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vibration, microbubble, strong alkaline water, immersed machine, thermal deformation, CO_2 emission

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DEVELOPMENT OF IMMERSED MACHINE TOOL AND MACHINING IN THE STRONG ALKALINE WATER FOR REDUCTION OF CO_2

Nowadays, eco-friendly manufacture has become common request in the manufacturing and production. The excessive electric power associated with the usage of large amount of oil for cooling and lubrication during machining can increase the CO_2 emission which is considered as large problem for environment. On the other hand, the presence of the unwanted vibration during machine can affect the quality of production. The influence of immersed machine tool in strong alkaline water has been investigated in previous work for normal machine operation when no vibration occurred. In present research, the influence of immersed condition to the vibration of the bench lathe machine was investigated. Thermal deformations of the spindle when operating bench lathe coincide with machine resonances were also measured for evaluation of accuracy. The calculation of CO_2 emission using immersed bench lathe machine was done by comparing with the conventional machining. It is concluded from the results that; (1) Excellent cooling efficiency can be achieved by using strong alkaline water added with microbubble, (2) Vibration of machine tool was reduced during immersed condition, (3) Thermal deformation of the bench lathe was very small despite no-forced cooling was used, (4) The large number of CO_2 that released annually can be reduced by immersed of machine tool.

1. INTRODUCTION

Since the end of the last century, scientists face serious problems on energy resources and destruction of natural environment on the global scale. Reducing electric usage, cutting oil usage, and the cooling fluid which are harmful to environment and human health become most important factors to be considered in manufacturing and production field. Especially, the major reduction in CO_2 emission is extremely important to prevent from the global warming. Nowadays, eco-friendly manufacturing [1] has become common request as a processing technology, as well as high accuracy and productivity of manufacturing with consideration to energy conservation. Various cooling system have been applied during machining to remove heat load for longer tool life and to obtain smooth surface roughness of final cutting result. However, optimum tool, cooling and cutting condition alone do not guarantee the achievement of optimum final cutting result. The heat load caused by bearing unit that support spindle in lathe machine also has influence on the final cutting result. The

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heat generates by friction inside bearing can cause thermal deformation to take place. When this condition occurs, work piece displaces from its original position resulting uneven shape and poor surface roughness of the final cutting result. Regarding to this problem, many countermeasures have been made to minimize thermal deformation on machine tool for high precision manufacturing [2],[3]. In addition, many forced cooling technologies for releasing heat have been established for high accuracy and productivity improvement [4],[5]. Many of those measures have effectively used high capacity refrigerators for forced cooling to eliminate heat and suppress thermal impact on machines and cutting tool. However, in consideration to environmental conservation, additional measures are required to meet those constraints.

In our previous work [6], we have investigated the immersion of machine tool in strong alkaline water by evaluating the effectiveness of the cooling and measuring thermal deformation of the bench lathe by operated machine at normal operation speed of 3600min^{-1} outside machine resonance zone. It was concluded that the evaporative cooling effect of strong alkaline water is capable to minimize thermal deformation of machine tool by immersed condition. However, as the vibration during machining has big influence to the production quality and final cutting result, therefore, in the present study, the influence of immersed condition to the vibration of the bench lathe machine was investigated. The cutting experiments were performed by immersed machine tool completely in strong alkaline water which has high corrosion resistance to most of materials. The immersed cutting processing system using forced evaporative cooling effect was investigated by operating machine coincide with machine tool resonance. Concretely, a small bench lathe is immersed completely in strong alkaline water, and then the resonance frequency and the vibration during operating coincide with resonance of bench lathe machine are measured. The thermal deformation of machine structure at machine spindle is evaluated by experiment. In addition, the evaluation on environmental preservation by this processing system was also performed.

2. THE INFLUENCE OF STRONG ALKALINE WATER AND THE OPTIMUM COOLING USING MICROBUBBLE

2.1 STRONG ALKALINE WATER

In recent years, strong alkaline water has been used for cooling in machining. The alkaline water is water with high concentration of pH level. Compared to other substances, water has high heat capacity which is best for cooling. Although the evaporative cooling effect of water is very large compared with other cutting fluid [7], there is still very low application for cooling machine tool using water in industry. This is because of water induce corrosion on the machine tool, work piece and machine elements. Generally, corrosion is the result of water with a low pH. Acidic waters have lots of H^+ ions in the water to react with the electrons at the cathode, so corrosion is enhanced. However, when the concentration of hydrogen in water is decreased with higher pH value, corrosion will not occur and therefore it is possible to be used as cutting fluid for cooling. According to the corrosion characteristic of strong alkaline water [8] in the case of steel, the corrosion will not be enhanced when the pH of strong alkaline water is more than 10.0. Other materials like nickel and nickel-based alloys show no corrosion at the range of pH 8.5 ~ pH 13.0. From these facts, the range between pH 10.0 ~ pH 13.0 is considered adequate to be used for cutting under immersed condition with effective evaporative cooling to reduce thermal loads on the machine tool. Furthermore, by using strong alkaline water, cleaning after processing is not necessary as the strong alkaline water can be acted as cleaning agent. The strong alkaline water was generated by strong alkaline water generating device by mixing chemical compound of calcium carbonate ($CaCO_3$) to the water with ratio 0.18 w/v%. During processing, the hydrolysis of amide bond is also taking place to separate acid from water. Although it is not hazardous, the precaution action such as by wearing safety glasses, dust mask, gloves and wash hand properly after processing are suggested. Moreover, strong alkaline water will lose it alkalinity and become normal water when keep longer in the ambient air. With this phenomenon, strong alkaline water does not require special treatment for storing and disposing, as it can be stored and disposed as normal water once it lose it alkalinity, which is considered safe for environment. It has been investigated in previous research [9] that most of machine tool related materials except aluminum were not corrode when submerged into strong alkaline water for two month. As alkaline water can maintain its pH longer, thus, machining with immersed condition is possible.

2.2. OPTIMUM COOLING USING MICROBUBLE

Microbubble has been used in various fields as a coolant and waste water treatment. The small bubbles that carry air coated by water can help improve cooling effect. In addition, separation process such as flotation of waste and oil recovery becomes easier by using microbubble. In order to verify the cooling capacity of microbubble supplied to the strong alkaline water, the experiment for measuring heat transfer coefficient was conducted. As shown in Fig. 1, a rubber heater (100×100×2mm) inserted between 2 flat steel plates (SPCC, 100×100×1mm), was hung in the vessel of strong alkaline water (L1190×W980×H790mm) together with bench lathe fully immersed. The structure of bench lathe was modified by higher motor stand in order to keep motor outside water. Considering to the potential of electric shock and fire hazard that may occur, precaution is required to be taken in case of wiring during installation of the machine.

The measurement of the temperature of bench lathe was performed by hanging rubber heater in the center of vessel and supplied with 50W of electric power. When the temperature of thermocouples on the both sides of the steel surface reached steady state condition, the temperature values were recorded and the heat transfer coefficient was calculated from the average temperature values on both surfaces and the average temperature of water. The experiments were conducted at four conditions such as, natural cooling condition of strong alkaline water without operating bench lathe, operating bench lathe inside strong alkaline water at spindle speed of 3600min^{-1}, supplying microbubble (8ℓ/min) to the strong alkaline water without operate the bench lathe machine, and by supplying microbubble (8ℓ/min) and operating bench lathe at spindle speed of 3600min^{-1}. Fig. 3 shows the average temperature for various cooling method measured every 5 minutes during 50 minutes.

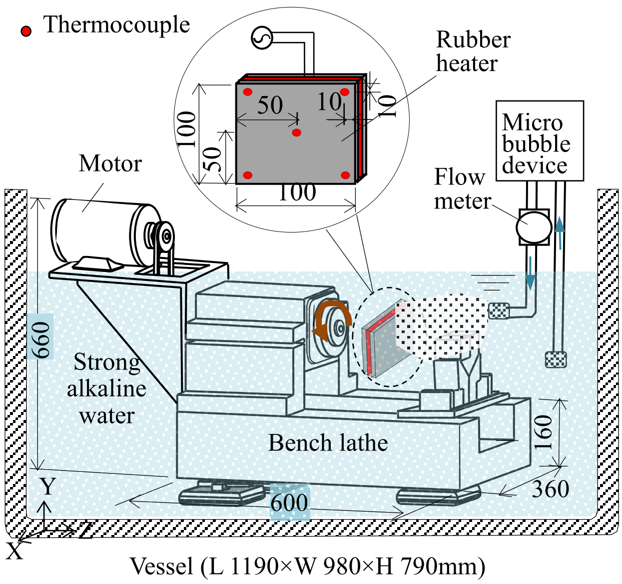


Fig. 1. Experimental setup for measuring heat transfer coefficient

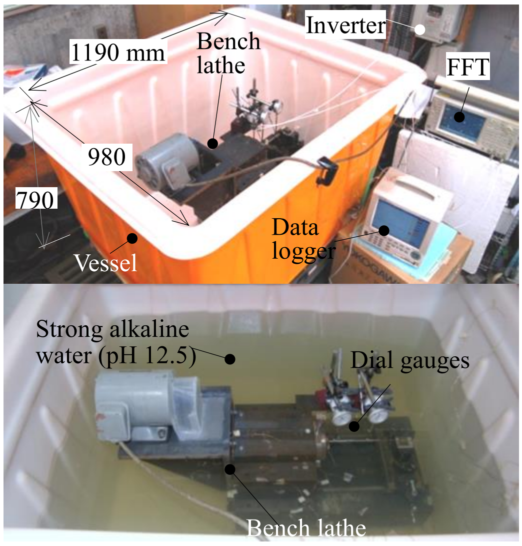


Fig. 2. Photograf of experimental

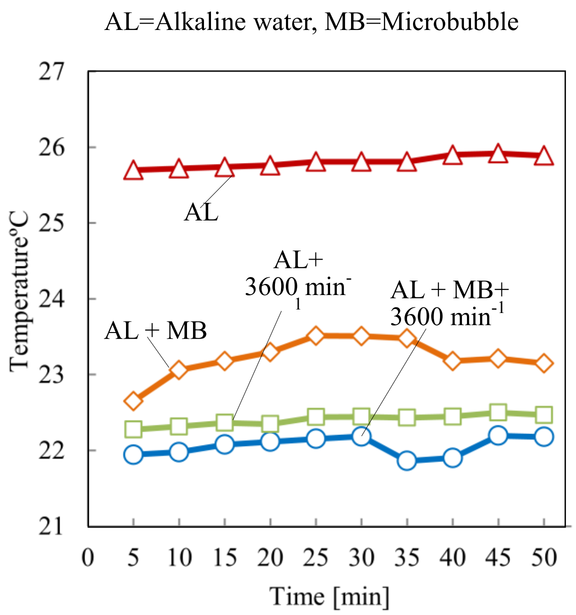


Fig. 3. Average temperature for various cooling

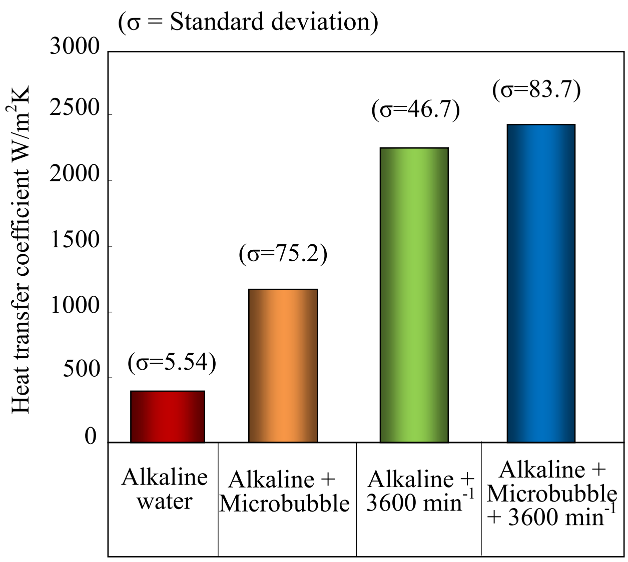


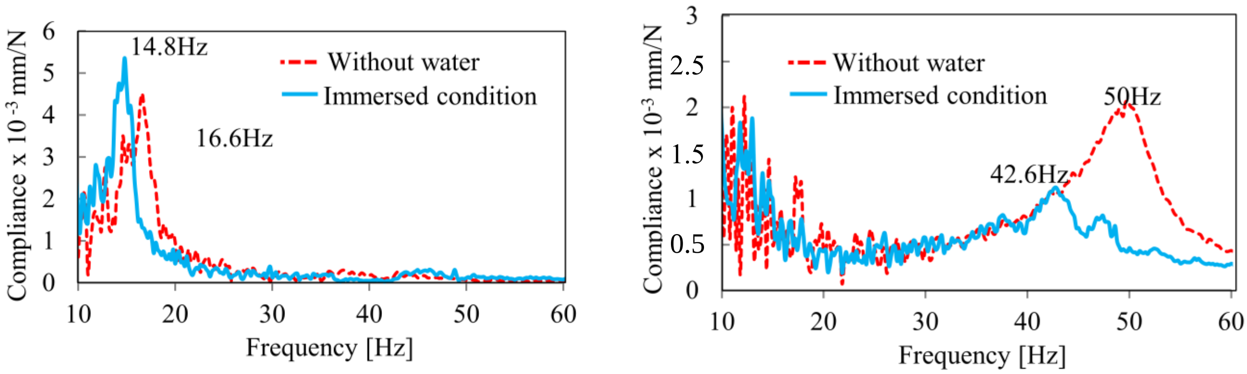
Fig. 4. Relationship between alkaline, micro bubble and 3600min^{-1} with the heat transfer coefficient

It is observed that by using convection cooling of strong alkaline water, the maximum temperature is about 26ºC. However, by operating bench lathe machine inside strong alkaline water and supplying with microbubble, the temperature can be suppressed to around 22ºC. Fig. 4 shows the calculation result of heat transfer coefficient. The result shows that compared to the natural cooling condition of the strong alkaline water, heat transfer coefficient improve about 5.5 times when operating bench lathe inside strong alkaline water and increase about 6 times when added with microbubble. From these results, it can be clarified that supplying microbubble in the strong alkaline water could achieve remarkable higher cooling effect.

3. INVESTIGATION OF THE EFFECTIVENESS OF COOLING SYSTEM UNDER IMMERSED CONDITION ON BENCH LATHE MACHINE

3.1. INFLUENCES TO THE VIBRATION OF BENCH LATHE

In this section, the influence of immersed bench lathe machine on the machine vibration was measured and evaluated. The experimental setup shown in previous Fig. 1 without rubber heater was used for evaluation. For vibration measurement, two accelerometers were attached on the upper part of machine head near spindle in x-axis and y-axis to measure vibration in horizontal and vertical direction. Impact test and operating machine coincide with machine resonance were performed for the evaluation of machine vibration. The measurement result for machine resonance is shown in Fig. 5. By applying impact force to the machine head from vertical direction the result shows that without immersed condition large vibration occurred at frequency 16.6Hz and 50Hz in X and Y direction respectively. When water is added, resonant frequency reduce to 14.8Hz in X direction and 42.6 in Y direction. As frequency shifted, the operation becomes smoother. The bench lathe machine was then operated at spindle speed of 996min^{-1} and 3000min^{-1} which corresponded to resonant frequency of machine at 16.6Hz and 50Hz respectively and analyzed their vibration. Fig. 6 shows the measurement result of vibration amplitude by operating at the bench lathe resonance. The measurement result shows that vibration amplitude reduce about 57% at spindle speed of 996min^{-1} and 68% at 3000min^{-1} when using immersed condition.



(a). Bench lathe resonance at X-axis (b). Bench lathe resonance at Y-axis

Fig. 5. Bench lathe resonant frequency measurment result by impact test

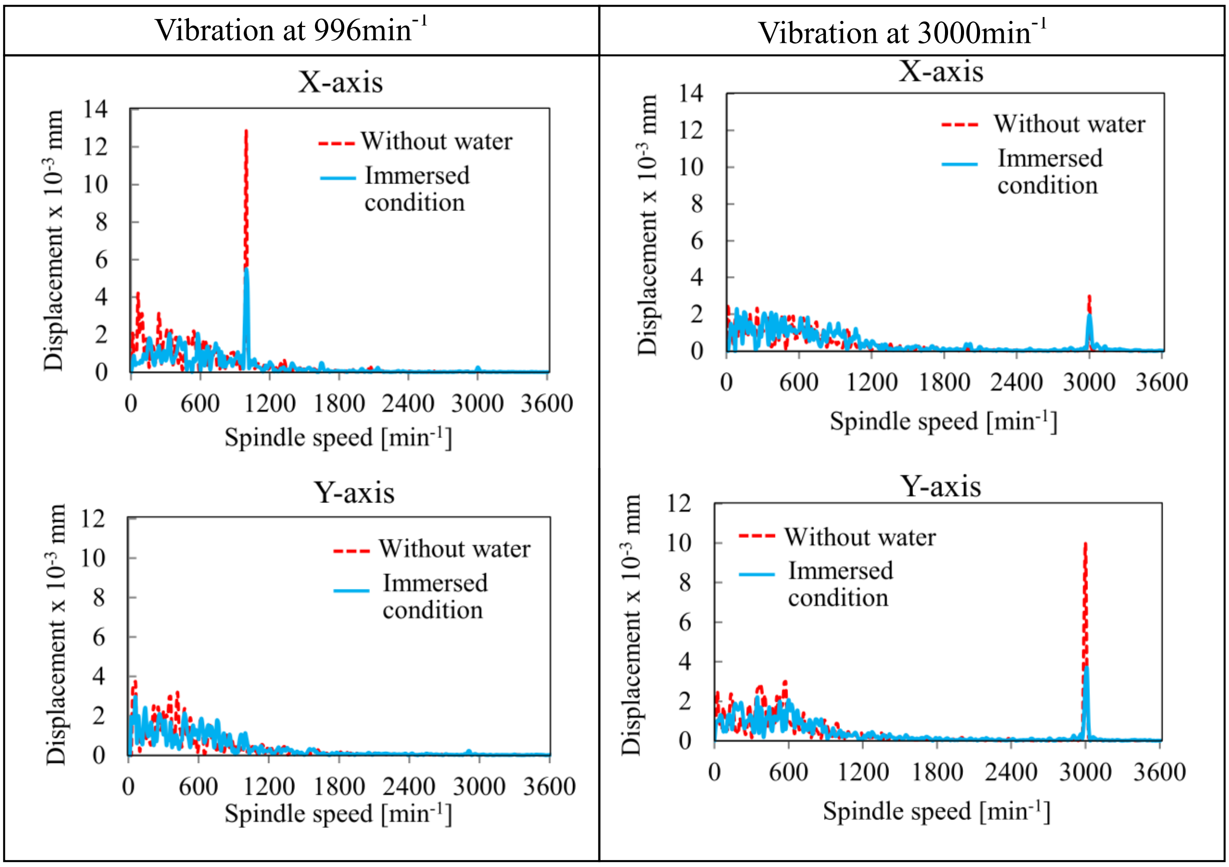


Fig. 6. Amplitude of bench lathe measured by operated coincide with machine resonance at 996 and 3000min^{-1}

Therefore, it is considered that immersed machine condition can reduce machine vibration which effective to optimize final cutting result.

3.2. INFLUENCE ON THE THERMAL DEFORMATION OF BENCH LATHE

Thermal deformation cause by heat from the friction of bearing unit that support bench lathe spindle can affect the surface roughness of workpiece. Here, the influence of immersed condition on the thermal deformation of bench lathe machine inside strong alkaline water was measured. The same setup of bench lathe machine showed in Fig. 2 was used with its specification shows in Table 1. The detail setup for this experiment is shown in Fig. 7. The test bar was inserted into the chuck of bench lathe and the 4 dial gauges were used to measure the displacement of the test bar in horizontal and vertical direction during experiment. The experiment was conducted at dry condition, the condition using strong alkaline water and added with microbubble. The bench lathe machine was operated at spindle speeds 996min^{-1} and 3000min^{-1} which are the resonances of the bench lathe based on the vibration data on previous section.

Fig. 8 and Fig. 9 shows the experimental results of the temperature on the bench lathe at spindle tip surface ① and ②. At spindle speed 996min^{-1}, the rise in temperature (the maximum values at steady state condition) at the spindle tip surface ①, which is the most influencing part to the machining accuracy, were 2.9°C at dry condition, 0.4°C for strong alkaline condition, and when condition added with microbubble, the temperature was suppressed within 1.5°C. While at spindle speed of 3000 min^{-1}, the temperature rises about 4.8°C in dry condition, 0.8°C on strong alkaline water, and rises to 1.8°C when alkaline water was added with microbubble. From these results, it was observed that when adding with microbubble, the change in temperature is larger compared to only strong alkaline water was used. This condition occurred because the heat generated by microbubble device affected temperature of microbubble to rise during continuous operation for two hours. However, for short time operation, adding microbubble is more effective. Thus, by this forced cooling effect, the thermal deformation is considered to be effectively suppressed.

Fig. 10 and Fig. 11 show the relative displacement and angular displacement (X and Y direction) of the tip of test bar measured at operation speed of 996 and 3000min^{-1}. The data between 20~120min were divided into 6 intervals and the average values and standard deviation of each of the six intervals are plotted. The results show that, in dry condition, relative displacements are large with ΔX=4.5μm, ΔY=4.8μm and angular displacements are α=40μm/m and β=42μm/m at 996min^{-1}.

Table 1. Specification of bench lathe machine

Head stock	Height of center from	177 mm
	Height of center from	337mm
	Spindle speed	Max. 3600 min^{-1}
Bed	Size (W×L×H)	600×360×
Tool	Stroke of Y axis	30 mm
Table	Stroke of Z axis	200 mm
Motor	Power	0.75 kW
Mass		200 kg

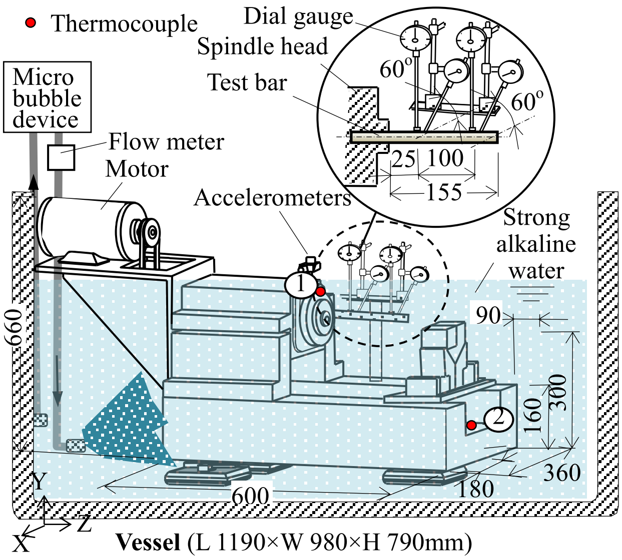


Fig. 7. Schematic view of the experiment using the bench lathe in strong alkali water with micro bubble

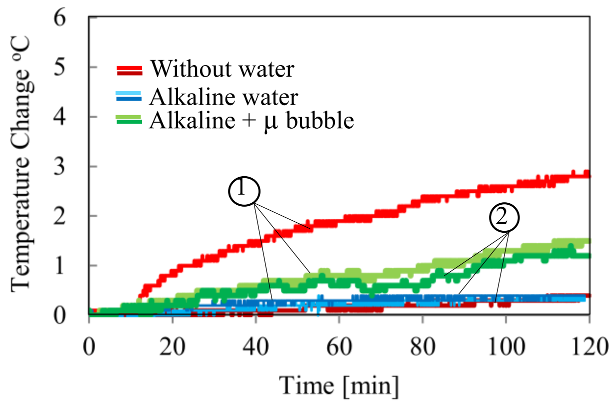


Fig. 8. Temperature change of the bench lathe in strong alkali water with micro bubble operated in 996 min^{-1}

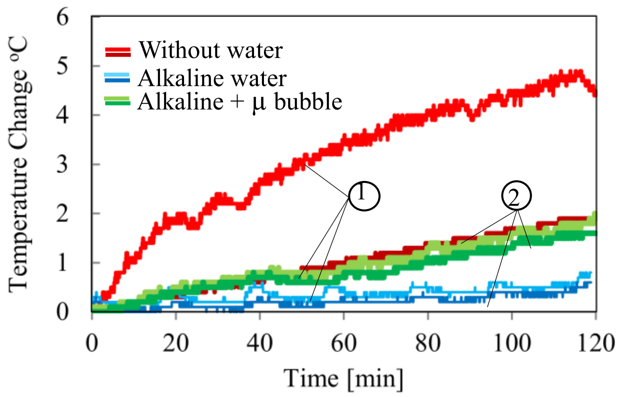
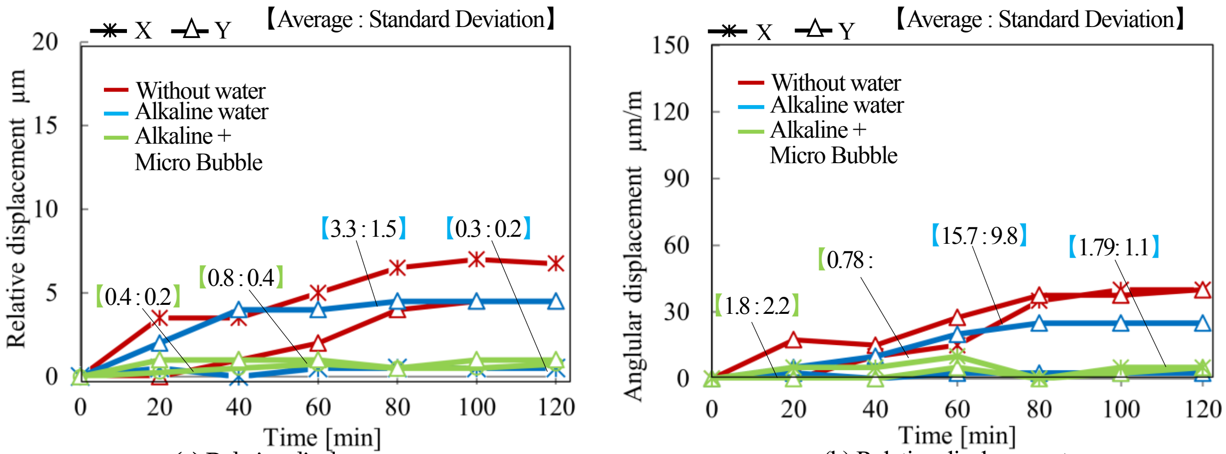
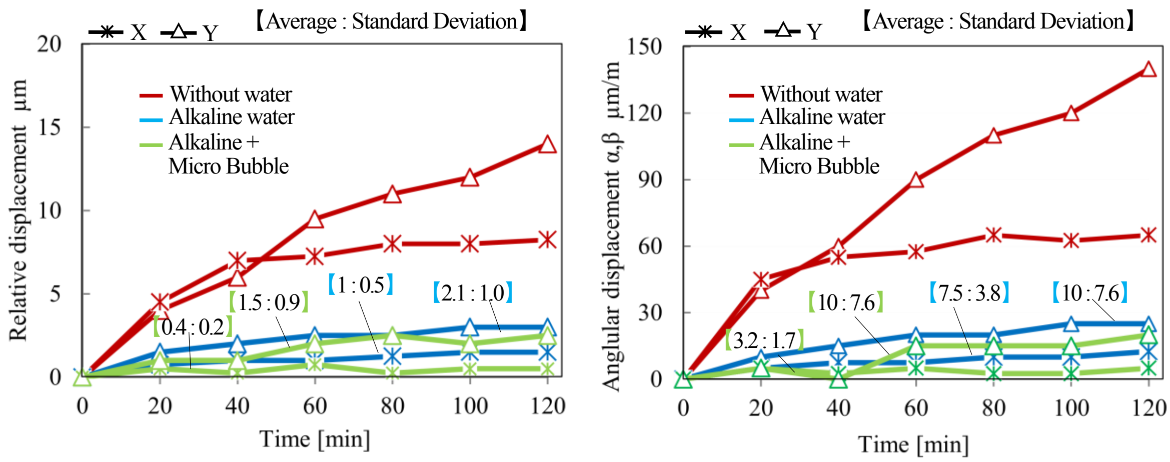


Fig. 9. Temperature change of the bench lathe in strong alkali water with micro bubble operated in 3000min^{-1}



(a) Relative displacement (b) Relative displacement

Fig. 10. Thermal deformation of bench lathe using proposed cooling operated at 99min^{-1}



(a) Relative displacement (b) Relative displacement

Fig. 11. Thermal deformation of bench lathe using proposed cooling operated at 3000min^{-1}

For spindle speed of 3000min^{-1}, the relative displacement are ΔX=8.3μm, ΔY=14.0μm and angular displacements are α=65 μm/m and β=140μm/m. When operated inside strong alkaline water, the thermal deformations in both operation speeds reduced significantly. The thermal deformation becomes even smaller when microbubble was added. For the condition using strong alkaline water added with microbubble, the relative displacement is less than 0.5μm in X-axis and 2.5μm in Y-axis, while, the angular displacement is less than 20μm in X-axis and 5μm in Y-axis for both operation speeds respectively. Therefore, thermal deformation is suppressed remarkably. The results clearly show that the suppression in relative displacement and angular displacement from the condition without water and influence of microbubble was large. Thus, it can be said that by using immersed bench lathe in strong alkaline water, the thermal deformation of machine structure can be effectively suppressed and resulting high processing accuracy.

4. THE CONSIDERATION ON THE ENVIRONMENTAL CONSERVATION

Finally, the impacts on the environment are evaluated by investigating the CO_2 emission. In this evaluation, the amount of CO_2 emission for proposed method and conventional wet cutting method are compared. In the conventional wet cutting, CO_2 emission was calculated from the usage of electricity during machining by using machine tool, oil pump, and cooling unit, and also calculated from the amount of disposed oil. For the proposed method, the amount of CO_2 emission was calculated based on the amount of electric power used for microbubble device, strong alkaline water device, and pump for chip removal.

Table 2 shows the amount of CO_2 emission by the conventional wet cutting. Firstly, the power consumptions for the bench lathe (0.75kW), for oil pump (1.2kW), and oil cooling unit (2.2 kW) were calculated for 250 working days (for a year) with 8 working hours a day. The total electricity usage for one year was 8300kW (4.15 kW×8 h×250 days). The amount of CO_2 emission electric power usage was calculated using CL_{CO2} in equation (1) by taking conversion factor for CO_2 emission 0.468 kg-CO_2/kWh. [10],[11]

$$CL_{CO2} = 0.468 \times W_E \tag{1}$$

$$CO_2 \text{ emission (kg-}CO_2) = \text{Disposed oil k}\ell \times \text{Calorific value GJ/k}\ell \times \text{Carbon emission t-C/TJ} \times (44 \div 12) \tag{2}$$

In equation (1), W_E is the amount of electricity (kWh) used in for each equipment. The total amount of CO_2 emission calculated for operating the bench lathe, oil pump and oil cooling unit were 3884.4 kg-CO_2. Next, the amount of CO_2 emission from the waste oil disposal was calculated. In this calculation, the amount of disposed oil is estimated to be 85 ℓ for 2 times a year. Moreover, 5ℓ of cutting oil were considered to be added up every month, which is 60ℓ (5ℓ×12 month) for a year. Therefore, the total amount of disposed cutting oil is 145ℓ. The amount of CO_2 emission was calculated based on this amount of disposed cutting by using equation (2) with the calorific value 40.2GJ/ℓ and carbon emission 19.22 t-C/TJ [12] was taken for calculation.

Table 2. CO_2 emission of conventional wet cutting

Bench lathe machine, Oil pump & Cooling unit		Waste oil disposal	
Power consumption kW	4.15	Cutting oil amount ℓ/year	170
Use condition /year	8 h ×250 days	Refill oil amount ℓ/year	60
Consumption electric quantity kWh	8300		
CO_2 emission kg-CO_2/year	3884.4	CO_2 emission kg-CO_2/year	411
Total CO2 emission kg-CO_2/year	4295.4		

Table 3. CO_2 emission of cutting in strong alkaline water

Calculation factors	Bench lathe	Micro bubble device	Pump for removing chip	Strong alkaline water device
Power consumption kW	0.75	0.56	0.0132	0.75
Electric quantity for strong alkaline water 1 ℓ kWh/ ℓ				0.075
Amount of strong alkaline water ℓ	-	-	-	794
Use condition /year	8 h ×250 days	8 h ×250 days	8 h ×250 days	24h×365 days
Consumption electric quantity kWh	1500	1120	26.4	60
CO_2 emission kg-CO_2/year	702	524	12	28
Total CO_2 emission kg-CO_2/year	1266			

By equation (2), the calculated amount of CO_2 emission for waste oil disposal was 2946.3kg-CO_2. As mentioned above, by wet cutting, the total amounts of CO_2 emission are 6830.7kg-CO_2.Table 3 shows the amount of CO_2 emission calculated for the proposed method. In this calculation, the same bench lathe machine was used for evaluation. The bench lathe machine with main power 0.75kW is running 8 hours in a day and assumed to be running 250 days a year. In this case, the calculated power consumption was 1500kWh (0.75 kW×8 h×250 days).

The conversion factor for CO_2 emission was taken 0.468 kg-CO_2/kWh, as shown in equation (1). Thus, the amount of calculated CO_2 emission for operating machining center was 702 kg-CO_2. Similarly, the calculated amount of CO_2 emission of microbubble device and pump for chips removal was 524 kg-CO_2 and 12 kg-CO_2 respectively. Furthermore, the amount of CO_2 emission for strong alkaline water device was also calculated. The volume of strong alkaline water used was assumed to be 794ℓ, from subtraction of the total volume of the whole bench lathe machine inside strong alkaline water 700ℓ (W1190mm × D980mm × H600mm×10^{-6}) to the volume of all machine part 26ℓ (The total mass of machinery 200 kg ÷ Density of steel 7800kg/m^3 ×10^3), and obtained necessary volume 674ℓ. In addition, the addition amount of 120ℓ (10 ℓ/month×12 month) of strong alkaline water was assumed to be filled up for one year. Thus, total volume of strong alkaline water was obtained 794ℓ. Since the strong alkaline water device (0.75kW) is capable of generating 10ℓ of strong alkaline water (pH 12.5) in an hour, the amount of electricity used for generating the strong alkaline water for 1ℓ was obtained 0.075kWh/ℓ (0.75kW × 1h ÷ 10ℓ). Therefore, the amount of electric power required to immerse the whole bench lathe under strong alkaline water for 1 year was 60kW. The amount of CO_2 emission for strong alkaline water calculated by using equation (1) was 28kg-CO_2. After applying the proposed method, the total amount of CO_2 emission is 1266kg-CO_2.

Fig. 12 shows the comparison of the amount of CO_2 emission. The amount of annual CO_2 emission was reduced to only 3029.6kg-CO_2, which is about 71% reduction compared to conventional machine tool. This large reduction is because of the proposed method does not use cutting fluid during machining and thus it can reduce CO_2 emissions emitted by waste oil disposal and other generating equipment's for cooling system. As mentioned above, this proposed method does not use cutting fluid, and also could maintain cutting tool life and processing accuracy without using forced cooling by oil cooling unit. Furthermore, it is not necessary to clean the oil on the product after processing, which reduces the environmental impact. It is considered that this method is friendly to environment and extremely effective for industrial applications.

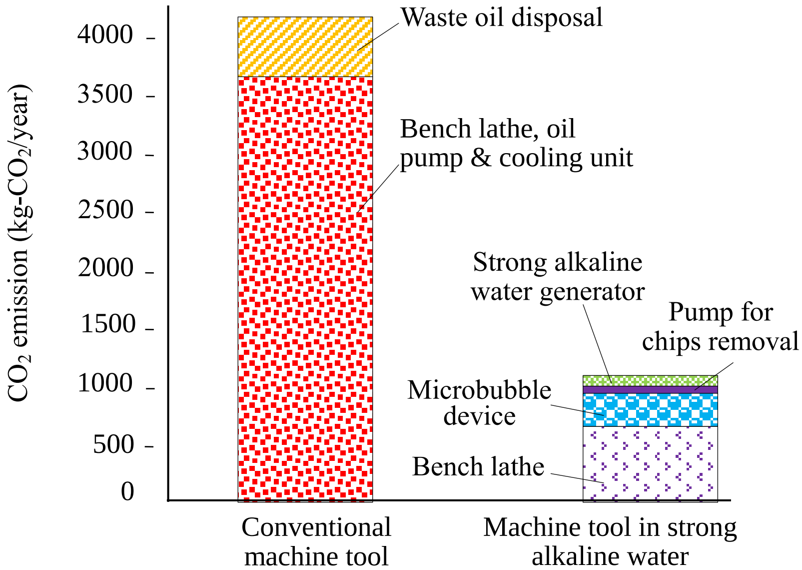


Fig. 12. Comparison of annual CO_2 emission between immersed machine tool and conventional machining

5. CONCLUSIONS

The results of this study are summarized as follow:

(1) Excellent cooling efficiency can be achieved by using strong alkaline water added with microbubble which has high heat transfer coefficient values.

(2) Immersed condition of machine can reduce and minimize the vibration amplitude.

(3) By immersing the whole machine tool in strong alkaline water, the rise in cutting tool tip temperature when operated coincide with machine resonance was suppressed about 57% and 62%, thermal deformation can be minimized as the relative displacements were reduced about 93% and 94%, while the angular displacements were reduced about 82% and 86% in operation speed of 996min^{-1} and 3000min^{-1}, respectively.

(4) By applying the proposed method of cutting under strong alkaline water mixed with microbubble, the emission of CO_2 can be reduced about 71% by avoiding the use of cutting oil and oil cooling unit and thus very effective for environmental conservation.

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