A fluid flow simulation in the cooling systems of the metal cutting process

I Olaru
“Vasile Alecsandri” University of Bacau, Faculty of Engineering, Department of Industrial Systems Engineering and Management, Calea Marasesti 157, Romania

E-mail: ionelo@ub.ro

Abstract. During processing of cutting materials due to friction between tools and materials, a considerable amount of heat is released to the development of high cutting forces. Excess heat from the cutting area may aggravate the cutting process, the surfaces resulting from the cutting process may have a several defects. By simulating the flow phenomena on the computer, different forms of nozzles that send the liquid to the work area are studied to make the cutting process more efficient. This study attempts to simulate the flow of cooling fluid in an integrated system and also to quantify the amount of heat entering the workpiece during the machining processes. Simulation using the finite element method for the machining area was done for conventional cutting processes, taking into account the environment. The simulation also takes into account the convective cooling of the working fluid in the MQL system. By assessing the cooling efficiency of different lubrication conditions of the coolant, based on their convective heat transfer coefficient and the temperature in the cutting zone.

1. Introduction

Various processes of mechanical processing of the metallic elements generate various products that can be environmentally polluted. It is known that a cutting fluid is used in the machining process to improve the life of the cutting tool as well as the integrity of the surface resulting from the machining process [1].

Various cooling systems have been developed over time that use different cooling fluids to remove this heat in excess. Also, the cooling liquids resulting from the cutting process must be removed after the machined parts have been made. Various studies have been carried out to reduce the amount of liquid introduced into the cooling system, but without diminishing the cooling/lubrication effect of these fluids. The design of special nozzles to obtain the best possible distribution of the cooling agent in the cutting area leads to the development of MQL performance systems (minimum quantity lubrication). Choosing fluid or even working fluids is very important [2, 3].

Fluids that are used to cool/lubricate the processing area generally contain potentially harmful pollutants or potentially harmful chemical constituents. Prolonged exposure of the operator to such a cooling system during operation may result in respiratory irritation, asthma, pneumonia, dermatitis, cancer, etc. In general, attempts are made to remove oils of petroleum origin as far as possible and to introduce vegetable oils into cooling fluid emulsions [4-6].

Particular care is taken with the energy consumption of such cooling systems because it is known that increased consumption is related to environmental pollution, because almost all methods of energy generation pollute the environment in some way. By optimizing manufacturing processes aims
to discover and use their own methods for creating an environmentally friendly manufacturing process. An inefficient manufacturing process leads to rapid deterioration of the cutting tool, requiring interference correction or premature replacement, thus adding additional costs in the process [7].

Many attempts have been made by various researchers to reduce cooling/lubrication consumption in cutting process, generally resulting in: the development of new cooling fluids, the development of efficient cooling systems, the development of new cooling fluids, machine tools integrated with the cooling system, optimization of the processing process, development of environment-friendly materials. Such an alternative to dry processing is the so-called system that uses minimal lubricating fluid (MQL), which involves the use of an air-oil mixture called an aerosol which is sprayed into the cutting [8].

2. Parameters of the cutting process

By way of research, a method can be developed which uses different comparisons of concrete cases to identify a concrete method of reducing the amount of cooling agent in the chosen cutting process.

Three main parameters can be considered for a good determination: the cutting force generated by the tool machine, the roughness of the surface thus obtained determines the degree of the workpiece and the cutting temperature that affects the dimensional precision and the life of the tool.

These methods can determine the amount of coolant, determining the effect on cutting energy, surface fineness, and processing temperature. At this time in addition to an optimization of the cooling surface quality respectively processed using a smaller amount of coolant must be taken into account environmental issues and economic issues associated with liquid cooling. In order to determine the efficiency of the cutting process, the average temperature, the specific cutting energy and the fineness of the resultant surface, several analyzes and comparisons are made for different amounts of coolant and various compositions [9].

In equation (1) the increase of the temperature of a tool due to the cutting process and the friction between the cutting tool and the workpiece is defined as the difference between the temperature at the beginning of the cutting operation (initial temperature $T_i$) and the temperature after a period of $n$ seconds (process temperature $T_n$).

$$\Delta T = T_i - T_n$$

(1)

The specific energy of cutting is defined as the energy per unit time or the stated energy per unit volume, as shown by the equation (2). Depending on the process conditions, it is the equation that most closely described as cutting process [9]:

$$E = \frac{F \cdot v}{f \cdot a} = \frac{F}{f \cdot a}$$

(2)

where $E$ is the cutting energy, $F$ is the cutting force (N), $v$ is the cutting speed, (m/min), $f$ is the feed rate (mm/rev), $a$ is the cutting depth (mm), is determined by the minimum processing margin. The feed rate is established with equation (3):

$$f = C_{SR} \cdot R_a^{e_5} \cdot r_e^{e_6}$$

(3)

In which the $C_{SR}$ coefficient depends on the main attack angle, $R_a$ is the roughness of the surface processed, $r_c$ the radius at the tool tip, $e_5$ and $e_6$ the roughness and radius exponent at the tip of the tool.

The cutting speed is determined by the equation (4):
\[ v = \frac{C_v}{T^n a^x f^y \left( \frac{HB}{200} \right)} \cdot k_1 \cdot k_2 \cdot \ldots \cdot k_9 \] (4)

where: \( k_1 \cdot k_2 \cdot \ldots \cdot k_9 \) are coefficients that depend on the cutting tool body section, the main active angle, the secondary active angle, the cutting tool radius, the cutting part material, the machined material, the way of obtaining the semi-finished products, and the shape of the release face. The coefficient \( C_v \) and exponents \( x_v, y_v \) have standardized values.

The Tukey method is based on honestly significant difference (HSD), being used when all sample sizes at factor level are equal. This procedure has the advantage of using a constant to test all pairs of processing means. HSD is expressed by an equation (5) of the form in which \( S^2 \) represents the mean square of the error with a reported degree of freedom and in units of the sample size [9].

\[ HSD = q(\alpha; v) \cdot \sqrt{\frac{S^2}{n}} \] (5)

where \( q(\alpha; t, v) \) is the percentage of the distribution of an interval of \( t \) independent observations with \( v \) of degrees of freedom and \( \alpha \) is the number of samples. If the absolute value of the difference between the two methods is higher than the HSD, then there is evidence that there is a significant difference between the two treatments.

3. MQL system and the choice of cooling fluids

In the case of the MQL cooling system, the aerosols are drops of oil dispersed in a pressurized air jet, the oil droplets are directly entrained by the air to the working area of the cutting tool, providing better cooling and lubrication.

Due to the divergent converging nozzle of the MQL cooling system immediately after the fluid leaves the nozzle hole, the jet begins to decompose into a conical spray at a certain angle, the jet being increasingly diluted downstream of the nozzle. If we look into the section of the formed jet, we find that most of the oil mass and larger and more concentrated droplets are close to the spraying axis, while the outside of the cooling jet contains less oil and much smaller droplets, figure 1.

\[ \text{Figure 1. Minimum Quantity Lubrication System.} \]

Droplet rates are maximum at the spray axis and they decrease in the radial direction due to interaction with ambient air. However, we find that the efficiency of the fluid jet is when it is 10°÷15° from the angle of the spray cone relative to the spraying axis.
The flow rate is approximately 100ml/h at a 5 bar air pressure. We find that in the spraying angle of 10°-15° most of the oil drops clump in the MQL cooling jet. All of these must be taken into account when selecting the angle of position of the cooling fluid spray nozzle relative to the workpiece in the chosen machining process. Optimization of the fluid jet as well as the cutting angle can be done experimentally by computer simulation. Depending on the cooling capacity, lubrication or cutting performance, liquids can be classified into [10]:

- **Aqueous solutions of electrolytes** - sodium carbonate, sodium and potassium silicate, etc., with very good cooling properties;
- **Hydrophilic soaps** - the active capillary substance may be a hydrophilic soap or different acids; corrosion inhibitors use trisodium phosphate and soluble glass; have good cooling, lubrication and cutting properties;
- **Oil-water emulsions** - prepared from automatically emulsifying mixtures, include water, active capillary substances, emulsifiable mineral oils and corrosion inhibitors; have good cooling, lubrication and cutting properties;
- **Activated emulsions** - they also contain more active capillary substances with higher affinity; are formed of water, active capillary substances and emulsifiable mineral oil; the addition of colloidal graphite in water increases the lubricating properties; these emulsions have very good lubrication and cutting properties and good cooling capacity.

In the preparation of the emulsions the best results are obtained with softened water; the preparation is made by mechanically agitating the oil-water mixture by introducing the oil into water; warm water is preferred at 300°C; the duration of use of emulsions with bactericidal additions may reach six months; it is not recommended to use the emulsion in the tanks of the machine tool [11].

The position of the nozzle and its profile are currently based on the three main parameters: the velocity of the fluid jet is selected in accordance with the rate of the cutting process, the nozzle is positioned as close as possible to the cutting area. The fluid jet will flow in a tangential direction to the cutting area, the angle being chosen depending on several factors of the machining process. Using the mixing inside nozzle equipment, the pressurized air and the lubricant are mixed into the nozzle through a mixing device, as shown in figure 2. The lubrication is obtained by the use of lubricant, while a minimal cooling action is achieved with the pressurized air that reaches the cutting surface [12].

![Figure 2. MQL type cooling device.](image)

The cooling mixture is mixed in the first chamber connecting the two inlet nozzles to both the coolant and the pressurized air. The mixture thus formed is passed through a convergent nozzle and sprayed as a jet to the cutting zone.

4. **Results and discussion**
The flow generator and fluid feeding system are developed depending of jet flow parameters: pressure, flow rate and cooling distance (the distance between nozzle and cutting zone) are controllable [13, 14].
The flow goes through a nozzle and mixes with air as another one-component, hence, it has different constituents at different locations in case of machining 6061 aluminum alloys at different cutting depths.

The experiments were conducted under different settings of spindle speed, feed rate, cooling technique, and cutting tool material. Conventional cooling (flood coolant), dry and MQL were used as the cooling technique. MQL was applied at flow rate of 5 ml/min at flow rate of 1,000 ml/min. A solution containing boron oil and water (ratio of boron oil/water = 1/10) was used for MQL and water for flooded technique. The cutting fluid in MQL was pulverized by means of a paint spray gun and an air compressor at 5 bars and was delivered to the interface of work piece-cutting tool. The study was carried out on an end mill with 10 mm diameter as cutting tool and 6061 aluminum alloy with 10 mm thickness as the work piece material.

If we look at the graphs that give the cutting element's flanks wear on the cutting time, we will notice that the MQL system is located midway between the dry and flooded processing, figure 3.

In the same way, we can say that for the surface temperature gradient plotting according to the depth of cutting, the use of the MQL system implies an intermediate classification between the graph for dry processing and the flooded process with coolant figure 4.

![Figure 3](image1.png)  ![Figure 4](image2.png)

Figure 3. Flank wear of the tool reported to cutting time for dry, flooded and MQL systems.

Figure 4. Temperature in depth of cutting for dry, flooded and MQL systems.

If we analyze the flow of fluid as a whole we see that a significant improvement compared to the dry method is the cooling in cutting zone with the cold air, however the MQL system based on a mix of coolants improves the better life of the tool reaching a degree of wear much lower compared to other methods cooling. This can be explained by a suitable choice of the method for cooling as well as the fluid used. The velocity of the jet flow has a directly influences for the lubricating and cooling effect.

We can say that, speeds of the cooling fluid are depending on the length of the nozzle analysis, it can be seen that the speed has a value of approximately 200 m/s in the first 15 section of nozzle, this increasing in the outlet of the nozzle at 450 m/s for the used MQL system. After exiting from the convergence-divergence nozzle, velocity of the fluid jet decreases proportionally with the length of fluid jet.

The study indicated an effectively performed the optimization of surface roughness in the milling operation with the MQL system for the multiple quality requests.

5. Conclusions

As can be seen from the study has been demonstrated that the use of an MQL system is advantageous in several ways. Analyzing the chart simulations for this type of nozzle can be seen as the MQL system with fluid jet allows a proper lubrication and cooling of the cutting area compared with dry and flooded cooling.
A smaller amount of fluid is important in terms of the economy lubricant, however using MQL system can be advantageous in milling processes. Due to launch velocity fluid jet can proper remove the resulted chips from machining process.

From analysis of comparison between different cutting methods graphs may be observed a lower traction force and lower friction coefficient in the case of using an emulsion based mixture of fluids reported at the various cutting depths for MQL systems, are recorded lower values of tensile and friction coefficient this leads to diminished of the temperatures from the cutting area for cutting depths and a better surface of the workpiece.

A minimal amount of lubricant may have a better impact on the environment and the health of the operator because the coolants in contact with overheated machined surface may develop a substantial amount of these gases that are not always beneficial to health.

6. References
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