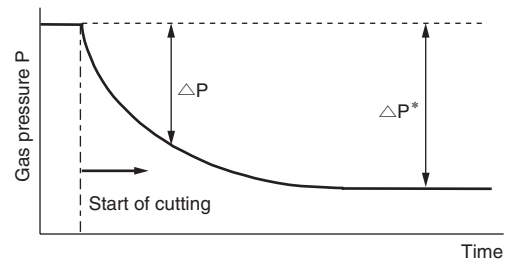


Fig. 4 Controlled atmosphere machining apparatus

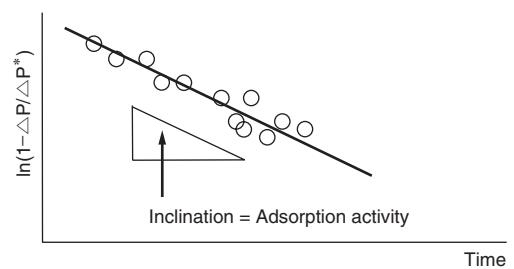
Table 1 Experimental conditions with controlled atmosphere machining apparatus

[Model compounds]
Ester: Methyl propionate $C_2H_5COOCH_3$
Hydrocarbon: n-Hexane C_6H_{14}
Coexisting gas: Oxygen (Purity: 99.9%)

[Cutting condition]
Workpiece material: JIS SCM435 steel
Cutting tool: Cemented carbide
Cutting speed: 12 m/min



(a) Change in time of gas pressure through adsorption



(b) Measurement of adsorption activity

Fig. 5 Measurement method of adsorption activity

target compound gases were introduced at a prescribed pressure to become constant. Steel machining was begun after that, and as the introduced compound adsorbed on the machined nascent steel surface, the gas pressure measured by mass spectrometer changed as shown in **Fig. 5** (a). If the method of Mori et al.¹²⁾ is applied to this measurement result, adsorption activity can be derived from the relational trend shown in **Fig. 5** (b).

The greater the inclination (i.e. the greater the degree of adsorption activity) is, the greater the chemical affinity is between the freshly machined surface and the adsorbed molecules. However, because of a limit on introducible vapor pressure, methyl propionic acid was used for the ester and n-hexane for the hydrocarbon base oil as model compounds instead of the cutting oil used in actual machining.

Also, since this machining apparatus was equipped with two leak valves making it capable of simultaneously introducing two types of gases, experimentation on ester adsorption activity was performed with the coexistence of oxygen and of argon. It is well known that argon is an inert gas and normally does not adsorb on machined nascent metal surfaces. Oxygen, on the other hand, is highly reactive and quickly adsorbs on such surfaces. Accordingly, the ester's independent adsorption behavior can be observed in the case the coexisting gas is argon, and the adsorption behavior mutually influenced by ester and oxygen can be observed in the case the coexisting gas is oxygen. The reason for using argon as the coexisting gas in the experiment to investigate ester's independent behavior was to avoid the influence caused by disappearance of the partial pressure of the coexisting gas on the adsorption behavior.

3. 2 Model Compound Adsorption Activity and MQL Machining

Figure 6 shows the values for adsorption activity of the model compounds on the machined nascent steel surface when they were introduced to achieve 10^{-1} Pa. First, in the case of n-hexane as the base oil model compound, the molecules do not have a polar group, and therefore adsorption does not occur and adsorption activity is zero. In the case of independent ester (coexisting with argon at 10^{-1} Pa), on the other hand, a comparatively high degree of adsorption activity is obtained. Further, in the case of oxygen coexisting at 10^{-1} Pa, the influence thereof causes the adsorption activity of the ester itself to rise, a highly interesting experimental result.

When the amount of oxygen existing prior to the start of cutting was changed and the adsorption activity of both the ester and oxygen were sought, the results shown in Fig. 7 were obtained. The horizontal axis shows the ion intensity which is detected by mass spectrometer and proportional to pressure within the machining chamber based on certain calibration coefficient determined for each substance. In other words, to the extent the oxygen amount increases, the adsorption activity of both the ester and oxygen rises, and therefore we understand their mutual adsorption behaviors augment one another.

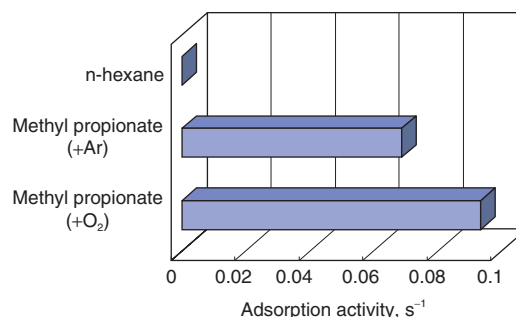


Fig. 6 Values of adsorption activity for model compounds

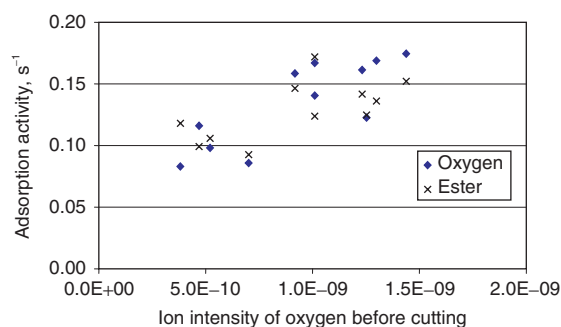


Fig. 7 Influence of ion current intensity of oxygen on adsorption activity

Based on the above experiment, it can be presumed that the presence of oxygen in the ambient atmosphere improves the ester's adsorption performance and promotes formation of a good lubrication film through stronger adsorption. The possibility is high that this phenomenon occurs during actual MQL machining. In other words, as shown in Fig. 8, whereas cutting oil surrounds fully the machining vicinity in the case of conventional flood oil supply, lubricant oil particles and large quantities of air coexist in the environment surrounding the machining vicinity in the case of MQL. Accordingly, it is presumed that when this lubricating oil is ester, the oxygen in the air aids in maximization of the ester's adsorption performance, resulting in unexpectedly excellent machining performance despite the extremely small amount of oil¹¹⁾.

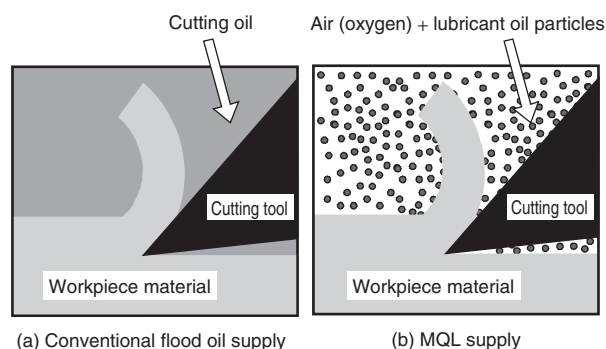


Fig. 8 Schematic illustration of the difference between (a) conventional supply and (b) MQL supply

3.3 Influence of Carrier Gas during MQL Machining

Based on the above presumptions regarding ester adsorption behavior and phenomena in the machining vicinity, it is predicted that during MQL machining, not only the oil but also the carrier gas exerts influence on machining performance. In order to verify this, using oxygen, air (normal MQL) and nitrogen as carrier gases, MQL machining was performed on JIS S45C steel as orthogonal cutting and cutting force was measured. Results, as shown in **Fig. 9**, clarify that the cutting force becomes lower as the concentration of oxygen in the carrier gas becomes higher and that the presence of oxygen improves cutting performance.

Moreover, it is of great interest that when the machined material is changed from steel to an aluminum alloy in MQL machining, a completely different trend is seen. As shown in **Fig. 10**, in the case of the aluminum alloy, the cutting force declines as the amount of oxygen in the carrier gas decreases, which is opposite from the case of steel. Put differently, in the case of aluminum alloy machining, even the existence of 20% oxygen in the carrier gas is detrimental, and the key becomes removing oxygen as much as possible.

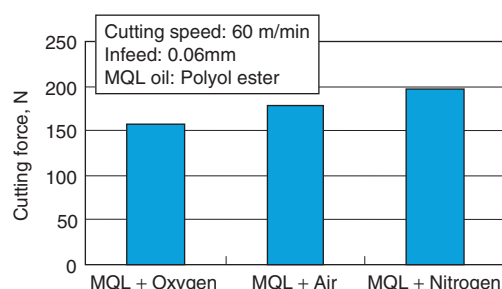


Fig. 9 Influence of carrier gas on cutting force in MQL machining (Workpiece: JIS S45C steel)

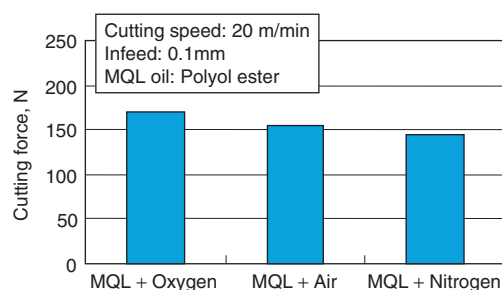


Fig. 10 Influence of carrier gas on cutting force in MQL machining (Workpiece: JIS A6061 aluminum alloy)

In regard to both steel and aluminum, cutting force increases and machining performance declines when a carrier gas having no ester is supplied, and therefore in order to obtain smooth machining, the lubricating effect of ester is considered indispensable¹³⁾. Also, regarding the fact that opposite trends are observed concerning the influence of oxygen in steel and aluminum MQL machining, at the present time the reason is thought to be as follows.

It is thought that oxygen adsorbs on the nascent metal surface created by machining, then reacts with it and forms an oxide film, so that not only is there the effect of the lubricant film formed through ester adsorption, the lubricating behavior of this oxide film also influences cutting performance during MQL machining. Iron oxide is generated in steel machining and this compound often functions like a solid lubricant in friction of steels because its shear strength is relatively low.

In the case of aluminum alloy machining, on the other hand, aluminum oxide, that is alumina, is generated, a compound known for its high hardness. It therefore has high shear strength and is not preferable from the viewpoint of friction reduction. Accordingly, the differing influence of oxygen during steel and aluminum machining is thought to result from a difference in oxide film lubrication behavior, but further clarification of this lubrication mechanism is a topic for future study.

The above results verify that the carrier gas influences cutting performance in MQL machining and that the existence of oxygen in the ambient atmosphere not only has a lubricating effect accompanying ester adsorption but also plays an important role in MQL machining. In particular, the behavior of oxygen is preferable in the case of steel and not preferable in the case of aluminum, and the same result concerning these opposing trends has also been obtained in practical MQL hole machining¹³⁾. This knowledge obtained through studies based on a tribological viewpoint further clarifies the action mechanism of lubricating oils in MQL machining and is believed to be useful in advancing this environmentally friendly machining method.

4. Conclusions

This paper has addressed the topic of MQL machining, a method enabling the significant reduction of cutting oil usage. It has been explained that with this method, cutting oils based on synthetic polyol ester having biodegradability are suitable from the viewpoints of oxidation stability and machining performance, and a minimal amount of cutting oil in the cutting vicinity can effectively perform lubrication. Further, from the viewpoint of the adsorption characteristics of both the ester itself and the ambient carrier gas onto the machined

nascent metal surface, we can say the cutting performance of the ester oil is closely related to tribological behavior, and while the existence of oxygen is advantageous in the case of machining steel, it is disadvantageous in the case of machining aluminum, an experimental result of great interest.

It is hoped that this paper is of benefit in aiding understanding of the role and importance of tribology in environmentally friendly MQL machining.

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