Cutting Fluids: Performance Measures and Health-Related Characteristics

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Abstract
Cutting fluids are used in machining operations for enhancing cutting process performance. The fluid removes heat from the cutting zone and plays a role in improving surface finish on the workpiece. There are health issues related to the use of cutting fluids, particularly because of the phenomenon of mist formation during machining. These two aspects of cutting fluid use, surface finish enhancement and mist formation during machining are investigated in the paper. The effect of cutting fluids on heat transfer is linked to surface finish, and models describing mist formation during machining are investigated and modified in order to analyze the health impact.

1. Introduction
Machining operations such as drilling, boring, grinding, and milling make liberal use of cutting fluids. The most common metalworking fluids used today belong to one of two categories based on the oil content of the fluid: i) oil-based fluids including straight oils and soluble oils, and ii) chemical fluids including synthetics and semisynthetics. Oil-based fluids are basically petroleum, vegetable, animal or mineral oils emulsified with water. They may contain a variety of additives (chlorine, sulfur, fatty oils, oxazolines, biocides, dyes, odorants, phosphorus, etc.) to achieve specific characteristics. Chemical fluids are made up of a combination of organic and inorganic salts dissolved in water, plus other chemical additives to achieve desired performance characteristics. Since cutting fluids are complex in composition, they may be more toxic than their components and may be an irritant or allergenic even if the raw materials are safe [Bienkowski, 1993]. Also, both bacteria and fungi can effectively colonize the cutting fluids and serve as a source of microbial toxins [Thorne et al., 1996]. The health effects of exposure to the fluids have been studied for over 50 years, beginning with the concern that cutting oil is a potential etiologic factor for occupational skin cancer [Leith, 1996]. It is estimated that over 100 million gallons of metal working oil are used each year in the United States [National Petroleum Refiners Association, 1991], and the volume of cutting fluids used is many times that of metalworking oil. The National Institute for Occupational Safety and Health (NIOSH) estimates that 1.2 million employees are exposed to cutting fluids [Hands et al., 1996]. The Manufacturing industry is devoting more and more attention to cutting fluid use and disposal under the pressure of increasing disposal costs and tighter environmental regulations, since spent cutting fluid is one of the most significant waste streams in manufacturing facilities.

An important function of cutting fluid is temperature control through cooling [Aronson, et al., 1994]. A fluid’s cooling properties are critical factors in decreasing tool wear and extending tool life. It is also important for achieving the desired size, finish and shape of the workpiece [Sluhan, 1994]. The impact of
cutting fluids on the machined workpiece surface error is examined in this paper. Dimensional errors on a machined surface increase due to workpiece deflection under load and due to thermally induced expansion. Cutting forces and workpiece temperature variations during cylinder boring were investigated. The results were used to predict surface finish during boring.

Cutting fluid related health hazards are mainly due to exposure to cutting fluid mist during machining. It is therefore instructive to analyze how mist is created during machining and examine associated health hazards. The following mist formation mechanisms are studied:
1. Atomization due to the fluid impinging on stationary and rotating targets.
2. Evaporation - condensation mechanism.

2. Effect of cutting fluid on dimension error
Boring was selected as an ideal machining process to study the effect of cutting fluid on surface finish errors, since it is a high precision operation carried out on automobile cylinder blocks. Dimensional inaccuracies in cylinder block boring is a critical error since it has a significant effect on engine performance. The effect of presence/absence of cutting fluid on dimensional inaccuracy during cylinder boring operations is examined. Analytic and finite element methods were employed to develop a predictive model relating surface error to cutting forces and heat generated during the machining process, and to compare the effect of dry and wet machining on surface error. Each of the factors causing surface errors (Thrust force on the workpiece and heating effects) are discussed individually.

2.1 Force-Induced Deflection
Thrust exerted by the tool on the workpiece results in elastic deformation during boring. This results in ‘out of roundness’ surface error. The relation used to calculate this error [Subramania, 1991] is:

\[ SE(\phi, Z) = F_r W C_r + F_t W C_t + F_a W C_a \]  \hspace{1cm} (1)

where \( SE(\phi, Z) \) is the radial deflection at the point of surface generation, and \( W C_j \) is the ‘influence coefficient’ at the point of surface generation due to a unit force in the radial, tangential or axial direction. The influence coefficients were found from a finite element model of the workpiece acted on by axial, tangential and radial forces. The coefficients were found to vary in a non-linear manner with axial distance. The forces input into the finite element model are given by:
\[ [F_x, F_y, F_z]^T \], where the tangential, radial and axial forces on the cutting tool are related to the \( x, y \) and \( z \) components by the relation:

\[
\begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix}
= \begin{bmatrix}
\cos \theta & -\sin \theta & 0 \\
\sin \theta & \cos \theta & 0 \\
0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
F_t a \\
F_r \\
F_a
\end{bmatrix}
\]  \hspace{1cm} (2)

where \( \theta \) is the angle between the ‘\( y \)’ axis and the line passing through the center of rotation and the point of contact of the cutting tool and the workpiece. The radial and axial forces at the tool tip are calculated by resolving the thrust force, \( F_{thrust} \), into components using the ‘effective lead angle’, \( \gamma_L \) is calculated as the ratio of the cutting forces in the radial and tangential directions [Li, 1997]. The resulting deflection is computed using a finite element model, which indicates a deflection of about 6 microns for a 8 cm high workpiece with 5 cm outer diameter and 0.6 cm wall thickness.

2.2. Heat Transfer Model for Boring Operation
Due to the very large thermal conductivity of die cast aluminum and the small wall thickness (0.6 cm), a one-dimensional heat transfer model with a longitudinally moving
heat source, assuming heat losses only through the two side walls of the bore is adequate. The governing equation is:

\[
\frac{d^2 \theta}{dz^2} - \frac{2H\theta + g(z, t)}{k} = \frac{w \partial \theta}{\alpha \partial t} \tag{3}
\]

where \( \theta \) is the difference between the wall temperature and ambient temperature, \( \alpha \) is the thermal diffusivity, \( k \) is the thermal conductivity, \( H \) is the ratio of heat convection coefficient and thermal conductivity, i.e., \( H = h/k \), \( w \) is the thickness of the bore wall, and \( g(z, t) \) is the heat source strength. The integer transformation approach is applied to obtain the solution of Eq. (3) subject to the initial and boundary conditions.

**Heat Source Strength and Cutting Fluid Convection Coefficient.** Several machining tests were carried out using cutting fluid, and the heat source strength and the heat convection coefficient were estimated by the inverse heat transfer method. In a boring process without cutting fluids, the heat convection coefficient for standing air, about 6 \( \text{W/m}^2\text{K} \), was used [Incropera, 1990]. Based on \( 2^3 \) factorial design, a set of boring experiments with die cast aluminum 308 (same as the workpiece used for force induced deflection) was conducted on a Cincinnati Milacron Vertical Machining Center (7VC-750). The variables investigated were cutting speed, feed, and presence/absence of cutting fluid. For each test, the cutting forces and the transient temperature response at five different locations were measured simultaneously. The experimental setup is shown in Figure 1.

**Fig 1. Picture of Experimental Set-up**

The temperature distributions in the axial direction in the workpiece were calculated as a function of time. Thermal deformation is also calculated using the finite element approach. The package used is I-DEAS developed by the Structural Dynamics Research Corporation. A comparison of the temporal temperature distribution (Figure 2) reveals significantly faster cooling with the application of cutting fluid, and lower maximum temperatures. This translates to smaller thermal deformation with the use of cutting fluids. Finite element model predictions of the surface error were made and validated with experimentally observed surface error.

**Fig 2. Comparison of Predicted Temperatures with Experimental Observations**
Fig 3. Measurements of the Surface Error on the Machined Bore and Comparison with Predicted Surface Error. A Brown & Sharp Validator System was used to measure the surface error. As seen from Figure 3, model predictions demonstrate very good agreement with experimental surface error values.

3. Cutting Fluid Mist Formation

The two mist formation mechanisms are (1) Liquid film disintegration, (2) Evaporation / condensation. Each mechanism is discussed in sequence.

3.1 Mist Formation by Liquid Film Disintegration

During machining, impingement of cutting fluid on the workpiece can produce a liquid sheet. The initial disturbances on the liquid film may set up unbalanced forces. Surface tension prevents the film from fanning, while inertial forces (aerodynamic forces or centrifugal forces) favor fanning and disturb the equilibrium. As it moves over the sheet, air may cause a pressure distribution due to the Venturi effect that increases the amplitude of the disturbances. Disintegration occurs when the wave amplitude reaches a critical value, and fragments of the sheet are torn off. These rapidly contract into unstable ligaments under the action of surface tension, and drops are generated as the ligaments break down.

The atomization model [Yue et al., 1996] considers a machining process where a cutting fluid jet with radius \( r_j \) and velocity \( V \) impinges on the flat workpiece at a right angle, and a liquid film develops and flows over the flat surface.

Using boundary layer equations and approximating the liquid film velocity profile with a third order polynomial, one can obtain the flowing fluid film thickness:

\[
\delta = r_j \left\{ \frac{1}{2} \left( \frac{r_j}{r} \right)^2 + \frac{3}{8} \frac{280}{39} (Re_j)^{-\frac{1}{2}} \left( \frac{r_j}{r} \right)^{\frac{1}{2}} \right\} \quad (4)
\]

where, \( Re_j = \frac{V r_j}{v} \), \( r \) is radial distance and \( v \) refer to shear.
is kinematic viscosity.

It is claimed that the mean diameter of the droplet is nearly proportional to the film thickness at the point of impingement and can be expressed as $D \propto \delta^x$ [Lefebvre, 1991], where $x$ has the value between 0.3 and 0.5. For liquids of low viscosity, $x$ is nearly equal to 0.5. For liquids of high viscosity, the dependence of mean drop size on $\delta$ is slightly higher.

For the turbulent jet, initial disturbances primarily caused by turbulent pressure fluctuations may be strongly amplified as the jet impinges and flows on the plate. The disturbance at the point of impact scales with the dimensionless group [Lienhard, 1992]

$$\omega = We_d \exp \left( \frac{0.9711}{d \sqrt{We_d}} \right)$$

where $We$ is the Weber number, $l$ is distance between nozzle and target and $d$ is liquid jet diameter.

The experimental work by Lienhard [Lienhard, 1992] indicates that splattering occurs when $\omega$ reaches 2120, irrespective of $l/d$ and the fraction of the total incoming liquid mass splattered, $\xi$, is given by:

$$\xi = -0.0935 + 3.41 \times 10^{-5} \omega + 2.25 \times 10^{-9} \omega$$

$$2200 \leq \omega \leq 8500$$

and,

$$\xi \leq 2.5 \% \quad (2120 \leq \omega \leq 3000)$$

When a cutting fluid jet impacts a workpiece of radius $R$ rotating in a horizontal plane with angular velocity $\omega$, three different disintegration modes are observed depending on the flow rate. The three modes are: drop mode, ligament formation mode and film formation mode.

**Drop mode.** For very low cutting fluid flow rates $Q$, a thin fluid film covers the surface of the workpiece with radius $R$. The drop separates from the edge of the surface when the centrifugal force exceeds the force due to surface tension $\gamma$. The equilibrium is given by:

$$\frac{\pi D^3}{6} \rho R \omega^2 = \pi D \gamma$$

where $\rho$ is fluid density.

Solving for the drop diameter, $D$, gives:

$$D = c \left( \frac{\gamma}{\rho R \omega} \right)^{1/2}$$

where $c = \sqrt{6}$ from Eq. (9). The experimentally obtained value of $c$ is 1.9-4.6.

![Fig. 4. Drop formation mode](image)

In theory, the drop diameter is defined by Eq. (9). However, disturbances in the process leads to a distribution of drop diameters. Large drops, together with numerous small satellite droplets are observed.

**Ligament formation mode.** As the cutting fluid flow rate increases up to a certain limiting value the film experiences wave disturbances.
Many unstable liquid ligaments appear at the circumference and break up into small drops of varying size (Fig. 5). The trajectory of a ligament developed at the edge is described by the following approximate system of equations [Bayvel and Orzechowski, 1993].

\[ x = R \cos(\omega t) + R \omega t \sin(\omega t) \]  \hspace{1cm} (10)

\[ y = R \sin(\omega t) - R \omega t \cos(\omega t) \]  \hspace{1cm} (11)

The ligament diameter, \( d_l \), can be determined from empirical relations as:

\[ d_l = c'R \left( \frac{1}{N_l} \right)^{\frac{2}{7}} \left( \frac{\gamma}{\rho R^3 \omega^2} \right)^{\frac{2}{7}} \left( \frac{\rho Q^2}{R^3 \gamma} \right)^{\frac{1}{7}} \]  \hspace{1cm} (12)

\( N_l \) is the number of ligaments, and \( c' \) is an experimentally determined constant.

The drop diameter obtained by substituting Eq. (12) into Eq. (13) compares favorably with the empirical equation for drop diameter (cm) reported by Kayano and Kamiya [1978]:

\[ D = 5.75 N^{-0.79} Q^{0.32} R^{-0.69} \rho^{-0.29} \gamma^{0.26} (1 + 0.2z)^{1.27} \]  \hspace{1cm} (14)

where, \( N \) is rotational speed and \( \mu \) is dynamic viscosity. The units of \( D, Q, R, \rho, \gamma \) and \( \mu \) are cm, \( \text{cm}^3/\text{s} \), cm, g/cm\(^3\), g/s\(^2\) and g/(cm.s) respectively.

**Film formation mode.** At high flow rates, the ambient medium (air) causes strong disturbances and the liquid film disintegrates into drops. A wide drop size distribution is observed.

A hardware testbed was recently established to validate the atomization model associated with a rotating workpiece. The cutting fluid mist droplet size distribution has been obtained with a Laser Aerosol Spectrometer for a variety of cutting conditions. The variables examined are speed, workpiece diameter, nozzle diameter, fluid jet velocity, and cutting fluid oil concentration.

### 3.2 Mist Formation Via Evaporation/Condensation

Cutting fluids contain a wide range of compounds. Under ambient conditions, some volatile components may evaporate at a rate governed by their partial vapor pressures. This changes the composition of the cutting fluid.

Mineral oils are commonly used as cutting fluids, either directly as straight oils or as soluble oils. They mainly contain a mixture of straight-chain, aliphatic hydrocarbons from \( C_{14} \) to \( C_{20} \). The evaporation rate of the pure oils at ambient condition is very low due to the low vapor pressure of these components. This is supported by experimental data as shown in Fig 6.

The process of mist formation in
atmosphere by vapor condensation on dust or soluble aerosol particles is known as heterogeneous nucleation.

\[ S = \frac{P_0}{P_s} > 1 \]  

(15)

where \( P_s \) is saturation vapor pressure and \( P_0 \) is actual partial pressure of vapor.

In the absence of foreign nuclei, phase change occurs by diffusion. The rate of condensation from heterogeneous nucleation depends on the exchange of matter and heat between a liquid drop and the continuous phase (air) and is expressed as [Friedlander, 1977]

\[ \frac{dv}{dt} = \frac{4\pi DP_s(S-1)(R_p - R_p^*)}{kT} \]  

(16)

where \( R_p^* \) is the critical droplet radius or the critical nucleus size which can be estimated [Fletcher, 1966]. Smaller nuclei tend to evaporate while larger ones grow. Eq.16 shows that the rate of condensation is proportional to the difference between the particle radius and the critical radius.

**Mist Droplet Motion**

During a drop discharging to the stationary air, its motion is controlled by the drag force,

\[ F_d = C_D \frac{\pi D^2 \rho G V_{\infty}^2}{4} \]

and the difference of gravitational and buoyancy forces.

\[ F_g = \frac{\pi d^3 (\rho_p - \rho_f)}{6} \]  

(17)

The drop accelerates upwards at the rate \( (F_d - F_g)/m \) until \( F_d = F_g \). The terminal velocity is:

\[ V_{\infty} = \sqrt{\frac{4\pi(\rho_p - \rho_f)D}{3\rho GC_D}} \]  

(18)

Assume the moving drop is a small sphere. The drag coefficient, \( C_D \) is a function of the Reynolds number \( Re_{\infty} = \frac{V_{\infty}D}{\nu_G} \).
\( C_D \) has been established experimentally in the wide range of Reynolds numbers [Bayvel, 1993].

\[
C_D = \frac{24}{Re_{\infty}}
\]

\( 1 \times 10^{-4} < Re_{\infty} < 0.4 \) (laminar range)

\[
C_D = \frac{18.5}{Re_{\infty}^{0.6}}
\]

\( 0.4 < Re_{\infty} < 500 \) (transient range)

\[
C_D \approx 0.445
\]

\( 1 \times 10^3 < Re_{\infty} < 2 \times 10^5 \) (turbulent range)

When \( Re_{\infty} < 1 \times 10^{-4} \), the influence of Brownian motion on the drop moving is dominant. Generally, for very small droplets (less than 0.1 micrometer in diameter) the drop experiences Brownian motion, which will suspend mist droplets in air for extended periods of time (several days).

Conclusions

The focus of our research was two fold:

1. Gaining an understanding of the effect of using cutting fluids on surface error in boring operations, and
2. To understand the mechanism of mist formation.

A coupled heat transfer / cutting force analysis was used in a finite element model to calculate surface error under various cutting conditions. The use of cutting fluid reduces temperatures at the chip-tool interface, but does not have a drastic effect on surface error.

Various mist formation mechanisms were studied and the motion of mist droplets was analyzed. It is apparent that under certain conditions, significant amounts of suspended cutting fluid droplets are created.

Continuing research work will emphasize development of new and refinement of existing models for mist-related mechanisms, as well as their experimental verification.

References


Hands, D., M.J. Sheehan, B. Wong, H. B. Lick, “Comparison of Metalworking Fluid Mist Exposures from Machining with


