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An experimental investigation into the effect of process conditions on the mass concentration of cutting fluid mist in turning

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Abstract

Cutting fluid mists that are generated during machining processes represent a significant waste stream as well as a health hazard to humans. Epidemiological studies have shown a link between worker exposure to cutting fluid mist and an increase in respiratory ailments and several types of cancer, prompting closer scrutiny from several regulatory agencies. In this work, statistically designed experiments were conducted to determine the machining conditions that have the most significant effect on PM10 and PM2.5 mass concentration levels of cutting fluid mist during a turning operation. Identification of these significant factors may lead to modifications in the machining process as a solution for minimizing cutting fluid mist, thus eliminating/reducing the need for costly mist control technology such as air filters, enclosures, and fluid additives. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Cutting fluid; Mist; Mass concentration

1. Introduction

Cutting fluids are widely used throughout industry in many machining operations such as milling, grinding, boring, and turning. Large machining facilities use central fluid systems with capacities as high as 760 000 liters, and it is estimated that over 380 million liters of metalworking fluids are used each year in the United States [1]. Depending on the machining process, one of several types of fluids can be used. Cutting fluids are usually classified into four main categories: straight oils, water soluble oils, synthetics, and semi-synthetics. The base oil used for straight and water soluble cutting fluids is usually petroleum based, whereas synthetics are water-based solutions of complex organics and contain no mineral oil. Semi-synthetics are a combination of both synthetic and mineral oils. Straight oils are applied undiluted, while water soluble, synthetic, and semi-synthetic fluids are usually diluted in water. In general, dilutions are between 1% and 20% cutting fluid concentrate in water, with 5% being the most common [2].

The traditional, oft-quoted reasons for using cutting fluids are to transfer heat away from the cutting zone, lubricate the chip–tool interface, flush away chips, and inhibit corrosion. Cutting fluids are usually applied to the cutting zone through jet application with a nozzle or by flooding the cutting tool and workpiece with fluid applied by several nozzles. Yue et al. [3] identified two primary mechanisms for cutting fluid mist formation: evaporation–condensation and atomization. Due to the extreme temperatures that are generated during machining, the cutting fluid may vaporise and subsequently condense around spontaneously generated liquid nuclei or other foreign particles to form droplets. Atomization is a purely mechanical process. The impact of the fluid jet as well as the rotation of the workpiece or cutting tool transmit mechanical energy to the fluid, which becomes unstable and disintegrates into droplets.

Cutting fluid mists that are generated during machining processes represent a significant waste stream as well as a health hazard to humans. The National Institute for Occupational Safety and Health (NIOSH) estimated that over 1 million workers in the US are exposed to cutting fluids daily [4]. Medical evidence has been gathered that

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links worker exposure to cutting fluid mist with respiratory ailments and several types of cancer [5–8]. Respiratory illnesses associated with cutting fluid inhalation include respiratory irritation, bronchitis, occupational asthma, and loss of lung function. Several epidemiological studies have also shown statistically significant increases in cancer of the esophagus, stomach, pancreas, larynx, colon, and rectum due to prolonged exposure to cutting fluid mists.

The concern over worker exposure to cutting fluid mist has prompted regulatory scrutiny by several organisations. Many industry experts believe that the air quality inside machining facilities should be as good as that of the outdoor air. Standards set by several government agencies as well as industry organisations closely follow the National Ambient Air Quality Standards (NAAQS) established by the EPA. The NAAQS established in 1987 set maximum mass concentration levels for PM10, airborne particulate matter less than 10 microns. This represents the thoracic fraction of particulate matter, the portion of inhalable particles that pass the larynx and penetrate into the conducting airways (e.g., trachea) and the bronchial region of the lungs. The larger particles that deposit in the thoracic region can be evacuated from the body in a relatively short amount of time. In July 1997, the EPA revised the NAAQS to include a PM2.5 standard due to the growing concern that smaller particles pose a greater risk to human health [9]. Particulate matter less than 2.5 microns (PM2.5) represents the respirable fraction of inhalable particles that enter the deepest part of the lungs, the non-ciliated alveoli. The Occupational Safety and Health Administration (OSHA) has defined a permissible exposure limit of 5 mg/m^3 for oil mist (8-hour time weighted average) that industry is legally required to meet. NIOSH [10] recommends an even stricter exposure limit to metalworking fluids of 0.5 mg/m^3 total suspended particulate (TSP) and 0.4 mg/m^3 for thoracic particulate mass (10-hour time weighted average). The UAW also supports a standard of 0.5 mg/m^3 TSP [11].

In order to prevent worker exposure to cutting fluid mist, common mist control strategies include enclosing the machine tool, using air filters and mist collectors, and adding antimisting agents to the cutting fluid. However, enclosures restrict access to the machine tool and in most cases the machine cannot be totally enclosed. Mist collectors are expensive to maintain and operate, and often exhibit rapidly decreasing efficiencies as they become loaded with fluid [12]. The addition of high molecular weight polymers to cutting fluids have been shown to be effective in suppressing mist formation [13,14]. However, the polymer additives represent an added cost to the fluid and are subject to molecular breakdown as the fluid is recirculated and reused, and therefore must be periodically replenished.

The work presented in this paper experimentally examines the underlying process conditions that affect the mass concentration level of cutting fluid mist in a turning operation. Identification of these significant factors may lead to modifications in the machining process as an alternative solution for minimising cutting fluid mist, thereby eliminating/reducing the need for costly machine enclosures, mist collectors, or mist suppressant additives.

2. Experiment setup

In order to determine the role of machining conditions on cutting fluid mist formation in a turning process, a hardware testbed was constructed. An Emco Compact 8 table-top lathe was used to turn various workpieces at different speeds. The rotational direction of the workpiece was held constant for the experiment. The machine tool was surrounded by an enclosure to prevent inhalation of the mist and to collect the splattered fluid.

Cutting fluid was applied via a nozzle centered above the workpiece at a distance of approximately 10 cm and positioned orthogonally to the workpiece. Two different nozzle sizes were investigated, 0.3175 cm and 0.635 cm, while the fluid flow rate was held constant at 3.4 liters per minute. A photograph of the setup is shown in Fig. 1. From the photo, it can be seen that much of the fluid is splattered off as the jet impacts the rotating workpiece. The remaining fluid adheres to the surface of the workpiece and forms a thin film, from which smaller droplets are formed due to aerodynamic forces.

PM10 and PM2.5 mass concentration measurements (total particulate mass per volume of air sampled) of the thoracic and respirable fractions, respectively, were taken at various locations using a TSI DustTrak Aerosol Monitor, a photometer that uses a light scattering principle to determine aerosol mass concentrations in real-

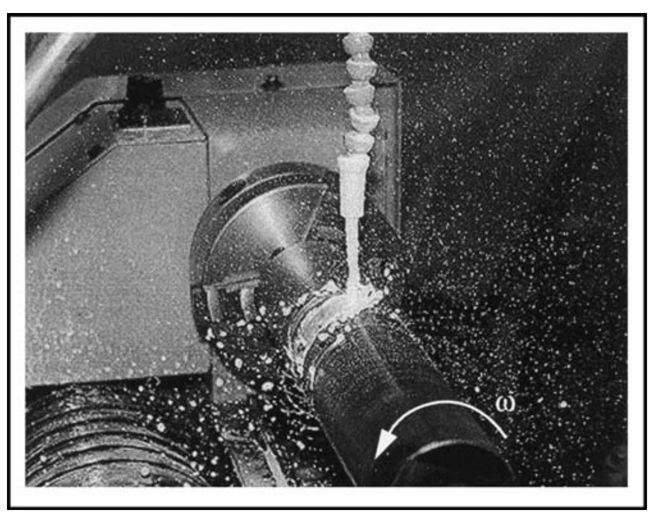

Fig. 1. Cutting fluid application to a rotating workpiece.

time. This instrument measures particles between 0.1 and 10 microns in size and mass concentrations between 0.001 and 100 mg/m^3. An isokinetic sampling probe was used with the DustTrak to minimise losses.

3. PM10 experiment design

In order to determine the effects of machining conditions on the thoracic fraction (i.e., PM10) of a typical soluble oil cutting fluid mist, a two level fractional factorial design was used to screen six variables for statistical significance with a minimum number of tests. The variables examined were spindle speed, workpiece diameter, nozzle diameter, cutting fluid oil concentration, and sampling location ("*x*" and "*z*" locations). The low and high levels used for each variable are listed in Table 1. The coordinate system describing the "*x*" and "*z*" locations of the sampling probe is shown in Fig. 2. The *x*-locations were chosen to determine the effect on mass concentration in front of and behind the rotating workpiece. The high level for the *x*-location represents a typi-

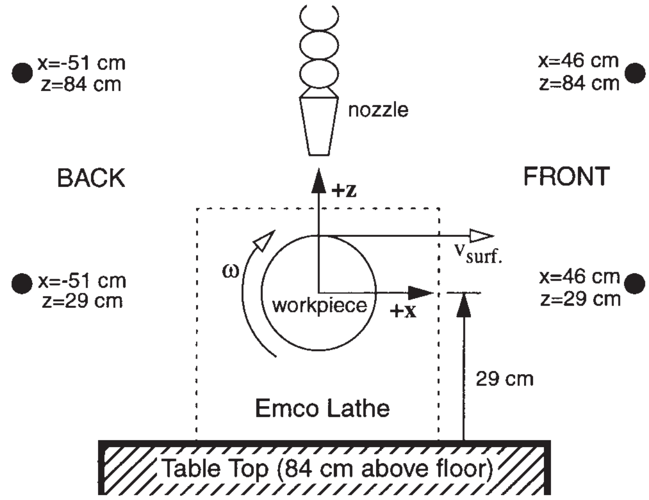

Fig. 2. End view of sampling probe locations.

Table 1
Design matrix for experiments studying PM10 mass concentration

Test No.	1: Spindle speed (rpm)	2: Workpiece dia. (cm)	3: Nozzle dia. (cm)	4: Oil conc. (%)	5: X-location (cm)	6: Z-location (cm)
1	600	6.35	0.3175	5	−50.8	29.2
2	2000	6.35	0.3175	5	−50.8	83.8
3	600	10.5	0.3175	5	−50.8	83.8
4	2000	10.5	0.3175	5	−50.8	29.2
5	600	6.35	0.635	5	−50.8	83.8
6	2000	6.35	0.635	5	−50.8	29.2
7	600	10.5	0.635	5	−50.8	29.2
8	2000	10.5	0.635	5	−50.8	83.8
9	600	6.35	0.3175	10	−50.8	83.8
10	2000	6.35	0.3175	10	−50.8	29.2
11	600	10.5	0.3175	10	−50.8	29.2
12	2000	10.5	0.3175	10	−50.8	83.8
13	600	6.35	0.635	10	−50.8	29.2
14	2000	6.35	0.635	10	−50.8	83.8
15	600	10.5	0.635	10	−50.8	83.8
16	2000	10.5	0.635	10	−50.8	29.2
17	600	6.35	0.3175	5	45.7	83.8
18	2000	6.35	0.3175	5	45.7	29.2
19	600	10.5	0.3175	5	45.7	29.2
20	2000	10.5	0.3175	5	45.7	83.8
21	600	6.35	0.635	5	45.7	29.2
22	2000	6.35	0.635	5	45.7	83.8
23	600	10.5	0.635	5	45.7	83.8
24	2000	10.5	0.635	5	45.7	29.2
25	600	6.35	0.3175	10	45.7	29.2
26	2000	6.35	0.3175	10	45.7	83.8
27	600	10.5	0.3175	10	45.7	83.8
28	2000	10.5	0.3175	10	45.7	29.2
29	600	6.35	0.635	10	45.7	83.8
30	2000	6.35	0.635	10	45.7	29.2
31	600	10.5	0.635	10	45.7	29.2
32	2000	10.5	0.635	10	45.7	83.8

cal distance from the machine tool that the operator would stand. The high level for the *z*-location corresponds to the head level of an average adult, and was chosen so as to determine the effect on inhalable mass concentration with respect to the mass concentration at the level of the workpiece (i.e., the low level of the *z*-location). The *z*-location values in Table 1 are heights above the table top, which was 84 cm above the floor. The direction of rotation was kept constant during all experiments and was set so that the surface velocity of the workpiece at the point of fluid application was in the "+*x*" direction (see Fig. 2).

A 2^{6-1} fractional factorial design was used to conduct a total of 32 tests. The fractional factorial design has a factorial base design with additional test variables assigned to interactions. In this experiment, the sixth variable (*z*-location) was assigned to the 12345 interaction. Such a test plan has a defining relation of I=123456. The test design matrix with the levels for the six variables studied is displayed in Table 1. The consequence of using a fractional factorial design is the confounding or confusing of variable effects. The resolution of a design is a measure of the confounding in a test design. A higher design resolution confounds main (first order) effects with higher order effects. In general, the higher the order of an effect, the less likely it is to be significant. Therefore, the highest design resolution is desirable. The 2^{6-1} design is of resolution VI, which means that no main effect or two-factor interaction is aliased with any other main effect or two-factor interaction.

Effect values are obtained by multiplying the elements within the desired column of the calculation matrix with the corresponding elements in the response vector. The calculation matrix is composed of the coded positive and negative values corresponding to the high and low states of each variable, and the interaction states are products of the main effect states. Since there are 32 unique tests, there are 32 columns in the calculation matrix. The elemental products are summed and the sum is divided by the number of high levels (the total number of tests divided by two). Under the common assumption that three-factor interactions and higher are negligible, unaliased estimates of all main and two-factor interaction effects can be obtained [15]. The estimates of the 32 linear combinations of the effects are listed in Table 2.

The tests in Table 1 were performed in random order. The measured response for each test was the PM10 mass concentration, which was obtained using the DustTrak Aerosol Monitor with a sampling rate of one per second. A representative plot of the mass concentration versus time is displayed in Fig. 3. It can be seen from the plot that after four minutes the mass concentration has reached a near-steady state level. Similar behavior was exhibited in each of the tests. For the responses, mass concentration values were taken at 1 minute, 2 minutes, and 4 minutes. In order to account for changes in ambient particulate levels, a time weighted average of the ambient mass concentration over a period of 1 minute was subtracted from the three responses. The responses at 1 minute, 2 minutes, and 4 minutes were then used to calculate the estimated effects.

Due to the Central Limit Theorem, effect estimates tend to be normally distributed. Therefore, the statistical significance of the effects can be determined using normal probability plots [15]. To obtain the normal probability plots, effects were ranked in ascending order and the effects were plotted versus their corresponding cumulative probability. In a normal probability plot samples from the same normal distribution will lie on a common straight line, meaning that if the test variable effects are representative of a single normal distribution they will form a line. If this line passes through the point (0,0.5) on the plot, then the effects are assumed to be from an error distribution with a mean of zero. Statistically significant effects will have true means that are

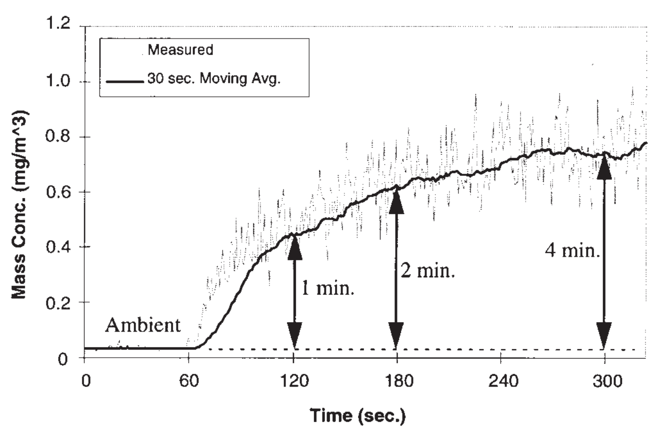

Fig. 3. Mass concentration measurements with response values indicated.

Table 2
Estimates for the linear combinations of effects

l_0 estimates mean	l_{12} estimates 12	l_{25} estimates 25	l_{1245} estimates 36
l_1 estimates 1	l_{13} estimates 13	l_{34} estimates 34	l_{1345} estimates 26
l_2 estimates 2	l_{14} estimates 14	l_{35} estimates 35	l_{2345} estimates 16
l_3 estimates 3	l_{15} estimates 15	l_{45} estimates 45	l_{12345} estimates 6
l_4 estimates 4	l_{23} estimates 23	l_{1234} estimates 56	$l_{123}\rightarrow l_{345}$ estimate error
l_5 estimates 5	l_{24} estimates 24	l_{1235} estimates 46	

non-zero and will therefore lie off the line passing through (0,0.5) on the plot. Fig. 4 shows the normal probability plot for the effects associated with the 1 minute responses. Examination of the plot reveals several outliers from the straight line, indicating that the main effects of variables 1, 2, and 5 as well as the interactions 12 and 15 are significant.

Once the significant effects were determined, a linear regression model based on these effects was developed. The model can be used to predict the response for various combinations of the input variables. The model residuals (difference between actual and predicted responses) were then plotted against response and test variables. Ideally, the residuals should appear normally distributed about zero with a constant variance. Nonrandom patterns in the residual plots indicate model inadequacy. Analysis of the plots revealed an increasing variability in the responses, as can be seen from Fig. 5. A log transform of the responses was performed in an attempt to remove this trend. Residual analysis of the model based on the log responses confirms that the trend was successfully removed, shown in Fig. 6. The calculated effects based on the log responses are plotted in Figs. 7–9.

4. PM10 experiment analysis

An examination of the plots in Figs. 7–9 reveals that only the main effects of spindle speed, workpiece diameter, and *x*-location are significant. Furthermore, each of these variables has a positive effect, indicating that an increase from the low level to the high level will result in an increase in PM10 mass concentration. From the plots it is evident that spindle speed is clearly the most significant variable. Intuitively, this is to be expected

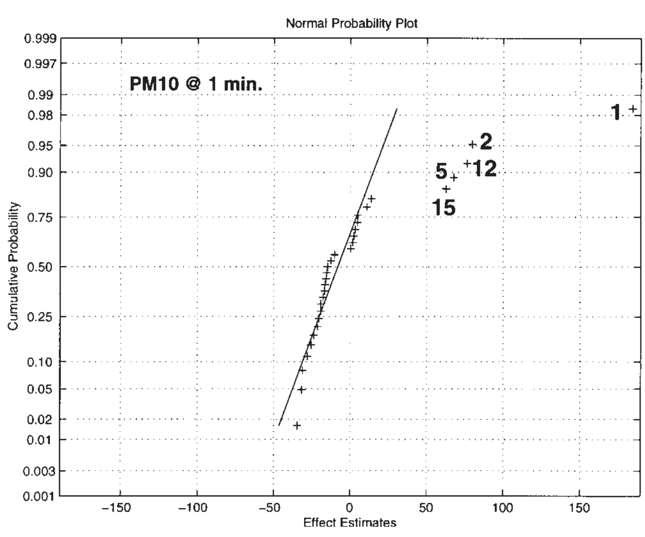

Fig. 4. Significant effects on PM10 mass concentration, based on 1 minute responses.

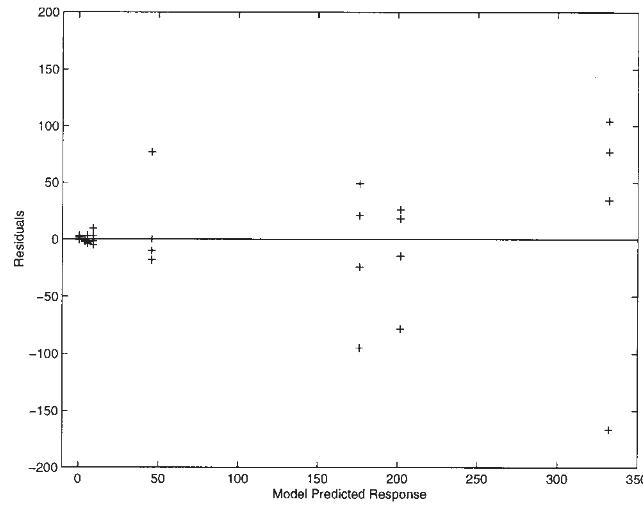

Fig. 5. Nonrandom pattern in residual plot indicating increasing variability in responses

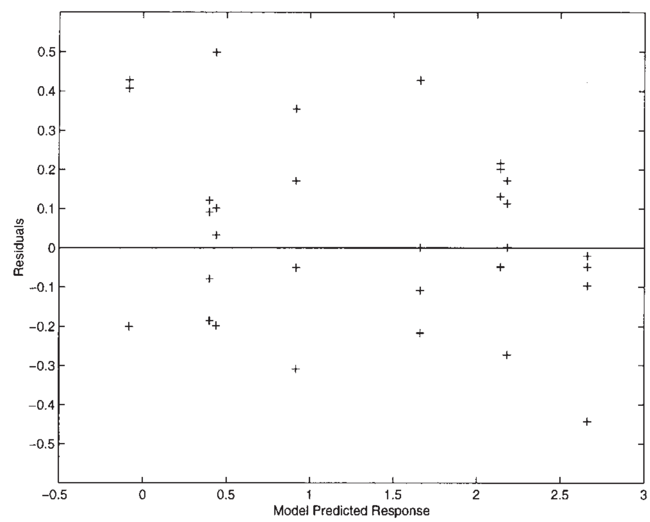

Fig. 6. Residual plot after log transform. Nonrandom pattern has been removed.

since increasing the workpiece velocity produces an increase in mechanical energy, which in turn is transferred to surface energy. A greater surface energy creates a greater instability in the fluid, leading to the formation of droplets [3]. The effect of increasing the workpiece diameter is also shown to be significant, since a larger diameter results in a greater surface velocity for a fixed spindle speed. The mass concentration is higher in front of the workpiece (i.e., the high level of *x*-location) which is to be expected since the surface velocity of the workpiece is in this direction and most of the larger droplets are splattered off as the fluid impacts the workpiece.

The effect of oil concentration for the particular soluble oil cutting fluid studied is not significant for concentrations between 5% and 10%. Nozzle diameter also did not show a significant effect on mass concentration

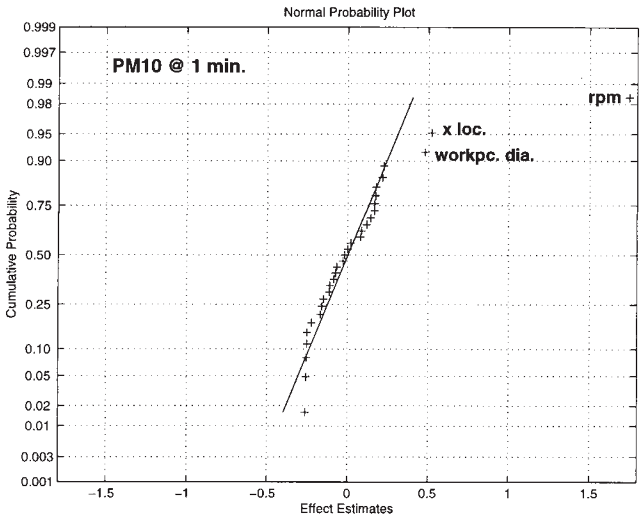

Fig. 7. Significant effects on PM10 mass concentration, based on 1 minute log responses (l_0=1.2893).

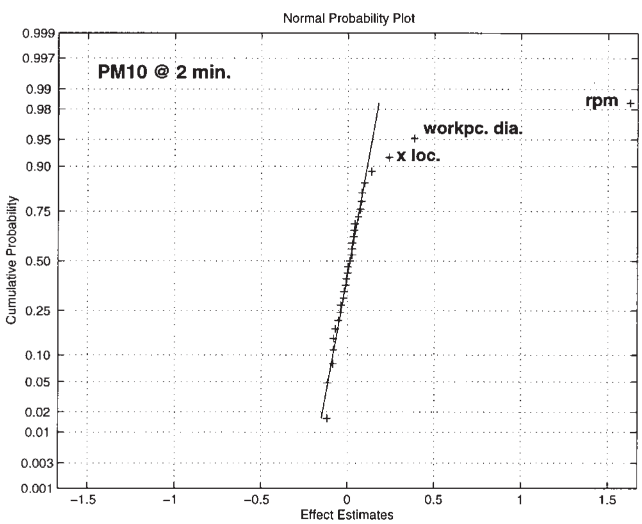

Fig. 8. Significant effects on PM10 mass concentration, based on 2 minute log responses (l_0=1.6672).

for a constant flow rate. Interestingly, z-location is also not significant, implying that there is no difference in the mass concentration of cutting fluid mist at head level compared to the concentration at the level of the workpiece.

Assuming that all third-order and higher interactions are negligible (i.e., the true main effects of these interactions are zero), an estimate of the standard error of estimated effects can be obtained by the following formula [15]:

$$s^2_{effect} = \sum_{higher\ order\ interactions} \left(\frac{l_i^2}{\text{no. of higher–order interactions}} \right)$$

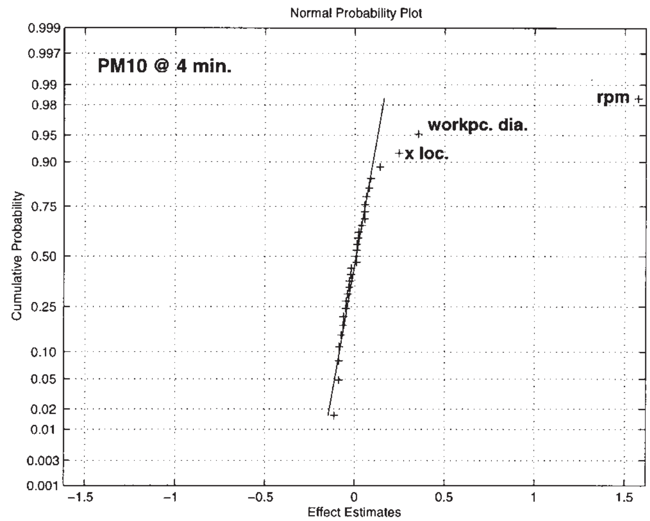

Fig. 9. Significant effects on PM10 mass concentration, based on 4 minute log responses (l_0=1.8733).

For the specified 2^{6-1} fractional factorial design, the number of sets of linear combinations of higher-order interactions available for error estimation is ten. Substitution of the ten higher-order effects from each response (1 min., 2 min., and 4 min. mass concentration values) into the above equation produces the estimated standard error of an effect, which can be used to construct a 95% confidence interval. The results are shown in Table 3, and the 95% confidence intervals for the effects based on the 1 minute and 4 minute log responses are displayed graphically in Fig. 10.

From Fig. 10 it can be seen that only the confidence intervals associated with spindle speed, workpiece diameter, and x-location do not include zero, which is the hypothesised true mean for all main and interaction effects. The results are entirely consistent with those obtained from the normal probability plots. It can also be seen that the 95% confidence intervals shrink in size as time increases. This decrease in variability with time is due to the fact that the mist concentration rises rapidly during the first couple of minutes before approaching a steady state level. Any uncertainties associated with the process could lead to much larger measurement differences in this “ramp-up” region than in the steady state region.

Table 3
Estimated standard errors and 95% confidence intervals

Response @	Standard error	95% Confidence interval
1 min.	0.153	l_i±0.3409
2 min.	0.0658	l_i±0.14668
4 min.	0.0552	l_i±0.12298

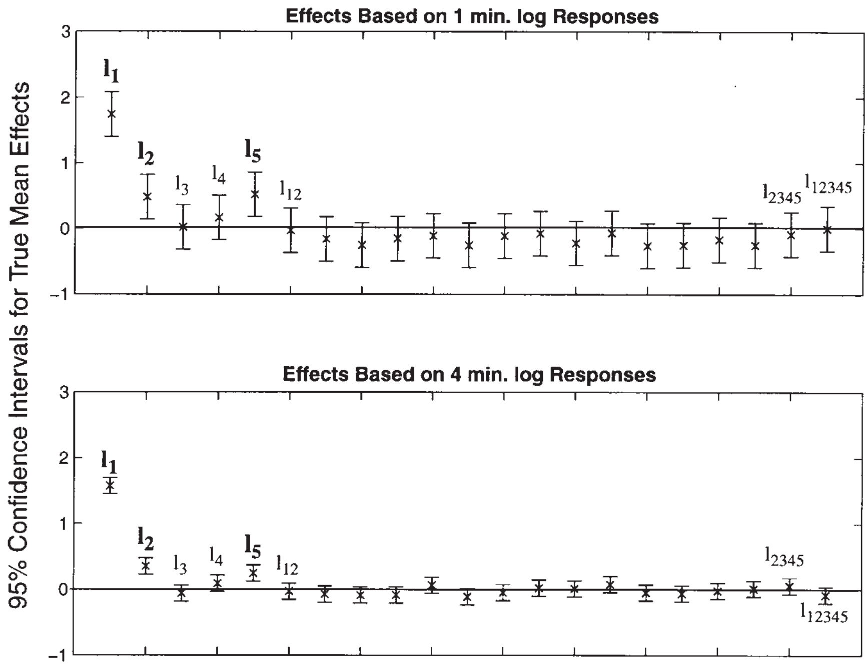

Fig. 10. 95% confidence intervals for effects based on log responses. Note: The 10 effects used for error estimation are not shown.

5. PM2.5 experiment design

A two level full factorial design was used to study the effects of the three previously determined significant variables (spindle speed, workpiece diameter, and *x*-location) on the respirable fraction of cutting fluid mist, i.e., PM2.5. A fourth variable, cutting fluid type, was also added to determine the effect of a semi-synthetic versus water soluble cutting fluid. The low and high levels used for each variable as well as other process conditions are listed in Table 4. The 2^4 full factorial design results in a total of 16 tests. The test design matrix with the variables from Table 4 is shown in Table 5.

The tests in Table 5 were performed in random order and the respirable fraction of cutting fluid mist was measured using the DustTrak Aerosol Monitor fitted with an impactor to filter out particles larger than 2.5 microns. Due to the dependence of the variability on the magnitude of the response, a log transform of the responses at 1 minute, 2 minutes, and 4 minutes was performed as before. The estimates associated with each linear combination were calculated and normal probability plots were constructed to determine the significant effects (see Figs. 11–13).

Table 4
Variable levels for PM2.5 experiment

Variable	Low level (−1)	High Level (+1)
Spindle speed (rpm)	600	2000
Workpiece diameter (cm)	6.35	10.48
x-location (cm)	−50.8	45.7
Fluid type	Water soluble	Semi-synthetic
Oil concentration (%)	5	5
Nozzle diameter (cm)	0.635	0.635
z-location (cm)	83.82	83.82

Table 5
Design matrix for experiments studying PM2.5 mass concentration

Test no.	Spindle speed	Workpiece diameter	*x*-location	Fluid type
1	600	6.35	−50.8	Water soluble
2	2000	6.35	−50.8	Water soluble
3	600	10.48	−50.8	Water soluble
4	2000	10.48	−50.8	Water soluble
5	600	6.35	45.7	Water soluble
6	2000	6.35	45.7	Water soluble
7	600	10.48	45.7	Water soluble
8	2000	10.48	45.7	Water soluble
9	600	6.35	−50.8	Semi-synthetic
10	2000	6.35	−50.8	Semi-synthetic
11	600	10.48	−50.8	Semi-synthetic
12	2000	10.48	−50.8	Semi-synthetic
13	600	6.35	45.7	Semi-synthetic
14	2000	6.35	45.7	Semi-synthetic
15	600	10.48	45.7	Semi-synthetic
16	2000	10.48	45.7	Semi-synthetic

6. PM2.5 experiment analysis

Examination of Figs. 11–13 reveals that only spindle speed is significant. Workpiece diameter and *x*-location, which have a significant effect on PM10 mass concentration, do not appear to have a significant effect for

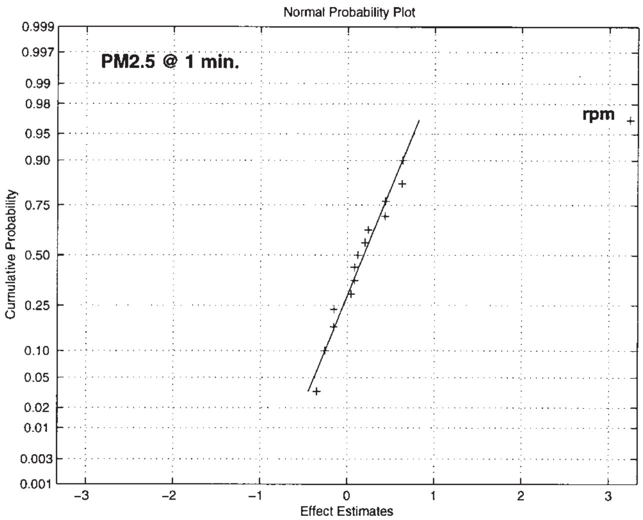

Fig. 11. Significant effects on PM2.5 mass concentration, based on 1 minute log responses (l_0=1.4386).

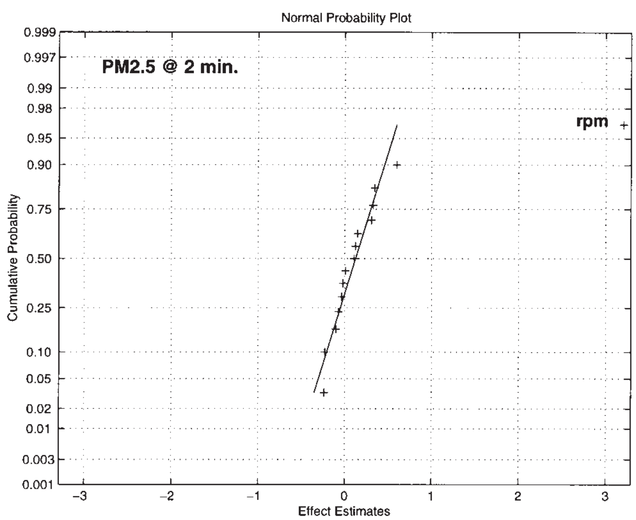

Fig. 12. Significant effects on PM2.5 mass concentration, based on 2 minute log responses (l_0=2.2650).

PM2.5 mass concentration. It can be concluded that fine mist particles (i.e., particles less than 2.5 microns) are uniformly distributed in the air around the machine tool while coarse mist particles (i.e., particles larger than 2.5 microns) are mainly distributed in front of the workpiece (when rotation is in that direction). Furthermore, a larger workpiece diameter results in more coarse particles, but has little effect on the number of fine particles generated.

It is of interest to note from Figs. 11–13 that while the average PM2.5 mass concentration increases with time, the estimate of the main effect of spindle speed is nearly constant at an approximate value of 3.2. This suggests that the effect of spindle speed on PM2.5 mass concentration is independent of time.

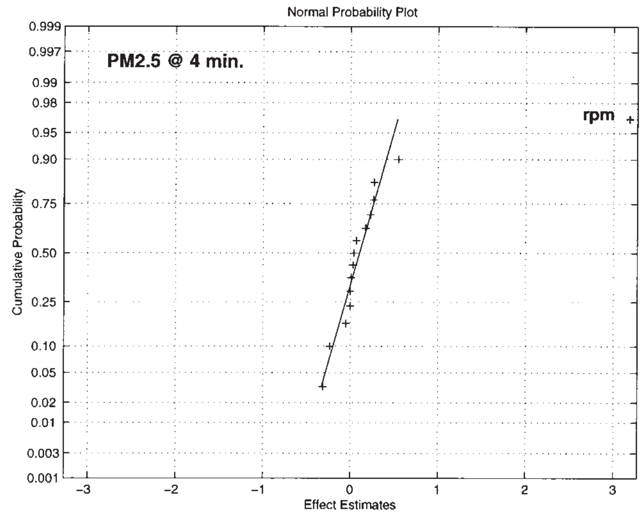

Fig. 13. Significant effects on PM2.5 mass concentration, based on 4 minute log responses (l_0=2.8138).

7. Discussion

Analysis of the experimental results leads to several conclusions about the process conditions affecting cutting fluid mist mass concentration during turning. The most dominant variable effect is speed. The fact that spindle speed is significant for both PM10 and PM2.5 mass concentration means that the number of coarse and fine particles increases as speed increases. The workpiece diameter has a significant effect on PM10 mass concentration, but is not statistically significant for PM2.5 mass concentration. A larger workpiece diameter results in a greater surface velocity, and hence a greater amount of energy is transferred to the fluid. Since the workpiece diameter is only significant for PM10 mass concentration, it may be concluded that increasing this variable results in the formation of more coarse particles (2.5–10 microns) while the generation of fine particles (less than 2.5 microns) remains constant. However, the failure of the analysis to reveal workpiece diameter as a significant variable on PM2.5 may be due to the choice of variable levels. While speed is increased by more than three times, the workpiece diameter is increased by a factor of only 1.65. Therefore, the significance of workpiece diameter may not be evident in the face of experimental error.

The fact that *x*-location is significant for PM10 but not for PM2.5 mass concentration reveals that there is an accumulation of larger particles in front of the lathe (the high level of *x*-location) while the fine particles are more evenly distributed around the machine tool. This suggests that the larger particles are being generated primarily due to the “splattering” effect that occurs when the fluid jet initially impacts the rotating workpiece, while the fine particles are being formed due to the aerodynamic forces on the fluid film that adheres to the workpiece surface. Since z-location was not found to be significant, it can also be reasoned that the particles are uniformly distributed as a function of height, between the top of the table and head level of a typical adult.

The dominance of workpiece velocity on cutting fluid mist formation is also exhibited by the investigation of nozzle diameter (and therefore jet velocity) as a significant variable effect. The relative difference between the jet velocity and the workpiece surface velocity is so great that changing the nozzle diameter from 0.3175 cm to 0.635 cm has no significant effect on mass concentration. The increased jet velocity associated with the smaller nozzle is not high enough to influence the amount of mist generated.

Finally, fluid concentration and fluid type (water soluble or semi-synthetic) were not found to have a significant effect on mass concentration. For the particular fluids studied, it is reasonable to conclude that the changes in fluid properties were not substantial enough to influence the mass concentration levels of mist formed.

8. Summary and conclusions

Statistically designed experiments were conducted to determine the machining conditions that have the most significant effect on cutting fluid mist formation during a turning operation. A real-time aerosol monitor was used to measure the PM10 and PM2.5 mass concentrations corresponding to the thoracic and respirable fractions, respectively, of cutting fluid mist. The effects of spindle speed, nozzle diameter, workpiece diameter, fluid concentration (for a water soluble cutting fluid), x-location, and z-location on mass concentration were investigated in the PM10 experiment. For the PM2.5 experiment, spindle speed, workpiece diameter, x-location, and fluid type (water soluble and semi-synthetic) were investigated. Spindle speed is the most significant variable affecting PM10 mass concentration and the only significant variable affecting PM2.5 mass concentration. For the variable levels studied, fluid concentration, nozzle diameter, and height above the machine tool have no significant effect on cutting fluid mist mass concentration. Furthermore, use of a semi-synthetic versus a water soluble cutting fluid showed no significant effect for the particular fluids used.

For the PM10 experiment, workpiece diameter and x-location (the location in front of or behind the workpiece) were found to be significant. A larger workpiece results in a larger surface velocity at the point of jet impingement, thus increasing the energy transferred to the fluid. PM10 mass concentration is greater in front of the workpiece (i.e., in the direction of the surface velocity of the workpiece at the point of jet impingement, see Fig. 2) since the larger droplets created by jet impaction with the workpiece are thrown off in this direction. However, workpiece diameter and x-location were not found significant for the PM2.5 experiment. This suggests that the coarse particles are concentrated mostly in front of the workpiece, whereas the fine particles are more uniformly distributed around the machine tool.

Finally, PM2.5 mass concentration levels were found to be significantly greater at the high level of spindle speed. On the average, the mass concentration increased by a factor of 24.5 when the speed was increased by a factor of 3.33 (from 600 to 2000 rpm). Since smaller particles are believed to pose a greater health risk, the significant increase in PM2.5 mass concentration at higher speeds is a potentially important consideration.

The results of this study suggest that attention should be focused on high speed machining operations such as turning, face milling, and boring, whereas machining processes that employ lower speeds (e.g., drilling) create less cutting fluid mist and therefore pose a lesser health risk. Since high speed machining is becoming increasingly important for higher productivity, lowering machining speeds to reduce the amount of cutting fluid mist formed may not be an economically viable solution. Attention must then be focused on developing more effective air cleaning methods as well as novel approaches to cutting fluid mist reduction, such as improved cutting fluid application strategies.

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