*Journal of Machine Engineering, 2024, Vol. 24*
*ISSN 1895-7595 (Print) ISSN 2391-8071 (Online)*

Received*: 02 October.2023* / Accepted: *12 October 2023* / Published online: *21 November 2023*

*coefficient of friction, cutting fluid,*
*lubrication, forced cooling,*
*tool polishing, tool life*

Ikuo TANABE[1*]
Hiromi ISOBE[2]

# DEVELOPMENT OF A CUTTING FLUID WITH ABRASIVE FOR INCREASING A TOOLS LIFE DURING MILLING

In wet cutting, lubricants are used to improve lubrication, forced cooling and chip evacuation. In particular, improving the lubrication between the tool and the chip results in a lower coefficient of friction, suppressing the tool temperature change and improving the cutting properties. For this reason, tools coated with DLC (Diamond Like Carbon) or diamond have been developed to further reduce the coefficient of friction. However, the tool life is still not sufficiently long. Therefore, in this study, a cutting fluid for polishing tools during cutting was developed and evaluated. First, using the author's previous research, the function, effect and influence of several cutting fluids on milling were identified. Secondly, a new criterion for determining tool life was defined and, based on this criterion, a cutting fluid was proposed to polish the tool during the cutting process. Next, the machining conditions under which the proposed cutting fluid would be effective were identified. Finally, the cutting properties of the proposed cutting fluid were evaluated. The results showed that (1) the cutting fluid was developed to polish the tool during the cutting process and the optimum machining conditions were clarified, (2) the proposed cutting fluid was very effective in increasing the tool life.

## 1. INTRODUCTION

There are three main purposes for using cutting fluids in wet cutting: forced cooling, lubrication and chip removal [1, 2]. Forced cooling effectively removes the heat generated by cutting [3, 4], thereby improving machining accuracy and tool life [5, 6]. Lubrication also reduces the coefficient of friction [7, 8] between the tool and the chip, contributing to a reduction in the cutting heat generated on the tool. From the point of view of environmental protection [9], MQL (Minimum Quantity Lubrication), in which a small amount of cutting fluid is supplied in mist form, is also used for machining [10]. Some tools are coated with diamond or DLC to reduce the friction coefficient of the tool itself and thus reduce frictional heat generation, but at present, research on improving the life of the coated diamond or DLC is being actively studied [11, 12]. The author has also studied the forced cooling effect of strong alkaline water mist for tool cooling [13].

---

[1] Technical and Management Engineering, SANJO CITY UNIVERSITY, Japan
[2] Mechanical Engineering, Nagaoka University of Technology, Japan
[*] E-mail: tanabe@mech.nagaokaut.ac.jp / tanabe.ikuo@sanjo-u.ac.jp
https://doi.org/10.36897/jme/175130

The objective of this study was to develop a cutting fluid that continuously reduces the coefficient of friction between the tool and chips and continuously suppresses cutting heat generation. Therefore, A cutting fluid that performs tool polishing during cutting was developed and evaluated. Firstly, the functions, effects and influences of cutting fluids are summarized, and then a new tool life determination is defined. Then, the effect of cutting fluid on the surface roughness of the workpiece for each cutting operation is discussed, and a new cutting fluid specializing in tool grinding properties is proposed. Finally, the cutting properties of the proposed cutting fluid are evaluated experimentally. In this paper, the technical term "cutting fluid" is used, but "oil" is not. This is in order to aim for environmentally friendly manufacturing and to respond to the SDGs (Sustainable Development Goals) and carbon neutrality (Balancing the emission and absorption of greenhouse gases, such as carbon dioxide, and keeping their emissions to "virtually zero") [14].

## 2. FUNCTION, EFFECT AND INFLUENCE OF CUTTING FLUID

When cutting load and cutting heat generation are small, as in the case of aluminium finishing, cutting fluid for forced cooling is not necessary and dry cutting is performed. On the other hand, for heavy cutting loads, wet cutting with various cutting fluids is used. The purpose of these cutting fluids is to provide forced cooling and to improve lubrication properties. Improved lubrication characteristics can reduce the coefficient of friction between the tool and chips, thereby reducing cutting heat, tool temperature rise, tool thermal deformation, and tool wear. Therefore, the improvement of lubrication characteristics also works effectively for forced cooling.

Table 1. Consideration for cutting fluid regarding functions, effects and influences (Workpiece: Ti6Al4V, Cutting condition for the milling: cutting speed: $V$ = 80 m/min, feed/tooth: $fz$ = 0.15 mm/tooth, width of cut: $wc$ = 1mm, depth of cut: $dc$ = 1 mm, end-mill with 1 throw away tip and cemented carbide without coating

| | |
|---|---|
| Forced cooling using strong alkaline water mist.<br>(Heat transfer coefficient: 12,000 W/m$^2$・K) [16], [17] | Lubricant the cutting fluid with lower coefficient of friction using strong alkaline water, polymer PEO-8 and graphite. [16] |
| Tool life (Limit at flank wear $v_b$ = 0.15 mm):<br>6.3 times the tool life of dry cutting<br>1.9 times the tool life of wet cutting with VG68 | Tool life (Limit at flank wear $v_b$ = 0.15 mm):<br>18.4 times the tool life of dry cutting<br>4.5 times the tool life of wet cutting with VG68 |
| Surface roughness:<br>1/3 times (35.9 %) the surface roughness of dry cutting<br>4/5 times (80.0 %) the surface roughness of wet cutting with VG68 | Surface roughness:<br>3/16 times (18.8 %) the surface roughness of dry cutting<br>2/5 times (41.7 %) the surface roughness of wet cutting withVG68 |
| Remarks: Direct forced cooling on the tool top can performed during air cut process. However, the air cut process was very short, and the influence of the forced cooling was also very low because of the results for workpiece surface roughness. | Remarks: Lubricant the cutting fluid with lower coefficient of friction was effective for the tool life and the work piece surface roughness. DLC coating on the tool was also effective. However, this effect at low temperature (500 °C under). |

Based on the authors' previous studies in Table 1 [15], [16] the function, effect and influence of cutting fluids are discussed. Forced cooling with a strong alkaline water mist with a heat transfer coefficient of 12,000 W/m$^2$K for continuous end-milling [15, 16] and lubrication with a cutting fluid featuring a low coefficient of friction only for intermittent end-milling [15] were evaluated. Although not shown in the table, as for the effect of forced cooling, the effect of forced cooling is limited in the continuous turning process because the tool tip, which requires the most forced cooling during machining, is blocked by chips, so direct forced cooling is not possible and the tool tip area is indirectly forced cooled. In intermittent end-milling, forced cooling can be achieved directly during the air cut, but only for a short period of time, so that the forced cooling effect is not sufficient to extend the tool life, although it is more effective than in turning. The “oil” and “electricity” used for the forced cooling are calculated as $CO_2$ emissions in the LCA (Life Cycle Assessment) and are negative factors when considering sustainability. As for the effect of lubrication, the lubricating properties of cutting fluids are effective when interposed between the tool and the chips. Therefore, the lubricating effect was effective in end-milling with cutting fluid supplied during air cutting. And lubrication with cutting fluids characterized by a low coefficient of friction [15, 16] has improved both tool life and workpiece surface roughness. This reason is thought that the friction coefficient between the tool and the chip is reduced, cutting heat is suppressed, and the temperature rise and thermal deformation of the tool are suppressed. This lubrication also is a sustainable cutting fluid [15, 16] because it does not use “oil” and “electricity” for environmental conservation. Another way to reduce the coefficient of friction between the tool and the chip is to use DLC coated tools. The DLC coating has a coefficient of friction of 0.1 and is present between the tool and the chip from the initial state, which makes it exactly the right material for the job. However, DLC-coated tools have difficulties in machining carbon-containing workpieces and the use of cutting fluids [17] and their coating life is short in high temperature conditions [18]. Therefore, it is currently desired to extend the coating life.

## 3. EFFECT OF CUTTING HEAT ON TOOL LIFE AND WORKPIECE SURFACE ROUGHNESS

### 3. 1. APPLICATION OF WORKPIECE SURFACE ROUGHNESS FOR TOOL LIFE DETERMINATION

In general tool life tests, the tool life is defined when the flank wear $v_b$ reaches 0.15 mm, 0.3 mm or 0.4 mm. However, for practical purposes in industry, tool changes may be timed for safety and productivity reasons. In practice, tool life itself is not used as a measure of machining accuracy, but as a guide to machining accuracy and normal machining. As tool wear progresses and reaches the end of its life, the dimensional accuracy and surface roughness of the workpiece are affected and consequently tool change is required. A decrease in dimensional accuracy can be corrected by the tool wear compensation function built into the CNC machine tool, but if the surface roughness deteriorates, it is necessary to change the tool or regrind the tool. This deterioration in surface roughness leads to a decrease in workpiece accuracy, insufficient performance and deterioration in quality. Therefore, in this research, tool life is not controlled by the amount of flank wear $v_b$, but by the workpiece surface roughness. The tool life is defined as the point at which the surface roughness $Ra$ of the workpiece reaches 1.6 μm.

### 3. 2. SURFACE ROUGHNESS OF WORKPIECES IN TURNING, END-MILLING AND FACE MILLING AND THE EFFECT OF CUTTING HEAT ON IT

The theoretical surface roughness $Rz$ [μm] in the feed direction of end-milling is given by Equation (1), where $f_z$ [mm] is the feed rate per flute of the end-mill (= feed speed $f$ / (spindle speed $N \times$ number of inserts $Z$)) and $\phi D$ [mm] is the diameter of the end-mill [mm].

$$Rz = \frac{fz^2}{4D} \times 1{,}000 \tag{1}$$

This is the result of an end-mill of diameter $\phi D$ moving to the right by $f$ [mm] in the feed direction on the workpiece, and the end-mill radius $\phi D/2$ being transferred onto the workpiece. The surface roughness is smaller in the direction perpendicular to the feed direction.

The theoretical surface roughness $Rz$ [μm] in the feed direction for frontal milling is given by Equation (2), where $f_z$ [mm] is the feed speed per flute of the end-mill (= feed speed $f$ /(spindle speed $N \times$ number of inserts $Z$)) and $\varepsilon$ [mm] is the corner radius of the insert.

Table 2. Influences of the cutting heat generation for each surface roughness regarding the end-milling and the face milling. Machining conditions for the example: workpiece Ti6Al4V, cutting speed $V$ = 70 m/min, feed rate $f$ = 0.08 mm/rev, cutting width $wc$ = 3.0 mm, depth of cut $dc$ = 10 mm

| Kinds | Factors for surface roughness on the feed direction | Influences of the cutting heat generation for the corner radius ε of the insert | Influences of the cutting heat generation for end-mill diameter $\phi D$ | Influences of the cutting heat generation for the others |
|---|---|---|---|---|
| End-milling | Feed speed $f$, End-mill diameter $D$, Insert number $Z$, Spindle speed $N$ | Nothing | Fall under into the category, however very small.<br>※Ex.<br>$D$=16.0 mm → 16.2 mm,<br>$Rz$=3.00 μm → 3.01 μm | The thermal deformation on the deepest cutting point during a milling process have large influence. The thermal deformation was added to the theoretical surface roughness.<br>※Ex. The thermal deformation amount of the insert tip of the end-mill is 3.0 μm, which directly affects the surface roughness. As a result, this thermal deformation amount of 3.0 μm is superimposed on the theoretical surface roughness of Rz 3.01 μm, resulting in an actual surface roughness of 6.01 μm. |
| Face milling | Feed speed $f$, corner radius ε Insert number $Z$, Spindle speed $N$ | Fall under into the category, however very small. | Nothing | The thermal deformation on the deepest cutting point during a milling process have large influence. The thermal deformation was added to the theoretical surface roughness. |

$$Rz = \frac{fz^2}{8\varepsilon} \times 1{,}000 \tag{2}$$

This is the result of each revolution of the frontal milling machine, moving *f* [mm] in the feed direction, with each of the insert cutting the workpiece with a corner radius $\varepsilon$.

The workpiece surface roughness for each of the two machining and the effect of cutting heat generation on it are shown in Table 2. In end-milling, the thermal deformation of the end-mill diameter has a direct effect on the surface roughness of the workpiece, but the change in the end-mill diameter due to thermal deformation is also small and does not significantly affect the surface roughness of the workpiece. For example, when the machining conditions are workpiece Ti6Al4V with medium finishing conditions (cutting speed 70 m/min, feed rate 0.08 mm/rev, cutting width 3.0 mm, depth of cut 10 mm), the end-mill diameter is thermally deformed from $\phi$ 16.0 mm to $\phi$ 16.2 mm, and the theoretical surface roughness *R*z is changed from 3.00 μm to 3.01 μm. However, in end-milling, the tool tip is forcibly cooled during air cutting, but the tool tip undergoes significant thermal deformation during cutting, and this thermal deformation amount is superimposed on the theoretical surface roughness. For example, when the machining conditions are workpiece Ti6Al4V with medium finishing conditions (cutting speed 70 m/min, feed rate 0.08 mm/rev, cutting width 3.0 mm, depth of cut 10 mm), the thermal deformation amount of the insert tip of the end-mill is 3.0 μm, which directly affects the surface roughness. As a result, this thermal deformation amount of 3.0 μm is superimposed on the theoretical surface roughness of *R*z 3.01 μm, resulting in an actual surface roughness of 6.01 μm. Therefore, in later experiments (see Figure 4), when the surface roughness of the workpiece after machining becomes smaller, it is thought to be due to a smaller coefficient of friction between the chips and the tool, which also generates less cutting heat. In face milling, the surface roughness in the feed direction just before the end of the cutting process is greatly affected by the thermal deformation of the tool due to the heat generated by cutting, as in end-milling. This effect is greater when the specific cutting resistance of the workpiece is high, when the workpiece is made of a difficult-to-cut material with low thermal conductivity, and when the machining load is heavy. The proposed cutting fluid, which performs tool polishing during cutting, is considered to be effective under these conditions.

## 4. PROPOSAL OF A CUTTING FLUID FOR POLISHING TOOL DURING CUTTING

In the author's previous study [13], as shown in Table 3, a new cutting fluid was developed for environmentally friendly; it is that strong alkaline water was used instead of “oil” in order to give full consideration to environmental protection, and 8 wt% of graphite with a diameter of 5 mm was mixed in order to achieve a low coefficient of friction, and 4 wt% of polymer PEO-8 was mixed in order to facilitate the incorporation between the tool rake surface and the chips. The tool life was 18.4 times longer than that of dry cutting and 4.5 times longer than that of wet cutting with VG68 (Non-water-soluble cutting fluids). The surface roughness *R*a of the workpiece is shown in Fig. 1. This is the result of a previous study [13], which is re-described in this chapter because it is a very important part of this research. Fig. 1 shows that the surface roughness at the initial stage of machining is in the following order: dry > wet (using VG68) > wet (using cutting fluids in Table 3). The surface roughness *Ra* of the workpiece is the result of the thermal deformation of the tool tip superimposed on the theoretical surface roughness. Therefore, as discussed in the previous chapter, if the friction coefficient between the tool and the chip is reduced during machining, the cutting heat generation and the thermal deformation of the tool are suppressed, and the surface roughness of the workpiece becomes smooth. Therefore, in this chapter, as shown in Table 4, based on the cutting fluid proposed in the previous study [13], cutting fluids containing 2 wt%, 4 wt% and 8 wt% alumina powder (particle size #3,200 and #1,000, respectively) are developed. In the next section, the optimum particle size and density of alumina powder to be included in the cutting fluid are determined. The alumina powder with a grain size of #3,200 was the finest grain for commercial abrasive.

Table 3. Specification for the used cutting fluid with low friction coefficient. The cutting fluid consists of strong alkaline water, polymer and graphite.

| Ingredient, Weight % | Specification |
|---|---|
| Strong alkaline water,<br>88 wt% | Value of pH: pH 12.5, Ingredient (Content): Potassium hydroxide (0.18 w/v%), Company: COOL TECH LTD. |
| Polymer,<br>4 wt% | Polyethylene oxide (PEO-8), Viscosity (0.5% AS): 20~70 mPa・s, Company: Sumitomo Seika Chemicals Company |
| Graphite,<br>8 wt% | Grain size 5~11μm, Density $2.3\times10^3$ kg/m$^3$, Company: AZ ONE Corporation |

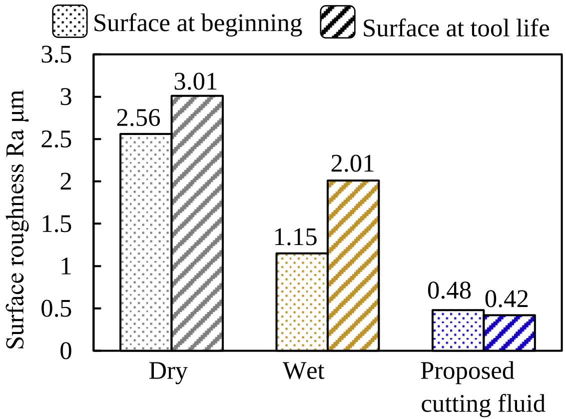


Fig. 1. Experimental results for roughness on workpiece with several forced coolings [13],[14].

Table 4. Component regarding the cutting fluid for polishing a tool during a cutting process

| Cutting fluid for grinding a tool during a cutting process (Proposed cutting fluid in this research) | | | | |
|---|---|---|---|---|
| Base fluid: Strong alkaline water 88wt% + Graphite 8wt% + $\text{PEO}_{-8}$ 4 wt% | | | | |
| Alumina powder for grinding a tool during a cutting process | Grain size | Alumina powder density in the base fluid | | |
| | # 1,000 | 2 wt% | 4 wt% | 8 wt% |
| | # 3,200 | | | |

The upper limit of 8 wt% of alumina powder was set to prevent wear of sliding parts due to scattering of alumina powder (at 8 wt%, there is no scattering due to non-Newtonian fluidization by the polymer). The alumina powders used were all commercially available for abrasive purposes. The cutting fluid actively accelerates the wear of the tool flank surface by abrasive alumina powder, but the polishing of the tool reduces the coefficient of friction between the tool and the chips and thus reduces the thermal deformation of the tool. The tool flank wear $v_b$ is sacrificed in order to improve the surface roughness of the workpiece.

## 5. EVALUATION OF CUTTING PROPERTIES FOR THE CUTTING FLUID

### 5.1. TOOL LIFE

The evaluation experiments were carried out by end-milling using the machining conditions in Table 5 and the experimental set-up in Figure 2. The parameters are the grain size and the weight ratio of the alumina powder contained in the proposed cutting fluid. For reference, dry cutting, wet cutting (using VG68) and cutting with the cutting fluid proposed in the authors' previous work [13] were also performed.

Figure 3 shows the results of the tool life test. In the previous study [13], the tool life was determined when the wear on the flank surface reached 0.15 mm, but in this paper, the tool life test was continued until the workpiece surface roughness *Ra* reached 1.6 μm.

Table 5. Cutting condition for evaluation regarding the proposed cutting fluid (dry cutting, wet cutting using VG68 and 9 wet cutting using the proposed cutting fluids)

| Cutting conditions for tool life | | | |
|---|---|---|---|
| Cutting speed: *V*= 80 m/min | Feed/tooth: *fz* = 0.15 mm/tooth | Width of cut: *wc* = 1 mm | Depth of cut: *dc* = 1 mm |
| Work piece | | | |
| Material: Ti6Al4V | | | |
| Cutting Tool (End-mill with 1 throw away tip) | | | |
| Material: Cemented carbide without coating and Cemented carbide with DLC coating | | | |
| Type and company: NDCW150308FRX KW10 by Kyosera | | | |
| Experimental parameter | | | |
| Dry cutting | Wet cutting (VG68) | Proposed cutting fluid with three grain sizes and three powder densities | |

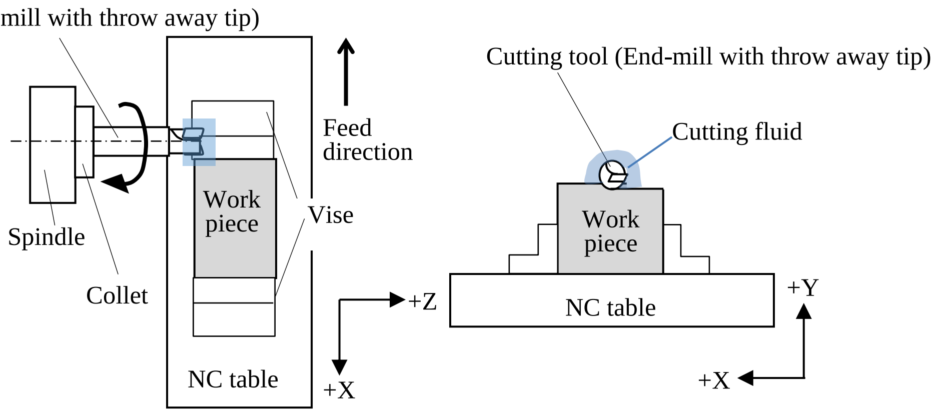


Fig. 2. Experimental set-up for evaluation regarding cutting fluid with low low friction coefficient and polishing property

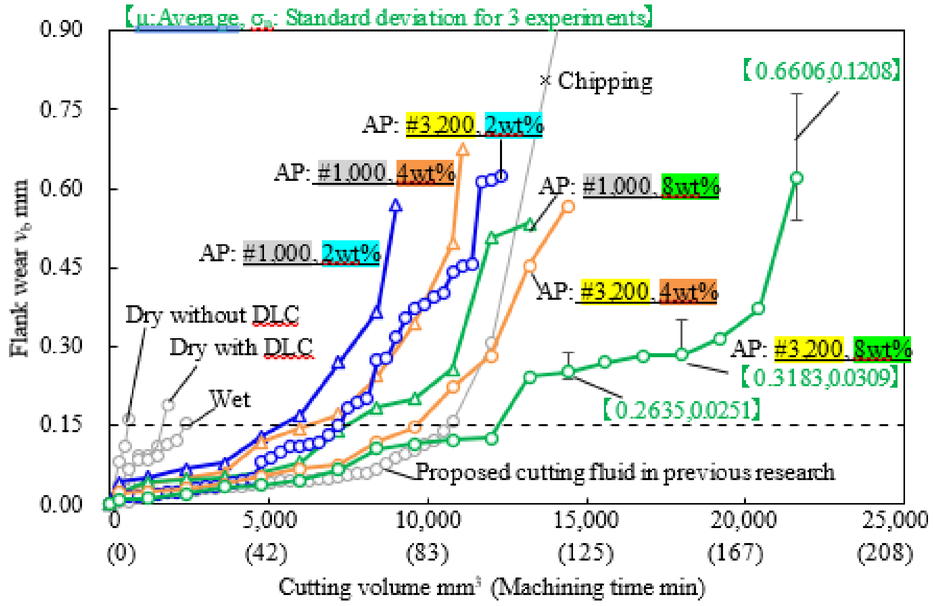


Fig. 3. Experimental results for tool life using the proposed cutting fluid. When the surface roughness was under than $Ra=1.6\mu m$, the turning was continued in spite of the tool life limit (Flank wear $v_b$ = 0.15 mm). At that time, the tool life using it was 36.8 times of one of the dry cutting, and was 9 times of one of the wet cutting (AP: Alumina powder)

The tool life of the proposed cutting fluid containing 8 wt% alumina powder was 37, 20 and 9 times longer than that of dry cutting without DLC coating, dry cutting with DLC coated tools and wet cutting (VG68), respectively. It was also 2 times longer than that of the cutting fluid proposed in a previous study [13]. Thus, the abrasive properties of the alumina powder incorporated in this research were effective. The appropriate amount of alumina powder was 8 wt%. The tool life of dry cutting with DLC-coated tools was about twice as short as that of dry cutting without DLC coating due to the effect of cutting heat. The tool life was affected by the accelerated wear due to the thermal softening of the tool and by the polishing of the tool by the cutting fluid. Note that in end-milling, this flank wear $v_b$ does not affect workpiece surface roughness (as described in Section 3.2.).

### 5.2. WORKPIECE SURFACE ROUGHNESS

Figure 4 shows the variation of the surface roughness *Ra* of the workpiece with time; for the two types of dry cutting and wet cutting (using VG68), the surface roughness of the workpiece deteriorates quickly with time. In contrast, when the proposed cutting fluid is used, there is no change in the surface roughness of the workpiece at the end of the tool life (0.15 mm clearance wear in Figure 3), indicating that the friction coefficient between the tool and chips is small and the tool tip temperature changes little (as described in Section 3.2.).

Figure 5 shows the workpiece profile at the end of the tool life. The theoretical surface roughness $R_z$ was 0.93 μm (from tool diameter $\phi$16, Table 2, Eq. (1)). In a cutting fluid containing 8 wt% alumina powder, the workpiece shape was extremely smooth after a long tool life.

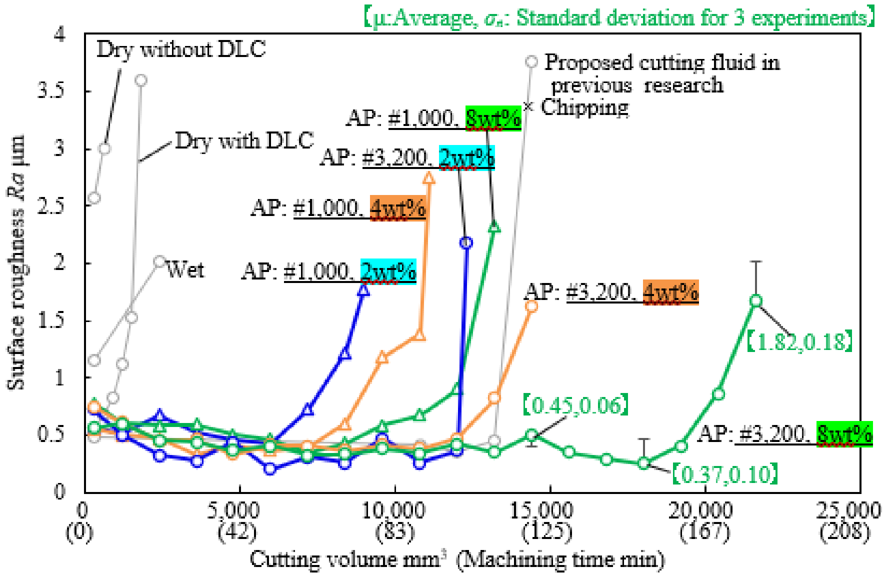
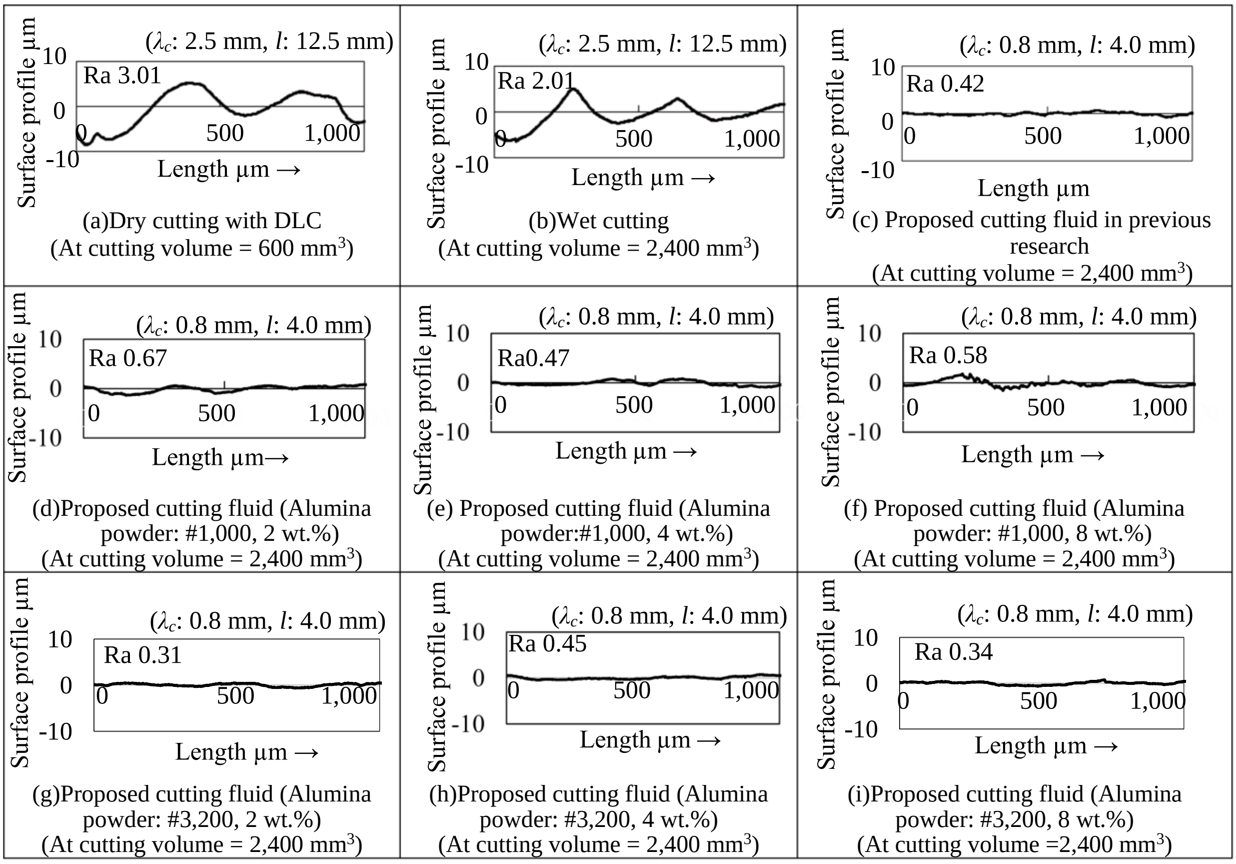


Fig. 4. Experimental results for surface roughness on the workpiece using the proposed cutting fluid. The surface roughness using the proposed cutting fluid is smaller than that of the dry cutting because of the low temperature on the top of the tool. Thermal deformation of the tool influences to the surface roughness for the workpiece (AP: Alumina powder)



(a)Dry cutting with DLC (At cutting volume = 600 mm$^3$)

(b)Wet cutting (At cutting volume = 2,400 mm$^3$)

(c) Proposed cutting fluid in previous research (At cutting volume = 2,400 mm$^3$)

(d)Proposed cutting fluid (Alumina powder: #1,000, 2 wt.%) (At cutting volume = 2,400 mm$^3$)

(e) Proposed cutting fluid (Alumina powder:#1,000, 4 wt.%) (At cutting volume = 2,400 mm$^3$)

(f) Proposed cutting fluid (Alumina powder: #1,000, 8 wt.%) (At cutting volume = 2,400 mm$^3$)

(g)Proposed cutting fluid (Alumina powder: #3,200, 2 wt.%) (At cutting volume = 2,400 mm$^3$)

(h)Proposed cutting fluid (Alumina powder: #3,200, 4 wt.%) (At cutting volume = 2,400 mm$^3$)

(i)Proposed cutting fluid (Alumina powder: #3,200, 8 wt.%) (At cutting volume =2,400 mm$^3$)

Fig. 5. Experimental results for surface profiles on the workpiece using the proposed cutting fluid. In the first half, the surface profiles on the workpiece using the proposed cutting fluid was very smoothly because of the low tool temperature. Thermal deformation of the tool influences to the surface roughness for the workpiece. In the latter half, that was also influenced by tool wear ($\lambda_c$: Cutoff value, $l$: Measurement length)

As shown in Equation (1), the theoretical surface roughness is determined by the feed speed and end-mill diameter. Therefore, the larger the temperature rise of the end-mill, the rougher the surface profile of workpiece. Furthermore, local thermal deformation of the end-mill tip during milling is superimposed on the earlier surface profile, resulting in an even rougher surface profile of workpiece. When the cutting fluid proposed in this study is used, the surface profile of workpiece at the start of machining is similar to the theoretical surface profile of workpiece, indicating that the effect of thermal deformation of the end-mill is small.

### 5.3. WEAR CONDITION OF INSERTS

Figure 6 shows the change in surface roughness of the tool tip over time. The surface roughness was measured in the direction of chip flow on the tool rake surface. The surface roughness *Ra* of the tool tip also shows the same trend as that of the surface roughness *Ra* of the workpiece in Fig. 4 above. This indicates that the cutting fluid proposed in this paper prevents the surface roughness from deteriorating due to the polishing of the tool during cutting, suppresses the increase in the friction coefficient, suppresses the increase in the temperature of the tool tip and the thermal deformation of the tool, suppresses the deterioration of the surface roughness of the workpiece as a result, and extends the tool life.

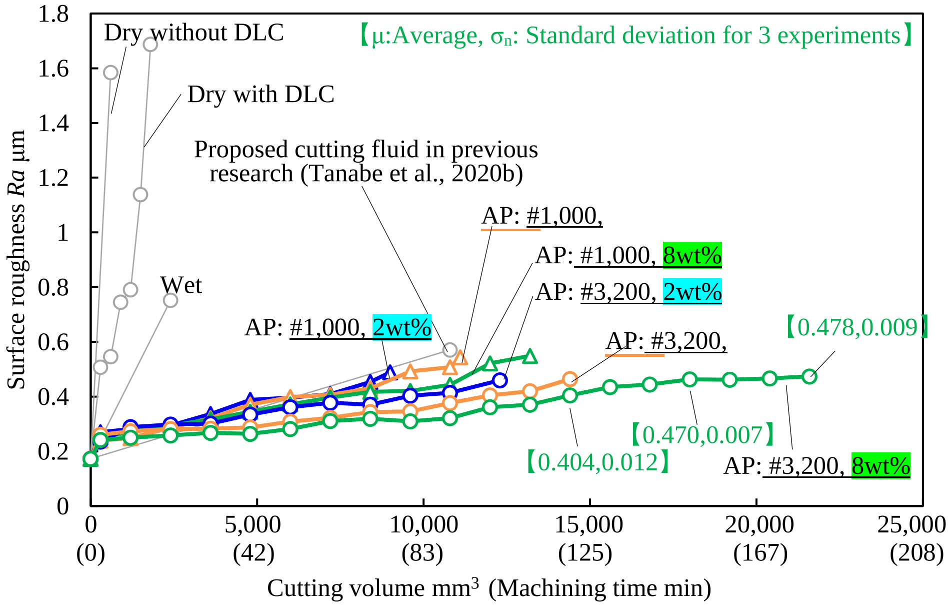
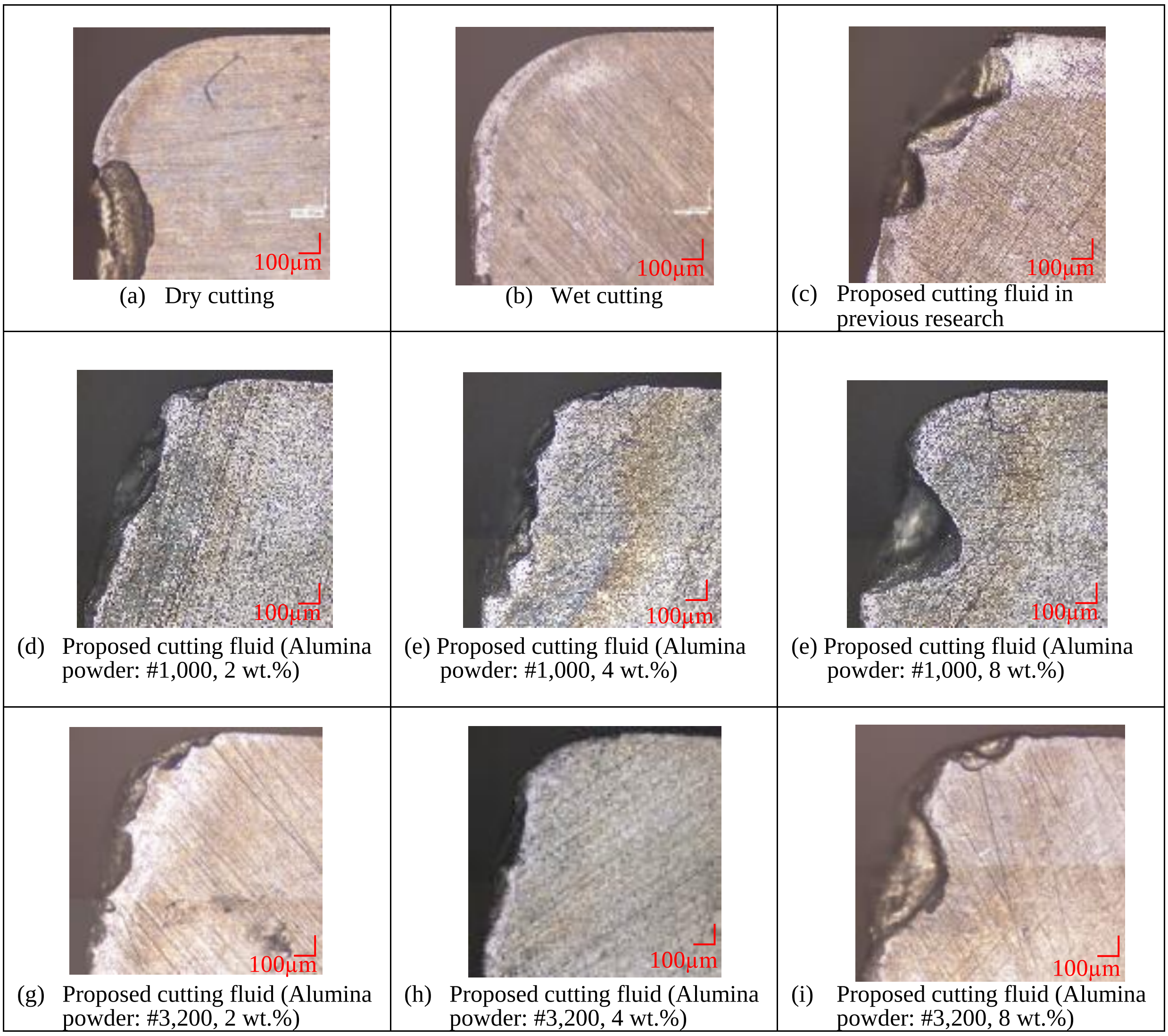


Fig. 6. Experimental results for surface roughness on the top of the insert using the proposed cutting fluid. The surface roughness on the insert influences to its friction on coefficient, then it influences to the tool temperature and lastly its temperature influences to the surface roughness of the workpiece (AP: Alumina powder). (Cut off: 0.25 mm, measuring length: 10 µm)

Photographs of the tools at the end of its life is shown in Fig. 7. In the proposed cutting fluid, deep grooves were rather formed on the flank surface due to the alumina powder contamination. In all cases, no chipping was observed at the end of tool life.

As above, in wet cut using the proposed cutting fluid, at the end of its life, the surface roughness in the direction of chip flow on the tool rake surface in Fig. 6 was very smooth. Therefore, the alumina powder in the proposed cutting fluid was effective to smoothly surface roughness in the direction of chip flow on the tool rake surface (See Fig. 6) and smoothly workpiece surface roughness after machining (See Fig. 4 and 5). At that time, the deep grooves were rather formed on the flank surface due to the alumina powder contamination in Fig. 7 did not affect workpiece surface roughness (as described in Equation (1) and Table 2 in Section 3.2.).



(a) Dry cutting

(b) Wet cutting

(c) Proposed cutting fluid in previous research

(d) Proposed cutting fluid (Alumina powder: #1,000, 2 wt.%)

(e) Proposed cutting fluid (Alumina powder: #1,000, 4 wt.%)

(e) Proposed cutting fluid (Alumina powder: #1,000, 8 wt.%)

(g) Proposed cutting fluid (Alumina powder: #3,200, 2 wt.%)

(h) Proposed cutting fluid (Alumina powder: #3,200, 4 wt.%)

(i) Proposed cutting fluid (Alumina powder: #3,200, 8 wt.%)

Fig. 7. Photographs for seven inserts at tool life limit. There are many influences of the alumina powder polishing in the photographs (e), (f) and (g)

As described above, the abrasive alumina powder, which would normally cause tool wear and shorten the tool life, was intentionally included in the cutting fluid to grind the tool during cutting, thereby reducing the friction coefficient, suppressing the generation of cutting heat, reducing the deterioration of workpiece surface roughness, and consequently extending the tool life. The accelerated tool wear reduces the dimensional and geometrical accuracy, but this can be compensated by the tool wear compensation function of the NC machine tool. In addition, the cutting fluid does not scatter due to the non-Newtonian action of the polymer PEO-8 and is present only on the workpiece and machine tool table. Therefore, Abrasives have no effect on the machine tool mechanism.

## 6. CONCLUSION

The results of this study are summarized as follows; (1) The proposed cutting fluid with a low coefficient of friction suppressed the increase in tool temperature. (2) The proposed cutting fluid has the corrosion resistance of strongly alkaline water, the non-Newtonian properties of polymer PEO-8, the lubricating properties of graphite and the abrasive properties of alumina powder. (3) Wet cutting with the cutting fluid developed in this paper resulted in an 18.4-fold increase in tool life and an 86% reduction in surface roughness *Ra* compared to dry cutting. Compared with conventional wet cutting, the tool life was extended by 4.5 times and the surface roughness *Ra* was reduced by 76%.

## REFERENCES

[1] GRZESIK W., 2021, *Investigation of Notch Wear Mechanisms in the Machining of Nickel-Based Inconel 718 alloy*, Journal of Machine Engineering, 21/1, 56–66, https://doi.org/10.36897/jme/131821.

[2] ZEMZEMI F., RECH J., BEN SALEM W., DOGUI A., KAPSA PH., 2009, *Identification of a Friction Model at Tool/Chip/Workpiece Interfaces in Dry Machining of AIS14142 Treated Steels*, Journal of Materials Processing Technology, 209/8, 3978–3990.

[3] LABIDI A., TANABE I., TAKAHASHI S., 2021, *A Study on Extending Technologies Lifespan for the Environment Safety*, Journal of Machine Engineering, 21/1, 109–120, https://doi.org/10.36897/jme/132577.

[4] WU B., PAN Z., DING D., CUIURI D., LI H., FEI Z., 2018, *The Effects of Forced Interpass Cooling on the Material Properties of Wire arc Additively Manufactured Ti6Al4V alloy*, Journal of Materials Processing Technology, 258, 97–105.

[5] KOBARU Y., NAGAOKA R., SHIMANA K., YOSHIMITSU S., KONDO E., 2020, *Tool Wear Characteristics in Machining of Hypereutectic Al-Si Alloys by Cemented Carbide Tool*, Journal of Machine Engineering, 20/2, 94–103, https://doi.org/10.36897/jme/117775.

[6] Wit GRZESIK W., 2020, *Modelling of Heat Generation and Transfer in Metal Cutting: a Short Review*, Journal of Machine Engineering, 20/1, 24–33, https://doi.org/10.36897/jme/117814.

[7] RECH J., ARRAZOLA P.J., CLAUDIN C., COURBON C., PUSAVEC F., KOPAC J., 2013, *Characterisation of Friction and Heat Partition Coefficients at the Tool-Workmaterial Interface in Cutting*, CIRP Annals Manufacturing Technology, 62/1, 79–82.

[8] TANABE I., YE H. S., IYAMA T., WATANABE T., 2012, *Surface Treatment for Improvement of Coefficient of Friction on Sliding Surfaces*, Journal of Machine Engineering, 12/1, 7–17.

[9] SILVA D.P., TANABE I., JUNIOR., D.C., TAKAHASHI S., 2018, *The Analysis of Environmental and Human Impacts of Using Strong Alkaline Water for Cooling During Machining*, Journal of Machine Engineering, 18/1, 32–44, https://doi.org/10.5604/01.3001.0010.8821.

[10] SHARMA A.K., TIWARI A.K., DIXIT A., 2016, *Effects of Minimum Quantity Lubrication (MQL) in Machining Processes Using Conventional and Nanofluid Based Cutting Fluids: A comprehensive review*, Journal of Cleaner Production, 127/20, 1–18.

[11] FUJIWARA J., ARIMOTO T., TASHIRO T., 2016, *Effect of MQL in High Speed end-Milling of Ti-6Al-4V with PVD Coated Tools*, Transaction of the JSME, 82/835 https://doi.org/10.1299/transjsme.15-00556, (in Japanese).

[12] KANDA K., *A Consideration on the Mechanism of Low Friction Coefficient of Diamond and DLC*, Journal of the surface finishing society of Japan, 69/9, 47–50, (in Japanese).

[13] TANABE I., YAMAGAMI Y., HOSHINO H., 2020, *Development of a New High-Pressure Cooling System for Machining of Difficult-to-Machine Materials*, Journal of Machine Engineering, 20/1, 82–97, https://doi.org/10.36897/jme/117776.

[14] TANABE I., 2022, *Application of the Pentagonal W-Eco Model for Manufacturing Based on "SDGs"*, Journal of Machine Engineering, 22/1, 25–42, https://doi.org/10.36897/jme/145758.

[15] TANABE I., OHTA S., TAKAHASHI S., 2020, *Development of the Cutting Fluid with Lower Coefficient of Friction and its Supply Methods*, Transactions of Japan Society of Mechanical Engineers, 86/886, https://doi.org/10.1299/transjsme.19-00389, (in Japanese).

[16] OHTA S., SILVA P., TANABE I., 2019, *Development of Cooling Fluid with Lower Friction Coefficient for Environmentally Friendly*, International Journal of Mechanical and Production Engineering, ISSN(p): 2320-2092, ISSN(e): 2321-2071, 7/10, 25–29.

[17] HARA K., ISOBE H., KYUSOJIN A., OKADA M., YOSHIHARA H., 2007, *Study on High Precision Machining of Die Steel with Ultrasonic Vibration Assisted Rotated Tools (1st report) – Experiments of Mirror Surface Machining for Three-Dimensional Shape*, JSPE Spring Conference, 901–902, (in Japanese).

[18] MELIH A M., CHAVIN J., WATANABE S., 2014, *Tribological Performance of Si-N-DLC Composite Thin Films Under High Temperature Environment*, Journal of the Surface Finishing Society of Japan, 65/12, 631–632, (in Japanese).