Analysis of Cutting Fluid Atomization and Environmental Impact through Spin-Off Mechanism in Turning Operation for Environmentally Conscious Machining(II)

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This paper presents the experimental results to verify the atomization characteristics and environmental impact of cutting fluid. Even though cutting fluid improves the productivity through the cooling and lubricating effects, environmental impact due to cutting fluid usage is also increased on factory shop floor. Cutting fluid's aerosol via atomization process can generate human health risk such as lung cancer and skin diseases. Experimental results show that the generated fine aerosol of which particle size less than 10 micron appears near working zone under typical operation conditions. The aerosol concentration also exceeds NIOSH regulations. This research can be provided as a basis of environmental impact analysis for environmental consciousness.

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NOMENCLATURE

D_{10} = Arithmetic mean diameter of aerosol particle
D_{32} = Volume to surface area mean diameter of aerosol particle

1. Introduction

Increasing concern of environment, health and safety is drawing the paradigm shift of technological needs for environmentally conscious machining process. The various reactions during typical machining process can produce a number of residual materials and emissions. A lot of machining companies are affected by government regulations for environment such as ISO 14000 series and Green Round in the world.

Through the machining process a few types of waste are produced as shown in Fig. 1. Worn tools, chips and scraps are solid state by-product in machining process. Otherwise, used oil or cutting fluid as liquid state wastes can pollute water system. In addition, cutting fluids can be atomized via machining mechanism and produced airborne mists, smoke, gases, and other particulate that cause hazard to the machine shop environment. Cutting fluid often applied in machining process to improve productivity and machined quality.

With increased concern of environmental intrusiveness and occupational hazards, environmental impact of cutting fluids has been reviewed. Skin exposure to cutting fluid can cause folliculities due to follicular orifice blockage. Another form of health threat by cutting fluids is inhalation, which can be connected to emphysema, lung cancer and other respiratory problems[1].

The aerosol size and concentration of airborne cutting fluid particulate in the machine shop environment are common attributes that quantify the environmental intrusiveness of cutting fluids. Aerosol size is a deciding factor for inhalation implications. OSHA(Occupational Safety and Health Administration) requirements for the metal cutting fluid concentration in a manufacturing environment is set to 5mg/m^3 as a permissible exposure level for personnel(PEL).

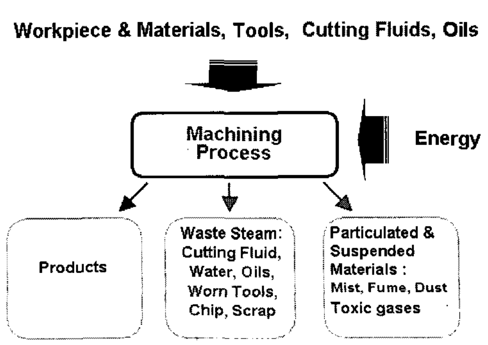

Fig. 1 Material balance for machining process

This PEL was consolidated to 0.5mg/m^3 by the NIOSH(National Institute for Occupational Safety and Health)[2] in 1998.

Currently, to reduce cutting fluid's aerosol generation, common control strategies include enclosing the machine tool, using air filters or mist collectors, and adding anti-misting agents to the cutting fluid. However, these methods add cost to the process and are not so effective. An alternative strategy is to modify the machining process itself to reduce the amount of cutting fluid usage. Such a strategy requires a fundamental understanding of the basic process conditions affecting aerosol generation. This paper presents the details and experimental investigation of the dominant operating conditions affecting cutting fluid's aerosol formation and its behaviors to describe the aerosol generation phenomena.

2. Aerosol Generation Mechanism

To understand the cutting fluid's aerosol generation process, this paper provides the physical mechanism based on fluid atomization theory in coupling with flow field governing principles and experimental measurements to quantify the aerosol characteristics resulted from the use of cutting fluid in a turning process as shown in Fig. 2. The primary mechanism considered in this study is the spin-off motion of fluid away from a rotating workpiece. The splash is a form of momentum transfer due to the impact of fluid particles on a solid tool or workpiece. The evaporation stems from the high temperature at the cutting zone that brings the contacting fluid to a vapor state. The spin-off is a result of the centrifugal force at the surface of the part in rotational motion. It is a dominant mechanism for over 80% of the total cutting fluid's aerosol generation in machining process.

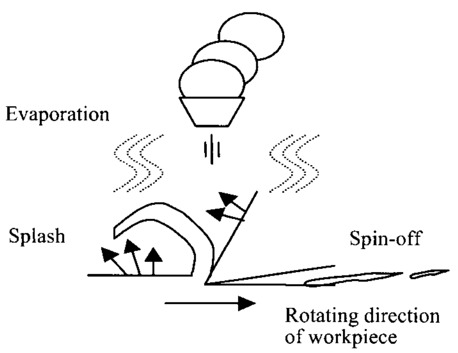

Fig. 2 Cutting fluid's aerosol generation process in turning process

Cutting fluid application configuration is shown in Fig. 3. The center part(Part B) of cutting fluid jet stream has a larger flow rate than Part A. The process of rotary disk atomization can be used to simulate the atomization of this part. Spin-off process was illustrated rotary disk atomization process as shown in Fig. 4. Cutting fluid is entering into contact with the workpiece at point A and moving around the cylindrical surface in the form of a thick film. When this film disintegrates, it does so in an irregular manner, which results in an appreciable variation in the droplet size. This process through a certain point B, ligaments form long the periphery and disintegrate into drops. This process taking place in Part 2 is termed atomization by ligament formation. There exists a critical point C at which the liquid spreads out at a low flow rate and is centrifuged off in the form of drops. This phenomenon is generally known as drop formation atomization, as shown in Part 3.

3. Measurement of Cutting Fluid's Aerosol

A few experiments were performed to understand the quantitative characteristics of cutting fluid's aerosol. The experiments were performed on a CNC engine lathe(TSL-6, Hwacheon). The quantity of suspended cutting fluid's aerosol within the closed control volume was

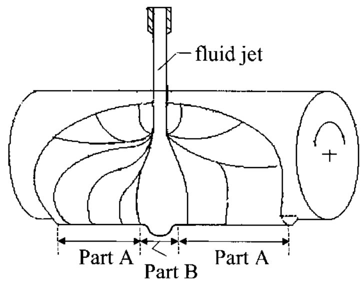

Fig. 3 Typical cutting fluid behavior in machining process

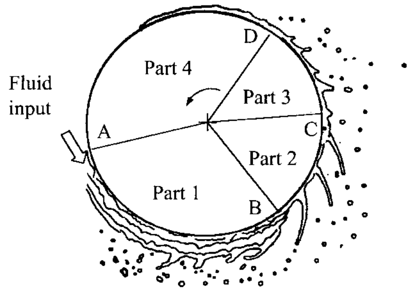

Fig. 4 Rotary disk atomization process and three formation modes

measured by Dual-PDA(Particle Dynamics Analyzer, Dantec/Invent) during the machining operation under various cutting speeds and cutting fluid flow rates.

Dual-PDA system can measure the average velocity, size and concentration of the cutting fluid's aerosol effectively. This system is operated with Ar-Ion laser source and can be used to measure the particles under a range of 0.5μ m to 13mm diameter moving at a maximum speed of 470m/s. It consists of 57X80 Dual PDA probe for optical devices and 58N80 Multi PDA process for signal processing. Measuring outputs were stored in a digital storage oscilloscope(LeCroy 9310A) and personal computer to analyze the results.

4. Experimental Results and Discussions

4.1 Analysis of Cutting fluid's Aerosol Velocity and Size Distribution

A few experiments were performed to know the quantitative characteristics of cutting fluid's aerosol. The experimental set-up consists of turning machine, Dual-PDA system to measure the cutting fluid's aerosol behavior. The quantity of suspended cutting fluid aerosol within the closed control volume is measured during machining operation under a various cutting speeds and cutting fluid flow rates and workpiece diameters.

Cutting fluid was applied via a nozzle centered above the workpiece at a distance of approximately 250mm.

The variation of average velocity of the fluid's aerosol is shown in Fig. 5 and 6. The atomized particles are moved into three step : drop generation, fly into air and fall down on the ground. The measured velocity were 3.75[m/s] in the u-direction(vertical) and 0.1[m/s] in the v-direction(horizontal) when rotational speed of workpiece is set to 2,000rpm, workpiece diameter is 100mm and cutting fluid flow rate is 18liter/min.

The diameter distribution histogram of cutting fluid's aerosol is shown in Fig. 7. Over 90% of cutting fluid aerosol size is less than 100 micron.

Figures 8 and 9 show the correlation between average velocity of cutting fluid's aerosol particles and particle size distributions. In these figures, it is seen that cutting fluid flow rate has significant influence on the number of cutting fluid's aerosol particles generation with the same rotational speed of workpiece and workpiece diameter. The cut-

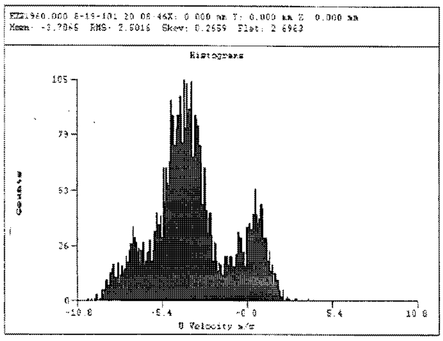

Fig. 5 Average velocity distribution of cutting fluid's aerosol particles on u-direction (2,000rpm, ϕ 100, 18ℓ /min)

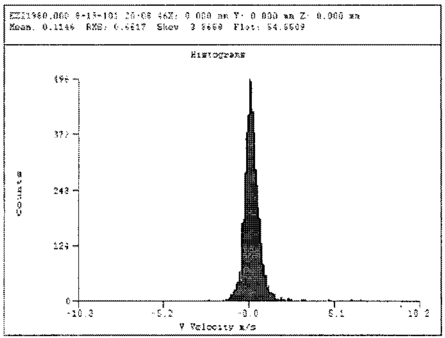

Fig. 6 Average velocity distribution of cutting fluid's aerosol particles on v-direction (2,000rpm, ϕ 100, 18ℓ /min)

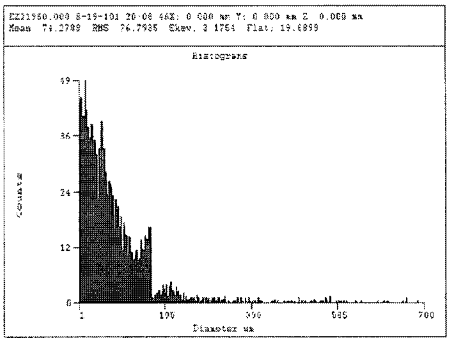

Fig. 7 Size distribution of cutting fluid's aerosol particles (2,000rpm, ϕ 100, 18ℓ /min)

ting fluid's aerosol generation generally increases with fluid flow rate increment. at a higher flow rate the average velocity of cutting fluid's aerosol spreads with much wide range of velocity. At a lower fluid flow rate the number of cutting fluid's aerosol of small size range deceases greatly. This result affects the calculation results of the mean drop diameter of fluid's aerosol particles and aerosol concentration.

The histogram of cutting fluid's aerosol particle distributions in terms of size, surface area and volumetric fraction is shown in Fig. 10. As shown in this figure the number of particle events and size distributions exert influence on surface and volume fraction of whole aerosol generation. The generation of large sized aerosol particles have influence on volumetric fraction growth effect of aerosol. Otherwise, the generation of small size aerosol have influence on surface area fraction growth.

Therefore, a few types of convention of aerosol mean drop diameter represent the characteristics of a set of uniform drops substituted for the real set. Depending on the way it is calculated the mean aerosol particle diameter determines such characteristics as number, diameter, surface and volume of aerosols.

In this study two types of aerosol particle diameter are adopted to

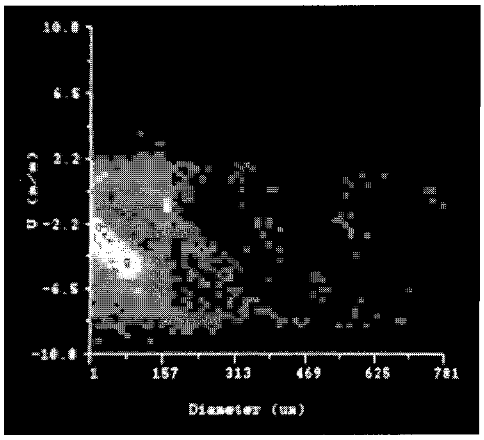

Fig. 8 Correlation plot of cutting fluid's aerosol particle size vs. velocity (2,000rpm, ϕ 100, 18ℓ /min)

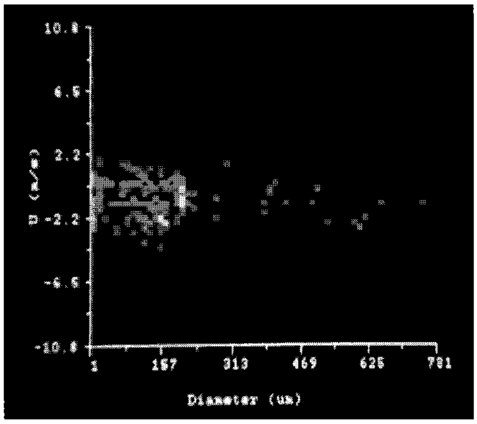

Fig. 9 Correlation plot of cutting fluid's aerosol particle size vs. velocity (2,000rpm, ϕ 50, 18ℓ /min)

represent the size of cutting fluid's aerosol. The arithmetic mean diameter D_{10} is the diameter of a uniform equivalent aerosol particle set with the same number of aerosol and sum of diameter as in the real set. The volume-to-surface-area mean diameter D_{32} or Sauter Mean Diameter (SMD) is the diameter of a inform equivalent drop set with the same total volume and the same surface of all aerosol as in the real set.

$$D_{10} = \frac{\Sigma D \, \Delta n}{\Sigma \Delta n} \tag{1}$$

$$D_{32} = \frac{\Sigma D^3 \, \Delta n}{\Sigma D^2 \, \Delta n} \tag{2}$$

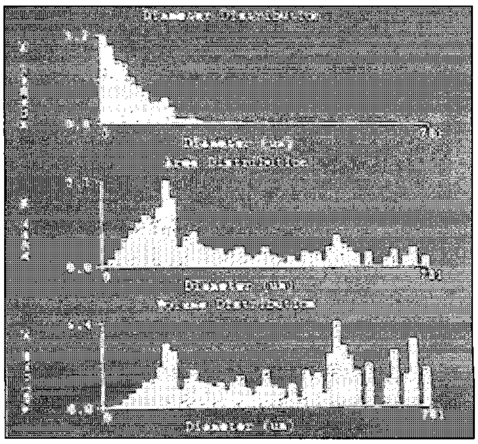

Fig. 10 Cutting fluid's aerosol distribution histogram in terms of aerosol size, surface area and volume (2,000rpm, ϕ 100, 18ℓ /min)

where, D is aerosol particle diameter and n is number of aerosol particles.

To investigate the characteristics of cutting fluid atomization a few experiments were performed with various operational conditions on turning process.

The experiments adopted cutting fluid flow rate, rotational speed of workpiece and workpiece diameter as the major operational conditions. As can be seen in Figs. 11 to 13, the rotational speed of workpiece and workpiece diameter has significant influence on the smaller diameter aerosol generation than that of fluid flow rate. Because the higher centrifugal force due to increased rotational speed of workpiece and workpiece diameter promotes atomization of cutting fluid. Otherwise, effectiveness of cutting fluid flow rate to the aerosol size shows the more complex features with combination of operational conditions. The aerosol size increases with respect to cutting fluid flow rate increment at a lower rotational speed of workpiece.

Air quality is an important issue that is drawing increasing concern throughout manufacturing fields. Because of health problems a number of government have become involved in establishing standards and regulations for particulate exposure.

Generally, ambient air quality standards has been established by Total Suspended Particulate(TSP). Aerosol associated with human health are treated by Respirable Suspended Particulate(RSP) which is set maximum mass concentrations levels for PM10(airborne particulate matter less than 10 microns). This standard represents the thoracic fraction of particulate matter, which is the portion of inhalation particles that pass larynx and penetrate into the conducing airways and bronchial region of the lungs.

Figures 14 and 15 show the measured results of cutting fluid's aerosol particle size less than 10 micron by Dual-PDA system in this research.

The diameter of mean aerosol particle, D_{10} is about 4 micron to 5 micron levels, D_{32} is 7 micron to 8 micron levels. The small aerosol particles are appeared in these operational conditions. The general operational condition range that is over 1,000rpm and 1 liter/min in turning process produces small cutting fluid's aerosol particle that can cause serious human respiratory problems.

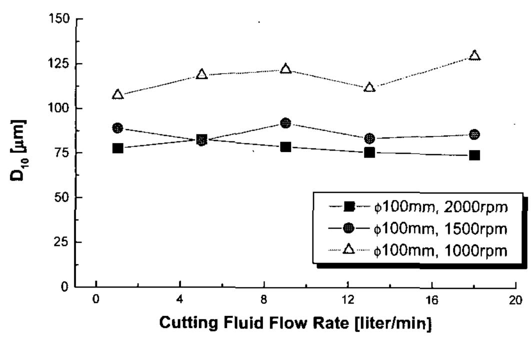

Fig. 11 Variation of particle size(D_{10}) of cutting fluid's aerosol with respect to cutting fluid flow rate

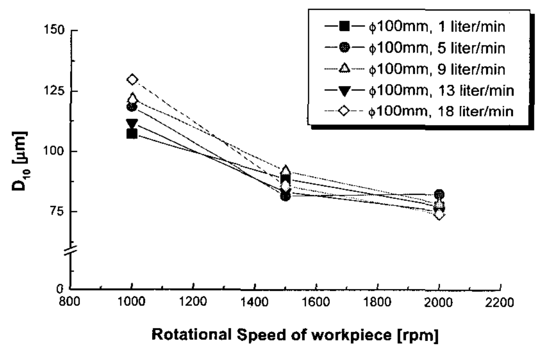

Fig. 12 Variation of particle size(D_{10}) of cutting fluid's aerosol with respect to rotational speed of workpiece

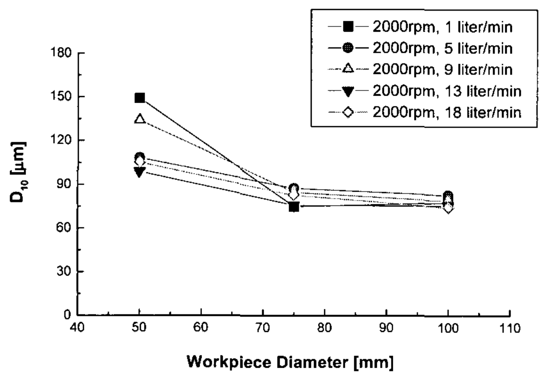

Fig. 13 Variation of particle size(D_{10}) of cutting fluid's aerosol with respect to workpiece diameter

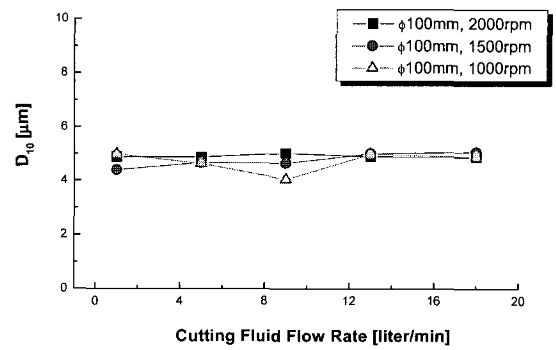

Fig. 14 Variation of particle size(D_{10}) of cutting fluid's aerosol less than 10μ m with respect to cutting fluid flow rate

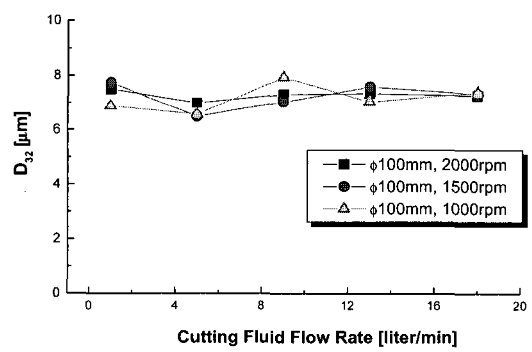

Fig. 15 Variation of particle size(D_{32}) of cutting fluid's aerosol less than 10μ m with respect to cutting fluid flow rate

4.2 Analysis of Cutting fluid's Aerosol Concentration

Current NIOSH recommends the aerosol mass concentration of $0.5mg/m^3$ as a permissible exposure level(PEL) for personnel to the manufacturing industries. It is a criterion to evaluate shop floor environment and workers occupational health and safety. This criterion will be consolidated to improve the Environment, Health & Safety(EH&S).

Concentrations of produced aerosol particles are defined in different ways depending on the applications. Particle number concentration or mass concentration is typically used to know the methods of characterizing the concentration. For aerosols composed of particles with all the same size, particle number concentration is easy to compare the characteristics of concentration of aerosol systems. Otherwise, mass concentration is useful for mixed size aerosol of this study.

Cutting fluid atomization process shows the very complex features in view of distribution of fluid's aerosol particle size, number of each particle size range and some disturbances or uncertainties as like ambient atmospheric environments.

Figures 16 and 17 show the variation of measured cutting fluid's aerosol concentration in view of number concentration and mass concentration, respectively. From these results, we can find that cutting fluid flow rate and rotational speed of workpiece have significant influence on cutting fluid's aerosol concentration. It is clear that the cutting fluid aerosol mass concentration exceeds NIOSH recommendation under typical operational conditions of machine tools which is used in factory shop floor manufacturing process as shown in Fig. 17. A lot of precise experiments must be performed to know the environmental impact of cutting fluid usage in manufacturing process. This effort will provide scientific understanding and methodology to reduce the environmental impact on the shop floors environment.

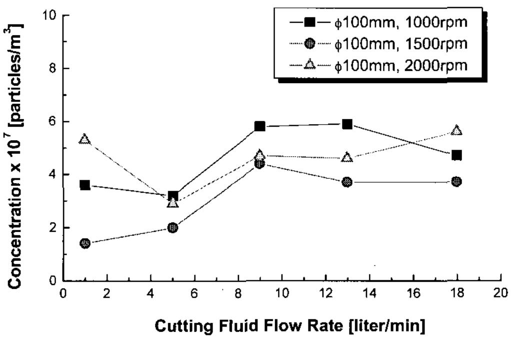

Fig. 16 Comparison of number concentration of cutting fluid's aerosol with respect to cutting fluid flow rate

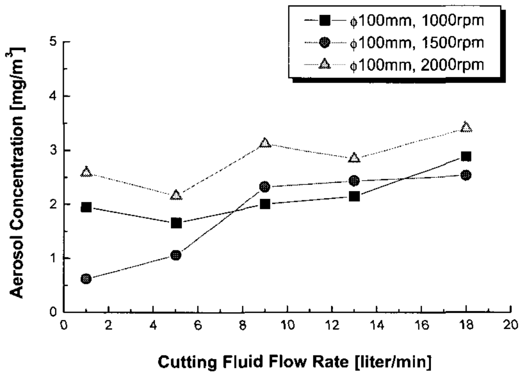

Fig. 17 Comparison of mass concentration of cutting fluid's aerosol with respect to cutting fluid flow rate

5. Conclusions

To investigate the characteristics of cutting fluid's aerosol generation in machining, several experiments were performed to measure the cutting fluid's aerosol behaviors under various cutting conditions. Small aerosol particles less than 10 micron which is associated with human respiratory diseases were observed and aerosol concentration also exceeded NIOSH recommendation with general operational condition range in turning operation.

This obtained results can be further applied to control the environmental impact in manufacturing processes. Process improvement and development for environmentally conscious machining should be continued through understanding of environmental impact due to cutting fluid atomization.

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