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*turning, DLC coating, forced cooling*
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*environmentally friendly*

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# DEVELOPMENT OF FORCED COOLING TECHNOLOGY USING A DLC COATING TOOL WITH A SMALL THROUGH-HOLE AND A COMMUNICATING TUBE REGARDING THE TURNING FOR DIFFICULT-TO-MACHINE MATERIAL

In turning, the insert tip is continuously covered with chips and the temperature at the tool tip is very high. Especially when difficult-to-machine materials are used as work material, the temperature is above the melting point and the insert tip melts. Forced cooling of tools in turning is necessary. On the other hand, environmentally friendly turning is also necessary. Therefore, in this research, the forced cooling technology using a DLC coating insert with a small through-hole and a communicating tube regarding the turning for difficult-to-machine material was developed and evaluated. A connecting tube is a system in which the hole in the insert and the bottom of the assistant tank are connected by a tube, which allows the cooling medium contained in it to flow freely, so that the height of the cooling medium in the hole in the insert and the height of the cooling medium in the assistant tank behave equally due to gravity. The communicating tube was used for supplying the cooling fluid without no-energy, and the cooling fluid using the strong alkaline water with pH 12.5 was used for environmentally friendly. This strongly alkaline water has a significant cooling capacity equivalent to that of tap water and, moreover, does not corrode metals other than copper and aluminum. The small through-hole was machined for the cooling function on the insert tip. To reduce cutting heat, the inserts are coated with a DLC coating with a small low coefficient of friction. The proposed method was finally evaluated using the difficult-to-machine material Ti6Al4V for the workpiece in several experiments; temperature rise on the insert tip, tool life, surface roughness on the workpiece after the turning. In addition, the machining time, the running cost and the $CO_2$ emission were also evaluated. It is concluded from the result that: (1) the proposed forced cooling technology was very effective for the turning of a difficult-to-machine material, (2) in the proposed method, it is important to maintain the tool tip temperature below 500°C, (3) the proposed method was superior in terms of the machining time and the running cost.

## 1. INTRODUCTION

In continuous cutting, such as turning, chips are continuously applied on the rake surface of the tool tip, and it is difficult to directly force cool the tool tip, which requires cooling, even if cutting fluid is supplied in wet turning [1–3]. In particular, in the turning of difficult-to-cut materials such as titanium alloys and nickel alloys [4] for which demand is increasing for use in aircraft and aerospace industry materials, much of the heat generated by

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cutting flows into the tool because of the small thermal conductivity for the workpiece and the chip, causing the tool tip to become hot and significantly shortening tool life [4–6]. Previous research by the authors has led to the development of cutting fluids characterized by a low coefficient of friction [7] and to the development of high-pressure forced cooling technology [1], but this is still not sufficient due to the difficulty of supplying the cutting fluid directly to the tool tip during turning. On the other hand, to comply with SDGs and carbon neutrality [8], [9], power saving and cutting oil saving are also required in machining.

Therefore, in this research, new forced cooling technique has been developed; specifically, firstly, a small through-hole for cooling is machined on the insert tip, and then the surface of the tool was coated with DLC, and a simple system is constructed to continuously supply strong alkaline water with pH 12.5 from the bottom of the tool using the communicating tube. Then, the cutting properties (tool tip temperature, tool life, tool edge observation, workpiece surface roughness) are experimentally evaluated using the system. Finally, the machining time, running cost and $CO_2$ emission were calculated and evaluated.

## 2. PROPOSE ON FORCED COOLING USING A DLC COATING TOOL WITH A SMALL THROUGH-HOLE AND A COMMUNICATING TUBE

In this chapter, the proposed forced cooling system is described. As shown in Fig. 1, the proposed system is a forced cooling based on a DLC-coated insert with a small hole and a connecting tube. The bottom of the small through-hole in the insert and the bottom of the assist tank are connected by a connecting tube. Therefore, when the water surface $H = 0$ mm in the assist tank, the water surface in the small through-hole of the insert coincides with the rake surface of the insert due to gravity. Here, if the water surface $H$ of the assist tank is moved in the + direction, strong alkaline water is supplied to the small through-hole of the insert without energy at a flow velocity corresponding to the water pressure. The optimum water surface height $H$ of the assist tank is considered in later experiments to accommodate the effects of the repulsive pressure associated with the boiling of the strong alkaline water and the replenishment of the strong alkaline water as it evaporates. The small through-hole of the insert is drilled by EDM. In the vicinity of the small through-hole exit at the tip of the insert, the strong alkaline water is always in a state of evaporation during cutting, causing a large cooling phenomenon due to evaporation. Strong alkaline water evaporates at the tool tip, but alternative strong alkaline water is continuously supplied from the assistant tank using a connecting tube. Strong alkaline water supply using the communicating tube is done without energy and is environmentally friendly. This turning using the cooling with strong alkaline water is not wet turning condition and is similar to dry turning. DLC coatings are used to reduce the coefficient of friction and hence the heat generated by the cutting. Strong alkaline water is the best cooling medium as it does not cause chemical changes to the DLC coating. The through-hole specification has the distance $S = 2.5$ mm from the tip of the tool to the centre of the through-hole for cooling and the diameter of the through-hole for cooling $\varphi_d = 3.0$ mm. In this research, the height $H$ of the assistant tank is used as a parameter for later evaluation experiments. The proposed system reduces cutting heat and allows intensive forced cooling of the tool tip. The proposed system is environmentally friendly, will be able to contribute to the achievement of SGDs and carbon neutrality.

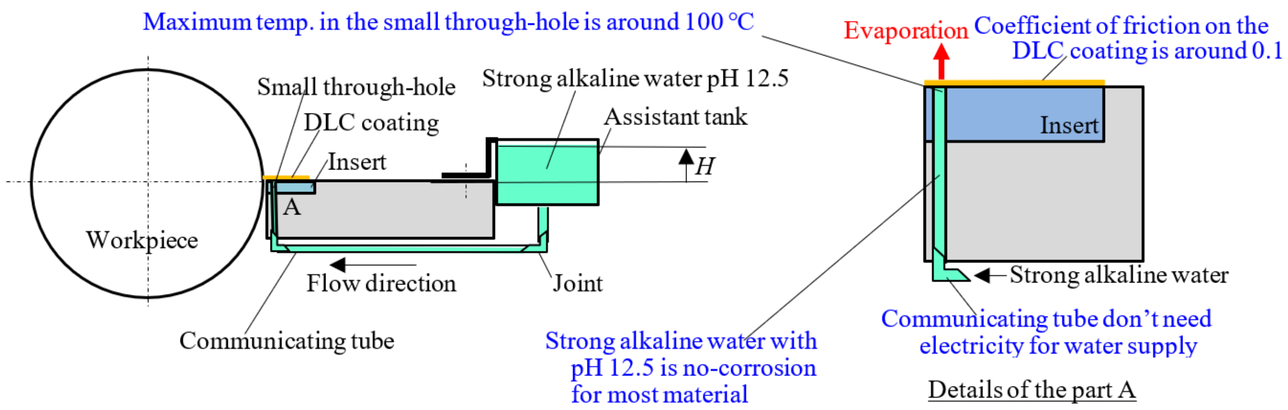



Fig. 1. Explanation the cooling using DLC coating insert with the small hole and the communicating tube (*H*: height from tool rake surface to strong alkaline water surface. See Fig. 7 and 8.)

## 3. EVALUATION OF THE CUTTING PROPERTIES FOR THE PROPOSED FORCED COOLING TECHNOLOGY

### 3.1. EVALUATION OF TOOL TIP TEMPERATURE

The effect of the proposed forced cooling was evaluated for the cutting properties by experiments. Ti6Al4V was selected as the workpiece because of its low thermal conductivity (7.5 W/mK) and extremely high thermal load on the insert. Carbide (CNGG120408R-P TH10 by Tungaloy), which is commonly used for middle cutting condition of steel, was selected as the insert. The specification of the fine through-hole in the insert was determined by considering the mechanical strength and its cooling effect in the FEM simulation. Depth of cut 0.5 mm, feed speed 0.2 mm/rev and cutting speed 150 m/min were selected for middle cutting condition. Turning at a cutting speed of 28 m/min (calculated using cutting theory) to keep the temperature rise at the tool tip below 500°C (the heat resistance temperature of the DLC coating). First, the temperature rise of the tool tip was evaluated as the first cutting characteristic. Table 1 shows the cutting conditions and Fig. 2 shows the experimental setup. As it is difficult to measure the tool tip temperature directly due to chips, the temperature rise values at two points on the rake face (points *C* and *D*) in Fig. 2 were measured by T-type thermocouples and interpolated using FEM unsteady thermal analysis [10]. Three types of experimental parameters were used: dry turning, wet turning (Type A2, diluted 20 times), and turning with the proposed tool with DLC coating and through-holes for cooling. In the case of turning with the proposed tool, the relationship between the height of the water surface of the assistant tank *H* (see Fig. 1) and the temperature rise at the tool tip was also measured and calculated.

Figure 4 shows a comparison of the steady-state values of the tool tip temperature rise interpolated from the temperature rise measurement results in Fig. 3. In the case of turning

($V$ = 150 m/min) with the proposed tool for cooling, the temperature rise at the tool tip (at the height of the water surface of the assistant tank $H$ = 180 mm) was 1254°C, which is 66% of that of dry turning and 102% of that of wet turning. Thus, the thermal effectiveness of the proposed forced cooling system for DLC-coated tools with through-holes for cooling has been confirmed as an alternative to wet turning. The tip temperature for the proposed insert was 1254°C and the heat transfer coefficient was 9500 W/m$^2$K at that time. Furthermore, when the cutting speed was reduced from 150 m/min to 28 m/min in order to keep the tool tip temperature below 500°C for DLC coating control (height of the water surface of the assistant tank $H$ = 180 mm), the tool tip temperature was 476°C, which is the optimum temperature for extending the life of the DLC coating. This is the optimum cutting speed under the machining conditions of medium cutting of workpiece Ti6Al4V by the proposed method. The temperature rise at DRY turning (calculated value) is 1886°C, which exceeds the melting point of Ti6Al4V, and melting of the tool tip was also confirmed in the experiment.

Table 1. Cutting condition for measuring the insert tip temperature regarding the DLC coating insert with the small through-hole and the communicating tube during the turning for difficult-to-machine material.

| Cutting conditions | | |
|---|---|---|
| Cutting speed 150, 28 m/min | Feed speed 0.2 mm/rev | Depth of cut 0.5 mm |
| Workpiece | | |
| Material: Ti6Al4V | | |
| Tools (Inserts) & Cutting type | | |
| Basic insert: CNGG120408R-P TH10 by Tungaloy | Dry | |
| | Wet (Type A2) | |
| | Proposed method using the insert using the small through-hole and the communicating tube | |
| Thermocouples | | |
| Type T | | |

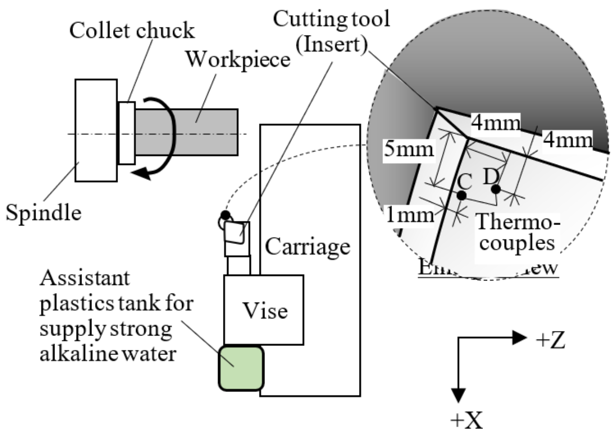



Fig. 2. Experimental set-up for measuring tool temperature regarding the DLC coating insert with the small through-hole and the communicating tube.

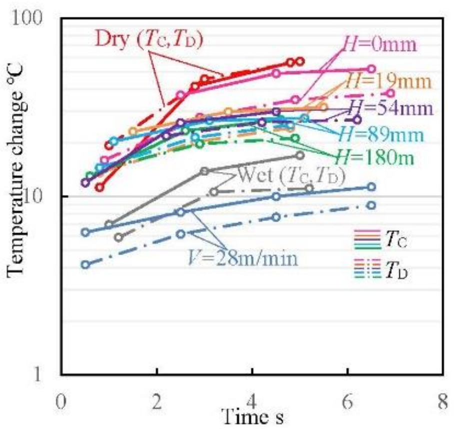



Fig. 3. Temperature changes of the points A, B, C and D on the insert during the turning. These were used for calculation of the tool tip temp.

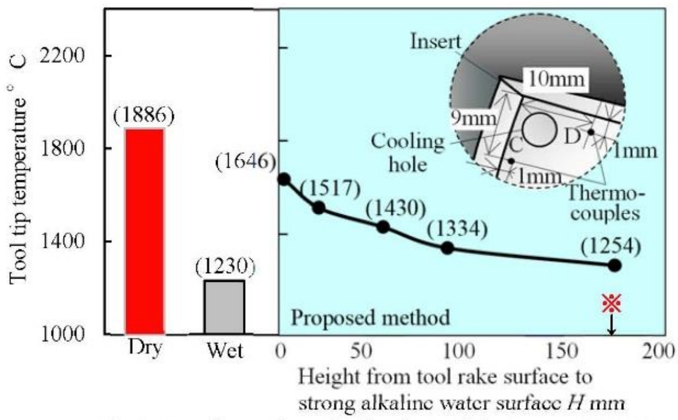



Fig.4. Experimental results for the tool tip temp at $V$=150 m/min. The temp. of the turning using the DLC coating insert with the small through-hole and the communicating tube was lower than the other cuttings. Tool tip temp. at $H$=180 mm and $V$=28 m/min was 476 °C※.

3.2. TOOL LIFE EVALUATION AND TOO LEDGE OBSERVATION

Figure 5 shows the results of the tool life test and Figure 6 shows a photograph of the tool wear at the end of the tool life, respectively. Tool life was measured using a laser microscope (KEYENCE, VK-X150) for flank wear. Tool life was determined when flank wear reached 0.3 mm. The five experimental parameters were the same three as in the previous section, plus two additional parameters; dry turning with a cutting speed of *V* = 28 m/min and turning with a cutting speed of *V* = 28 m/min using the proposed tool. At the cutting speed of *V*=150 m/min, the tool life of the proposed tool was 1.2 times longer than dry turning and 0.89 times longer than wet turning.

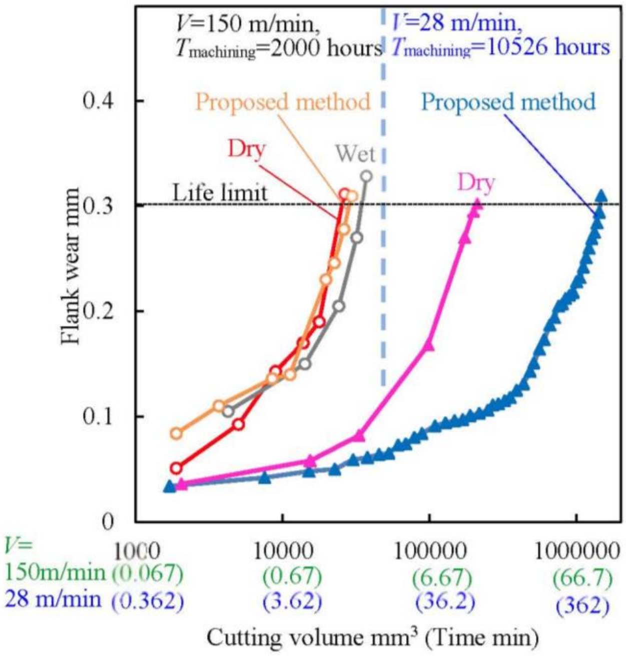
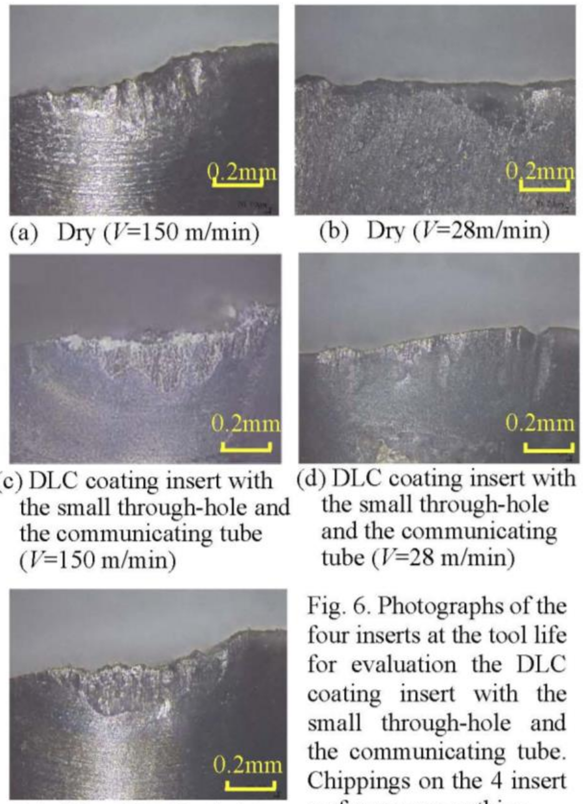



Fig. 5. Experimental results for tool life for evaluation the DLC coating insert with the small through-hole and the communicating tube. The tool life of the turning using the DLC coating insert with the small through-hole was longer than the other turnings




(a) Dry (*V*=150 m/min) (b) Dry (*V*=28m/min)

(c) DLC coating insert with the small through-hole and the communicating tube (*V*=150 m/min)

(d) DLC coating insert with the small through-hole and the communicating tube (*V*=28 m/min)

(e) Wet (*V*=150m/min)

Fig. 6. Photographs of the four inserts at the tool life for evaluation the DLC coating insert with the small through-hole and the communicating tube. Chippings on the 4 insert surfaces were nothing.

The tool life of the proposed tool for turning with the cutting speed reduced to *V* = 28 m/min was 56 times that of dry turning (at *V* = 150 m/min), 40 times that of wet turning (at *V* = 150 m/min) and 7 times that of dry turning (*V* = 28 m/min). Thus, the proposed through-hole tool for DLC coating and cooling had a sufficient effect on suppressing the temperature rise at the tool tip, which in turn suppresses the softening of the tool hardness and extends the tool life at the cutting speed *V* = 28 m/min. In the turning process (cutting speed *V* = 28 m/min) using the proposed tool, the DLC coating life was extended by the forced cooling effect of the through-hole for cooling, and the tool life was extended by the continuous suppression of cutting heat generation. The effect was more pronounced under machining conditions where the tool tip temperature rise could be controlled below 500 °C. Thus, forced cooling with through-hole for cooling has the effect of suppressing the rise in tool tip temperature and extending the life of the DLC coating. These two effects are expected to be useful for the evaluation of machining time and running cost in Chapter 5.

Thus, the proposed tool is considered to have suppressed the rise in tool tip temperature, which in turn suppressed the softening of the insert due to temperature rise and hence tool wear. These results are considered to be a superposition of the suppression of cutting heat generation due to the low friction coefficient of the DLC coating and the cooling effect of the proposed forced cooling. The proposed forced cooling is also used to control the temperature of the DLC coating.

### 3.3. EVALUATION OF THE SURFACE ROUGHNESS OF WORKPIECES

Figure 7 and Fig. 8 show the measured results of workpiece surface roughness *Ra* and the workpiece surface profile at the end of tool life, respectively. Surface roughness and surface profile of the workpiece were measured with a contact-type surface roughness meter (Mitutoyo, SJ-400).

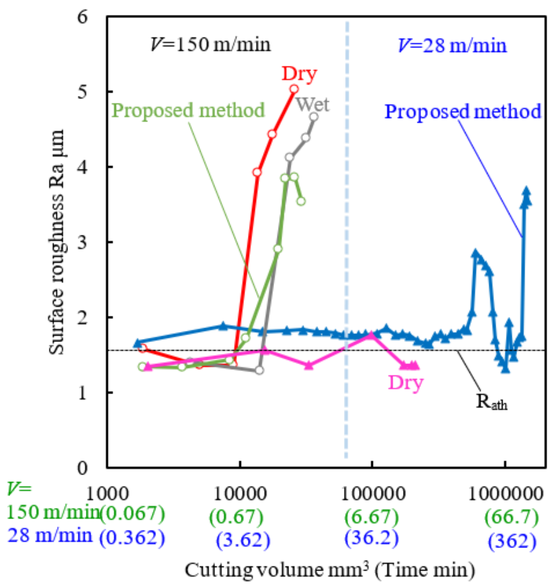



Fig. 7. Experimental results for surface roughness on workpiece for evaluation the DLC coating insert with the small through-hole and the communicating tube. The surface roughness of the proposed turning was smaller than the other turnings Surface roughness of the workpiece were measured with a contact-type surface roughness meter (Mitutoyo, SJ-400).

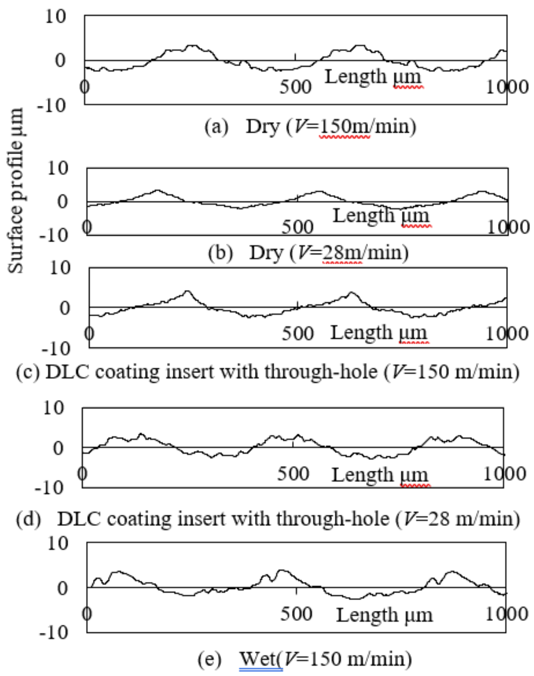



Fig. 8. Profiles of surface roughness after machining for evaluation the DLC coating insert with the small through-hole and the communicating tube. The surface profile of the proposed turning was smoother than the other cuttings because of the little thermal influence (Cutoff value $\lambda_c$: 0.8mm, Measurement length $l$: 4.0mm). Surface profiles of the workpiece were measured with a contact-type surface roughness meter (Mitutoyo, SJ-400).

Figure 8 shows that the surface roughness of the workpiece is smoothed in the following order: Dry (*V* = 150 m/min) > Wet (*V* = 150 m/min) > Proposed tool (*V* = 150 m/min) > Dry (*V* = 28 m/min) ≒ Proposed tool (*V* = 28 m/min). The proposed method was also effective in improving the surface roughness of the workpiece. As can be inferred from the surface profile of the workpiece in Fig. 8, the large local thermal deformation of the tool tip was superimposed on the theoretical surface roughness calculated from the feed rate and tool nose radius.

Therefore, it can be assumed that the DLC-coated tool with through-hole for cooling can effectively force cooling of the tool tip temperature rise and thus suppress the local thermal deformation of the tool tip, resulting in improved surface roughness (The surface roughness of the workpiece in turning is influenced by two factors: feed speed and insert nose radius (see Fig. 8). Therefore, the surface roughness is considered to be influenced by the fact that the proposed method can reduce the tool tip temperature rise, thus suppressing insert softening due to temperature rise and thereby tool wear, resulting in a smaller change in nose radius shape.).

As described above, these results were obtained by controlling the optimum temperature for the DLC coating to function effectively. In other words, the results were obtained by reducing the cutting speed from 150 m/min to 28 m/min in order to limit the temperature rise at the tool tip to 500°C (the heat resistance temperature of the DLC coating). This cutting speed of 28 m/min can be easily calculated using cutting theory.

## 4. EVALUATION OF MACHINING TIME, RUNNING COST AND SIMPLE LCA FOR THE PROPOSED METHOD

In this chapter, the impact of the proposed method on machining time, running costs and simple LCA is considered.

### 4.1. EVALUATION OF MACHINING TIME

The working $T_{working}$ hours for machining consist of the actual machining $T_{machining}$ hours and the setup $T_{setup}$ hours for tool change. Work was assumed to be available for 8 hours per day, 250 days per year (2000 hours/year). If the set-up time for each tool change is defined as $t_{setup}$ hours and the tool life as $T_{life}$ hours, the working time $T_{working}$ can be calculated using equation (1).

$$T_{working} = T_{machining} + T_{setup} = T_{machining} + T_{machining} \div T_{life} \times t_{setup} \quad (1)$$

The actual machining time $T_{machining}$ was set to 2000 hours per year at a cutting speed of 150 m/min. For the tool life $t_{setup}$, the data from the tool life test results (Figure 5) were used, as shown in Table 2. When the cutting speed was reduced from 150 m/min to 28 m/min, the actual machining time was increased to 10526 hours (= 2000 hours / 0.19) to ensure the same output as the productivity was reduced to 19%. In this case, the actual machining time would be 10526 hours (= 2000 hours / 0.19) longer to achieve the same output.

Figure 9 shows the results of the calculation of the relationship between the set-up time $t_{setup}$ and the annual working time $T_{working}$. The tool life $T_{life}$ and the single setup time $t_{setup}$ affect the annual setup time for tool change $T_{setup}$. The proposed method (with a cutting speed of 28 m/min) has a long tool life and a low number of tool changes, so that its operating time is reduced when the set-up time is long, under conditions that ensure the same output as dry cutting. However, the proposed method would rather increase the uptime if the set-up time is short. As a result, under the conditions of this section, the proposed method can reduce the operating time $T_{working}$ when the set-up time is more than 11 minutes, and the effectiveness of the proposed method is remarkable as the set-up time becomes longer. For example, when the setup time was 30 minutes, the operating time $T_{working}$ of the proposed method ($V$ = 28.5 m/min) could be reduced to 30.5% of that of dry turning ($V$=150 m/min) and 39.3% of that of wet turning ($V$ = 150 m/min). Difficult-to-machine materials are often used for high-precision aerospace components. Therefore, long set-up times for high-precision positioning and compensation for tool changes are necessary. The proposed method is effective in such cases.

Table 2. Tool life data in the turning (See Fig. 6). The data was used for calculation of the machining time and the running cost

| DLC coating | Cutting speed $V$ | Condition | Tool life $T_{life}$ (hour) |
|---|---|---|---|
| Nothing | 150 m/min | Dry | 0.029 |
| Nothing | 28 m/min | Dry | 1.250 |
| Nothing | 150 m/min | Conventional wet using Type A2 | 0.038 |
| With DLC coating | 150 m/min | Proposed turning | 0.033 |
| With DLC coating | 28 m/min | Proposed turning | 8.723 |

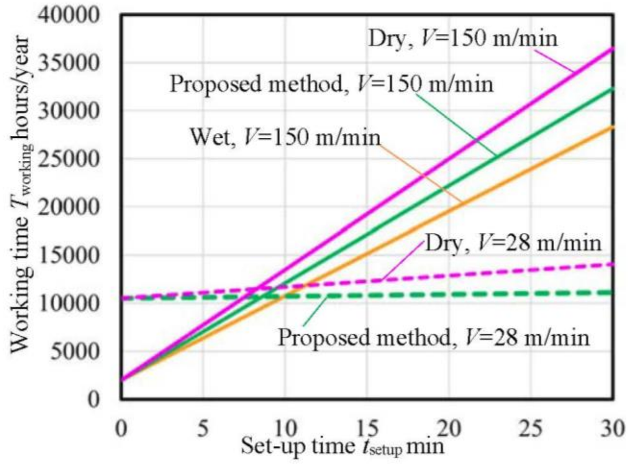



Fig. 9. Relationship between the set-up time and the working time for one year on the turning. When the proposed method was used, the working times becomes short and this productivity become high because of the short total set-up time ($V$: Cutting speed).

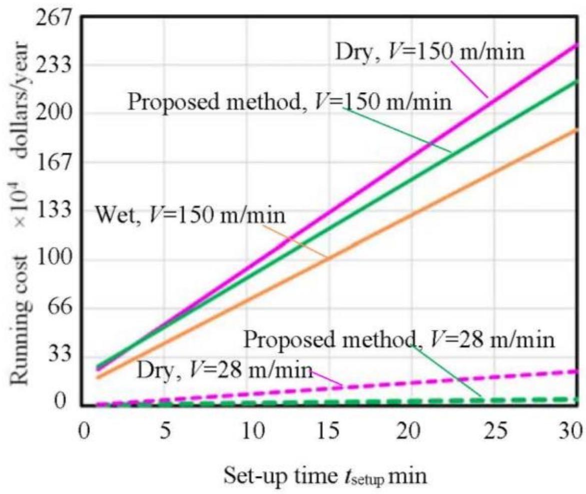



Fig. 10. Relationship between the set-up time and the running cost for one year on the turning. When the proposed methods were used, the running costs becomes very cheap ($V$: Cutting speed).

4.2. EVALUATION OF RUNNING COST

In the calculation of the running costs, the conditions were as follows; (1) the electricity costs for the machine tool MT (1.0 kW), the chiller CU (2.2 kW), and the pump OP (1.0 kW) [dry turning 1.0 kW (MT), wet turning 4.2 kW (MT, CU, OP) and proposed method 1.0 kW (MT), electricity cost 1 kWh = 0.13 dollars], (2) the tool costs for tool change [4 places used per insert, 10.0 dollars/piece, 13.3 dollars/piece for DLC coated tools], (3) the set-up costs (charge 66.7 dollars/h), (4) cutting fluid purchase cost (3173 dollars/year) and disposal cost (79.2 dollars/year) for wet cutting and (5) the cost of alkaline water (16.9 dollars/year) were used as cost tables. It was assumed that the machine and equipment in (1) operated for the annual actual machining time $T_{\mathrm{machining}}$ as described in the previous section, and calculated (2) and (3) from the actual machining time, tool life, and setup time $t_{\mathrm{setup}}$, and also incorporated (4) for wet turning and (5) for the proposed method into the respective annual running costs. We did not include the labour cost of the machining process in the running cost, because it is a real turning process with automatic operation.

Figure 10 shows the results of the calculation of the relationship between the setup time ($t_{\mathrm{setup}}$) and the annual running cost. Since the proposed method has a long tool life and a small number of tool changes, the running cost can be reduced efficiently. For example, when the setup time $t_{\mathrm{setup}}$ was 30 minutes, the running cost of the proposed method ($V$=28.5 m/min) could be reduced to 1.8 % of that of dry turning ($V$=150 m/min) and 2.3% of that of wet turning ($V$=150 m/min). In the turning of difficult-to-turn materials, a major problem is the extremely short tool life due to the large amount of cutting heat that flows into the tool, which has a direct impact on running costs. Therefore, the proposed method is effective for turning difficult-to-cut materials.

### 4.3. EVALUATION OF SIMPLE LCA

The annual $CO_2$ emissions were calculated and evaluated from two sources: power consumption and cutting fluid. For the dry turning and the proposed method, only the power consumption of the machine tool (1.0 kW) was used. For the wet turning, the power consumption of the machine tool (1.0 kW), chiller and pump (4.2 kW) and cutting fluid oil were used. In addition to the water-soluble cutting fluid used in this report (Type A2, diluted 20 times), the non- water-soluble cutting fluid (VG68) was also calculated for reference.

The amount of $CO_2$ emitted per year due to power consumption was calculated from the power consumption of the equipment for each machining method, using 2000 hours of actual machining time $T_{\mathrm{machining}}$ at a cutting speed of 150 m/min and 10526 hours of actual machining time $T_{\mathrm{machining}}$ at a cutting speed of 28 m/min. emissions per year from the power consumption of the equipment for each machining method (the power consumption during set-up work was not calculated). The amount of $CO_2$ emitted, $CL_{CO2}$ (kg-$CO_2$), estimated from the amount of electricity consumed, is obtained from equation (2) [11, 13].

$$CL_{CO2} = \text{Power consumption kWh} \times \text{Emission factor t-CO}_2\text{/kWh} \times 1000 \qquad (2)$$

Here, the emission factor from electricity consumption to $CO_2$ emissions is 0.000496 t-$CO_2$/kWh [11].

The amount of $CO_2$ emissions per year due to the cutting fluid used in the wet turning process can be obtained from equation (3), where the amount of $CO_2$ emissions $CL_{CO2}$ (kg-

$CO_2$) is estimated from the amount of waste oil processed per year of 1040 ℓ for one linear motor lathe used in this report (340 ℓ of waste oil / half year ×2 times + 30 ℓ ×12 months) [14–16].

$$CL_{CO2} = \text{Waste oil k}\ell \times \text{Heat generation MJ/}\ell \times \text{Carbon emissions t-C/TJ} \times (44 \div 12) \quad (3)$$

The heat generation (calorific value) is 40.2 MJ/ℓ and the carbon emission is 19.9 t-C/TJ [17]. The factor (44÷12) in equation (3) is a conversion factor for converting carbon to carbon dioxide. This equation (3) is used as the amount of $CO_2$ emitted $CL_{CO2}$ (kg-$CO_2$) in the case of the non- water-soluble cutting fluid (VG68) and the amount of $CO_2$ emitted $CL_{CO2}$ (kg-$CO_2$) in the water-soluble cutting fluid (Type A2) diluted 20 times is 5% of equation (3) (= 100 ÷ 20).

Figure 11 shows the results of the calculation of the annual $CO_2$ emissions. Wet turning with the non- water-soluble cutting fluid (VG68) had higher annual $CO_2$ emissions, but by changing to the water-soluble cutting fluid (Type A2, diluted 20 times) the annual $CO_2$ emissions for the "oil" could be reduced to 5%, but the $CO_2$ emissions from the electricity consumed by the pumps and chillers remained significant. When the cutting speed is reduced from $V$ = 150 m/min to 28 m/min to protect the DLC coating, five times the actual machining time is required to achieve the same productivity as when the cutting speed is $V$ = 150 m/min. This is a drawback of the proposed method. Therefore, research to increase the heat resistance of the DLC coating (currently 500°C) in order to increase the cutting speed $V$ = 28 m/min (see Fig. 9) and the development of DLC coating technologies with longer coating life (see Table 2, currently, 8.723 hours) are solutions to mitigate this drawback.

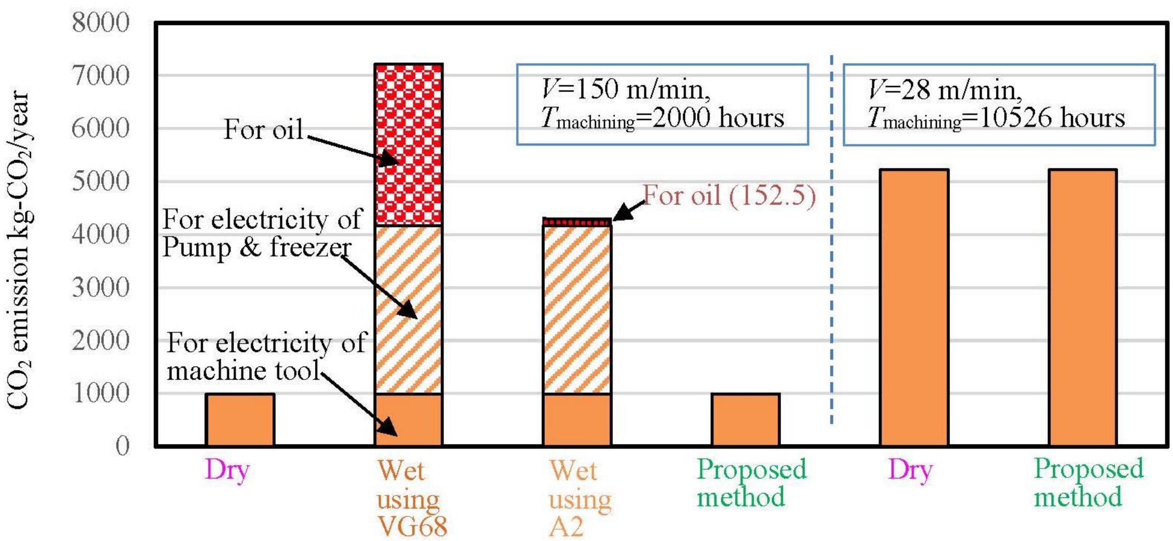



Fig. 11. Estimation for simple LCA regarding the proposed two methods. The cutting using the proposed methods are smaller quantity of the $CO_2$ emission. Sustainability for the proposed methods were excellent ($V$: Cutting speed). These results were calculated using Table 2, Equations (1), (2) and (3).

Although this section refers to $CO_2$ emissions due to the consumption of cutting fluid and electricity, the system does not require waste disposal of used cooling media in comparison with other cooling methods. Furthermore, equipment such as pumps, compressors and chillers for forced cooling are not required, which has the effect of saving energy, resources and space.

## 5. CONCLUSION

The results of this study can be summarized as follows; (1) The tool life of the proposed method of turning (cutting speed $V = 28$ m/min) is 55 times longer than that of dry turning ($V = 150$ m/min), 39 times longer than that of wet turning ($V = 150$ m/min, A2-20 dilution), and 6.7 times longer than that of dry turning ($V$=28 m/min), respectively. (2) Up to a cutting volume of 100000 mm$^3$, the surface roughness *Ra* of the workpiece remained below 2 μm when turning at a cutting speed of $V$=28 m/min. (3) The machining time and running costs of the proposed method (cutting speed $V$=28 m/min) were 30.5% and 1.8% of dry turning (at V=150 m/min) and 39.3% and 2.3% of wet turning (at V=150 m/min), respectively, under the setup time of 30 minutes. (4) For the proposed method (cutting speed $V$=28 m/min), the cutting speed was reduced from $V = 150$ m/min to 28 m/min in order to protect the DLC coating, so that five times more actual machining time was required to ensure the same output as when the cutting speed was $V = 150$ m/min, which resulted in a five-fold increase in annual $CO_2$ emissions.

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