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THE DEVELOPMENT AND ANALYSIS OF AN ENVIRONMENT FRIENDLY MACHINING FLUID APPLICATION SYSTEM

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Compliance with environmental regulations is becoming more and more costly for manufacturers as government scrutiny and global trade agreements become more stringent. Metalcutting fluid use and disposal is a major concern as these environmental issues become more prominent. A new method for cooling and lubricating machining processes using very small amounts of a vegetable oil based fluid transported by air stream is currently being developed. This new method will allow a dramatic reduction in hazardous waste management costs for machine shops. Shops employing this new method will greatly reduce, and in some cases nearly eliminate the hazardous waste management costs associated with the use of cutting fluids in machining.

This paper deals with the development and performance analysis of the new application system. In this system a high subsonic air stream carries the cutting fluid directly to the cutting zone. A discussion of the development, heat transfer, and lubricating characteristics of the system is provided. The performance of the system is then evaluated using metalcutting tests. Results obtained using the new cooling/lubricating system are markedly superior to those obtained with dry cutting. These results are at approximately the same levels as those obtained using traditional flood type coolants/lubricants, but at much lower cost.

INTRODUCTION

Background - Although cutting fluids have greatly improved machining performance, conventional metalcutting fluids have more recently become a source of non-value-added cost to businesses in the machining industry. As environmental and regulatory burdens become more onerous, profit margins for these enterprises decrease. With the introduction of ISO 14000 environmental series legislation, companies are further encouraged to reduce or eliminate metalcutting fluids from their processes. [1] As a result of these pressures, the development of new methods for the use and delivery of coolants and lubricants in machining operations has become necessary.

Modern metalworking fluids are quite effective if environmental issues are not considered. In wet cutting applications these fluids have historically reduced the unit cost of machined products by an amount greater than the purchase cost of the fluid, resulting in a net savings to the manufacturer. These cost reductions are achieved through increased performance in areas including: [2]

- i) Tool Life
- ii) Surface Texture of the Machined Product
- iii) Increased Cutting Process Speeds and Feeds

It is in the application and disposal of these fluids that problems are encountered and costs incurred rather than avoided. Some of the issues in this regard lie in the areas of application methods, worker exposure, regulatory compliance in disposal, foaming, and the requirement for secondary workpart cleaning operations.

Three application methods are typically employed: flood, spray, and mist application. In flood application, a high volume liquid stream is directed into the cutting zone. The high volumetric flow rate of this stream is a primary mechanism by which chips and thermal energy are carried away from the tool/work/chip interfaces. The removal of hot chips is a major factor in maintaining the tool and work at a relatively low temperature. If this objective is achieved, tool life is improved, and unwanted changes in the mechanical properties of the workpiece due to the rise in temperature in the heat affected zone are minimized. Rapid removal of chips from the cutting zone also reduces scoring of the cut surface, promoting good surface texture on the cut workpart. In addition, high volumetric flow rates help carry fluid into the tool/work and tool/chip interfaces, providing lubrication. [3]

Mist application, in which the coolant/lubricant is delivered to the cutting zone in the form of fine, airborne droplets, is well suited to operations in which the cutting speed is high and the area of the cut is low (e.g., end milling). This application method is often used in situations in which flood application is impractical. [4] The spray method of application is similar to mist application. The droplets in spray application are much larger than those in the mist method of application, however. A major disadvantage of each of these application methods (conventional flood, spray, and mist) is the potential for the exposure of the machine tool operator to harmful amounts of cutting fluid including airborne amines.

Metalcutting fluids often consist of complex chemical mixtures with up to 25 components such as base oil stocks, emulsifiers, corrosion inhibitors, extreme pressure agents, and biocides. [5] Some of the problems posed by worker exposure to metalcutting coolants and lubricants include inhalation and ingestion of the fluid droplets, and skin exposure leading to dermatitis. In order to reduce worker exposure, enclosures are often employed, hampering access to the work area. Vacuum operated air cleaners are typically used to capture fluid that escapes these enclosures. These measures are also often a part of the shop's plan for regulatory compliance in disposal.

The cost of environmental compliance is already significant for organizations that focus on metalcutting operations. The Environmental Protection Agency estimates that 90 percent of all costs associated with hazardous waste management for a machining enterprise arise from the use of machining coolants and lubricants. [2] The likelihood is high that environmental regulations concerning these fluids will become more strict across the United States in the future. Most users of machining coolants and lubricants must deal with problems associated with:

i) Chip Cleaning: This procedure is required by most metal chip reclaimers.
ii) Disposal of Used Coolants/Lubricants: Most waste haulers levy a surcharge for these types of materials.
iii) Filtering: The re-circulation of coolants and lubricants requires the filtering of chips and swarf, the removal of tramp oil from the liquid, the disposal of contaminated filters, and other measures.

In many applications, metalworking fluids are a necessary part of the machining process. Over the past two decades cutting fluid costs including management and disposal expenses have risen to 16% of total metal cutting costs. Due to this increase, some manufacturers have reverted to dry cutting for less severe processes. [6] This is often done at the expense of tool life, part quality, or productivity. In the foreseeable future, dry cutting cannot replace all coolant/lubricant use.

The Function of Metalworking Fluids. Metalworking fluids serve two major purposes in machining operations:

i) Heat Transfer: The tool and work are kept relatively cool by the removal of thermal energy from the tool/work and tool/chip interfaces. Lower tool and work temperatures provide extended cutting tool life, reduce the amount of unwanted mechanical property change in the workpiece, and result in better workpart surface texture. Metalworking fluids whose primary function is to serve as a heat transfer medium are known as coolants.

ii) Lubrication: The maximum temperatures generated during machining are usually found on the rake face of the cutting tool. [7] If significant lubrication is achieved, cutting forces and power required are reduced, as is the amount of heat generated at the tool/work and tool/chip interfaces. These two factors combine to promote good surface finish and increased tool life. [3]

The system described in this paper provides excellent cooling and lubrication properties while addressing worker exposure and environmental concerns.

2. THEORETICAL ANALYSIS OF CUTTING FLUID PROPERTIES

Heat Transfer and Lubrication. Effective heat removal from the cutting zone is one of the basic functions of a cutting fluid in a metal cutting operation. Most of the heat generated in a metal cutting operation is a result of the forming and deforming of the chip and is carried away with the chip. Of this heat generated, approximately 70-75% is associated with shearing action and deformation of the chip and 25-30% is a result of friction as the chip slides over the tool. Metalcutting fluids reduce tool temperature by the total combination of their cooling and lubricating properties. By reducing chip friction, not only is the frictional heat reduced, but the heat from the deformation process is also reduced due to the interrelationship between chip friction and amount of deformation. [8]

The heat transfer capabilities of a cutting fluid depend both on the fluid formulation and the application method used for the particular metalcutting operation. When evaluating a commercially available fluid, information concerning chemical composition and recommended concentration levels is readily available. However, many physical properties such as specific heat, thermal conductivity, and viscosity for the cutting fluid are usually not available. These property values are needed in order to conduct an analytical study of a cutting fluid's heat transfer characteristics, which are governed by the flow's Nusselt Number. The heat transfer rate in a machining process is given by the following equation: [9]

$$q = hA(T_w - T_f) \quad (1)$$

Where:
q = heat transfer rate
h = heat transfer coefficient
A = surface area
T_w = wall temperature of the workpiece
T_f = fluid temperature

The equation for the determination of the heat transfer coefficient is of the form:

$$h = f(Nu) = f(Re, Pr, \text{geometry}) \quad (2)$$

And for a cylindrical workpiece:

$$Nu = hD/k \quad (3)$$

$$Re = \rho v D/\mu \quad (4)$$

$$Pr = \mu c_p/k \quad (5)$$

Where:
Nu = Nusselt number
Re = Reynolds number

Pr = Prandtl number
D = diameter of workpiece
k = thermal conductivity of workpiece material
μ = dynamic viscosity
c_p = specific heat
ρ = mass density of work material
v = velocity

The Nusselt number is dependent on the values of the Reynolds number and the Prandtl number, and is related to them by the power law equation. [10] The Reynolds number and Prandlt number may be calculated based on physical constants of the fluid. Once this has been done, the Nusselt number may be calculated using empirical constants from heat transfer literature. The thermo-physical fluid properties that influence heat transfer rate when using a cutting fluid are: dynamic viscosity, constant pressure specific heat, mass density, and thermal conductivity. These properties for soluble oil emulsions vary as fluid concentration and fluid temperature change. As oil is added into water when forming an emulsion, viscosity increases as specific heat is reduced for the mixture. [9]

The thermo-physical properties of cutting fluids are influenced by operating temperature, fluid type, and oil concentration. When these properties are changed, the Prandtl and Reynolds numbers are affected along with the heat transfer rate from the workpiece to the cutting fluid. The convective heat transfer characteristics of a fluid for a particular operation and process are influenced by the Nusselt number. Water affords the highest heat transfer rate of all the cutting fluids examined. Synthetic cutting fluid is nearest to water in heat transfer performance, while semi synthetic and soluble oil fluids are poorer. [9] Heat transfer performance deteriorates as oil concentration is increased in soluble oil fluids. Cutting fluid heat transfer rates increase as cutting speed and fluid flow increase. However, as cutting speeds increase, improved heat transfer rates may be offset by increased overall heat generation. Considering the effect of fluid flow velocity, jet application of a cutting fluid can be very effective in rapidly removing heat from a precise location. Jet application aimed at the highest temperature area along with a secondary slower stream over the rest of the workpart maximizes heat transfer between workpiece and cutting fluid. [9]

The above conclusions can be verified from tabulated values in heat transfer literature. The average unit convective coefficient, c is dependent upon a fluid's physical properties and its velocity over a solid surface. These values affect the rate at which thermal energy may travel through a fluid, and the rate at which thermal energy may be carried away from the solid surface by the fluid. Huge variations in the c value can be observed depending on the fluid type and the application method. Table 1 confirms that a high velocity jet of a particular fluid would be much more effective in increasing heat transfer than a slower velocity stream of the same fluid. [10]

Table 1 Typical Values for the Average Unit Convective Coefficient

Mode	$\bar{h}_c$, W/(m$^2 \cdot$ K)
Free Convection, Air	5-25
Forced Convection, Air	100-200
Free Convection, Water	20-100
Forced Convection, Water	500-10,000

The new coolant/lubricant application system that has been developed uses a vegetable oil solution that exhibits good lubrication properties but poor heat transfer characteristics. As the above analysis indicates, a high velocity air stream can be an effective heat transfer media. By combining the oil with a high velocity air stream effective lubrication and cooling is provided.

The proposed system uses readily available vegetable oil based fluid carried in a stream of compressed air aimed precisely at the cutting zone. The oil is delivered in a fine spray instead of an atomized mist to minimize worker exposure. Such a small amount of these biodegradable, non-toxic fluids is required (1-2 ounces/hour in a moderate milling operation) that regulatory compliance becomes a non-issue. Practically all of the metalworking fluid is consumed in the machining process. The benefits gained from such a coolant/lubricant delivery system include:

i) Alleviation of the necessity for chip cleaning/drying before sale to the waste reclaimer
ii) Elimination of the need for tramp oil removal, filter disposal, and spent fluid disposal
iii) Reduction or elimination of the need for secondary workpiece cleaning operations
iv) Elimination of hazardous waste disposal involved with metalcutting fluid systems

Using the new system air acts as the primary heat transfer medium, while the oil forms a thermally insulating and lubricating boundary between the tool and work. The proposed system is comparable to the forced convection air condition in Table 1. Traditional flood systems are characteristic of slow moving liquids which most closely match the free convection water condition in Table 1. The heat transfer values indicated by these two conditions demonstrate that forced air convection has the potential to equal or exceed flood cooling in terms of heat transfer capacity. The combination of lubrication, insulation, and thermal energy removal is beneficial in terms of tool life, workpart surface texture, and power consumption.

3. EXPERIMENTAL DESIGN

Application System. The conceptual model of the new application system consists of a compressed air source, an air pressure regulator, and the cutting fluid application nozzle. Air enters the model from the shop air source and is reduced to the desired pressure by an air pressure regulator which functions as a throttling valve. The air is mixed with the oil in a specially designed application nozzle and applied directly into the cutting zone.

Response Variable. The proposed system was compared to dry cutting and to flood application to evaluate the new system against traditional cooling/lubrication systems. These experiments were randomized to avoid inadvertent process or environmental changes that could have affected the results. Using the t distribution, a t-test was utilized to determine if any differences between response means for the processes being evaluated were statistically significant.

The resultant of force for a metalcutting operation was the response variable evaluated. Cutting forces can be measured by using a dynamometer. A Kistler 3-axis quartz multi-component dynamometer was used to gather cutting force data. This device was bolted to the machine table and the workpart then securely bolted to its top surface. As the workpart was cut, the dynamometer generated a voltage proportional to force along an axis that could be amplified and read on an oscilloscope. The corresponding data was logged to a computer hard drive by way of a USB Interface. The voltage was then converted to force.

The dynamometer generated individual voltages corresponding to forces parallel and perpendicular to the feed direction in an end milling operation. Cutting forces are significant responses to measure because lower cutting forces indicate higher efficiency, less friction, lower cutting temperatures, better surface finish, and longer tool life.[11]

Cutting Force Data. The first experiment involved the use of a dynamometer to determine cutting forces using the new system and dry cutting. In this experiment cutting forces were recorded using an end mill and sample bars of 6061 T6 aluminum. A series of straight slots was cut in the surface of the aluminum samples randomly using either the new application system and dry cutting. The cutting conditions and other pertinent machining information for this experiment are listed as follows:

Cutting Tool -	½ in. diameter, two flute, high speed steel end mill
Cutting Speed -	293 ft/minute
feed -	0.004 in./rev
feed rate -	9.15 in./min
chip load -	0.002 in./tooth
cutting depth -	0.020 in.
length of cut -	5 in.

The application nozzle was positioned near the end mill and aimed directly at the cutting zone. A paper section pressed against the cutting tool served as a target to assist in aiming the device.

The signals from the dynamometer were reported as average root mean square (RMS) voltages by way of an oscilloscope. Assuming that it is sinusoidal, voltage (V) can be converted to RMS voltage by the following equation:

$$V_{RMS} = V/\sqrt{2} \qquad (6)$$

Theoretically, the voltage generated by a dynamometer in an end milling operation can be expected to be sinusoidal. Reporting the data as RMS voltage allowed the signal from each component to be quantified as a single number. [12]

During each experimental cut, six voltage readings for both the X and Y components were recorded and averaged. These components were then converted into a resultant value for each sample cut. The settings on the signal amplifier required that a conversion of 1 lb/27.5 mV be applied to determine the force in lbs. This force corresponding to RMS voltage was used as a comparative value when statistically analyzing various experimental designs. The experimental results indicate that the average resultant cutting force from the new system is 4.50 lbs. compared to 5.13 lbs. for dry cutting. Figure 1 shows the scatter plots for forces resulting from dry cutting and from the proposed system. As can be seen, the distribution from the new system and dry cutting appear to be substantially different with very little overlap. However, further statistical analysis was required to determine if these indications are statistically valid.

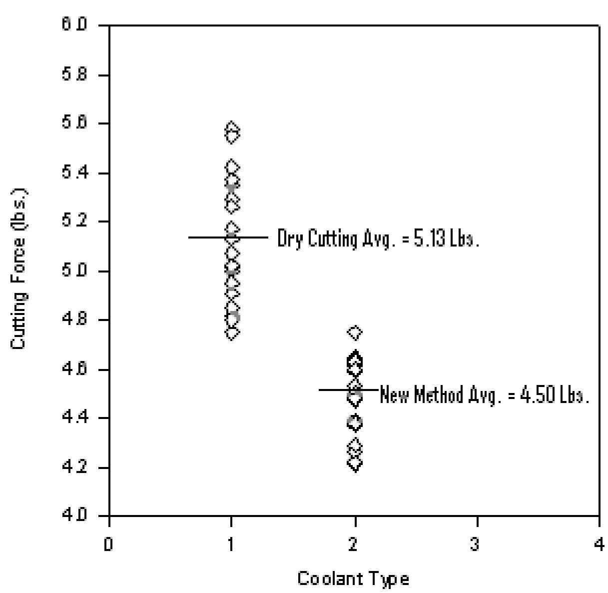

Figure 1 Scatter Plot Comparing Cutting Forces From Dry Cutting and the New Method

The t distribution was utilized to determine whether the difference in means indicated by the experimental data was statistically significant. A two-sample t-test was performed using the cutting force data for the new method and dry cutting. From the t-test results, the one tail P-value indicates that the difference in cutting force means is significant at a level of $1.6x10^{-12}$. This is far below the 0.05 level which is the usual basis for significance, indicating with an extremely high confidence level that the new system produces lower cutting forces than those associated with dry cutting. [13]

To determine the expected level of improvement gained when using the new system as compared to dry cutting, a confidence interval for the difference in means was calculated at a 0.05 significance level. This confidence interval was determined to be 0.630 +/- 0.127 lbs. This interval indicates with 95% confidence that dynamometer readings for the new system are between 0.503 lbs. and 0.757 lbs. lower than for dry cutting. This is equivalent to a reduction in cutting forces of at least 10%, and potentially as much as 15%.

The second experimental run evaluated the resultant forces measured while using the new system as compared to those measured when using a traditional flood system. Cutting forces were measured using the same cutting conditions and other pertinent machining information as those listed for the first series of tests. A new end mill with identical specifications as the tool from the first series of tests was used. The overall cutting force magnitudes were higher that those noted in the first set of tests. This is likely explained by the use of a new cutting tool for the second set of tests. The shift in magnitude is not significant in the data analysis since it is the differences within each test series that is being studied.

The cutting force magnitudes for the new system and flood cutting are very similar as indicated by the cutting force data. Figure 2 shows the scatter plots for forces resulting from each method.

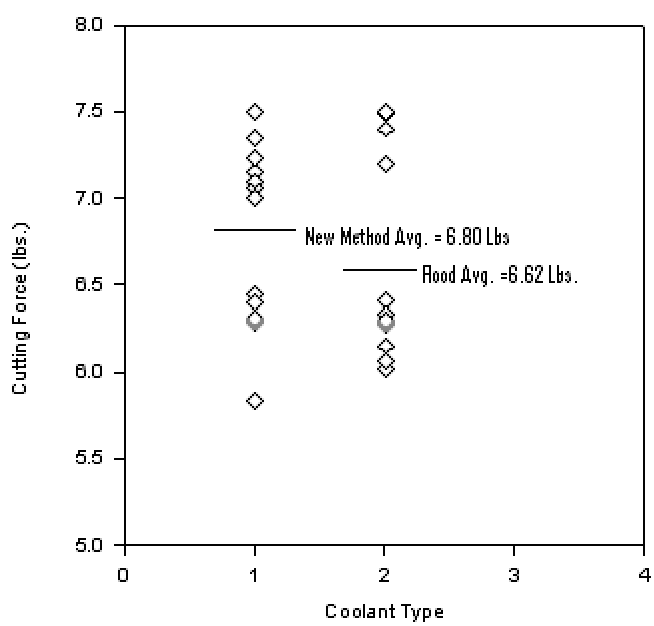

Figure 2 Scatter Plot Comparing Cutting Forces From the New System and Flood Cooling

The t distribution was again used to determine the statistical significance of the difference between means. A two sample t-test was performed using the cutting force data from the new system and from flood cutting. The two tail P-value of 0.42 indicates that the slight difference between cutting force means is not statistically significant.[13] A P-value of 0.05 or less would normally be required to indicate a significant differences between means. The information from the t-test along with the scatter plots indicate that cutting forces from the new system are very similar in magnitude and distribution to those from flood cutting. Table 2 summarizes the data analysis from both series of cutting force tests.

Table 2 Summary of Cutting Force Information

Cutting Fluid Method	Mean RMS Force	P Value (utilizing t-test)	95% Confidence Interval (difference between means)
Dry	5.13 lbs		
Proposed Method	4.51 lbs	$1.6x10^{-12}$	0.630 +/- 0.127 lbs.
Traditional Flood	6.62 lbs		
Proposed Method	6.80 lbs	0.42	None

4. RESULTS

Summary. In this research an alternative coolant/lubricant application system has been developed. This system uses a biodegradable vegetable oil-based fluid, which greatly decreases the cost of regulatory compliance. The high subsonic air stream used in this system provides for good heat transfer while the small amount of vegetable oil provides lubrication. Fluid flow analysis indicates that a high velocity air stream as used with the new system could be at least as effective as free convection water which is associated with traditional flood cooling.

Conclusions. The new system was found to perform favorably as compared to other coolant/lubricant application systems and was shown to reduce resultant cutting forces by at least 10% as compared to dry cutting. When evaluated against a traditional flood system, the resultant forces from the new system were found to be statistically indistinguishable from those resulting from flood cutting.

Based on experimental results and statistical analyses, proof of concept for the new system was clearly established. This application system has demonstrated strong potential as an alternative metalcutting coolant/lubricant system.

Future Research. After establishing the new system's comparative performance potential, the next step in this research will be an iterative factorial analysis. Various parameters of the new system will be evaluated at different levels to establish a region of optimal performance. The parameter settings associated with this region will then be reported. Future research is also planned to evaluate additional organic oil-based fluid formulations. Mixture analysis experiments will be performed using the new application system in an effort to develop a more effective mixture.

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