A Thermal Analysis in Solidworks for the MQL Systems of the Metal Cutting Processes

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Abstract. Through the cutting operations of the different metallic materials, large cutting forces are developed, they depend on the material to be processed and on the cutting parameters. During the cutting operation, due to the friction between the tool and the material to be processed, an important amount of heat is released. As the friction between the elements is higher, the heat generated by the attachment can disturb the cutting process. If the temperature from the cutting process is higher than a certain value, the resulting surfaces may have a number of processing defects. In order to reduce the temperature value of the cutting process, different cooling systems have been developed over time that use a wide range of cooling liquids. Cooling liquids have a number of advantages and disadvantages, after the cutting process they have to be discharged and their negative influence on the environment to be minimal. Recent studies have attempted to reduce this amount of coolant by streamlining fluid flows. Systems that use minimal amount of lubricant or coolant are MQL (Minimum Quantity Lubrication) type. These systems have special nozzles so as to obtain the best possible distribution of the coolant in the cutting area, as well as a good mixing if different cooling liquids are used. This paper aims to study the cooling systems for the cutting processes, forms of nozzles to send the fluid in the working area, thereby thermal analysis, from the desire to use an efficient MQL system.

1. Introduction
During the machining operation, some forces occur between the tool and the workpiece, leading to the release of excess heat, to reduce it are used cutting liquids. From the literature it is known that the cutting fluid improves the life of the tool, at the same time improves the surface resulting from the cutting. While reducing processing temperature coolants helps to remove chips produced during cutting process and their removal from the cutting area [1].

In addition to these advantages, cutting liquids also have some disadvantages: due to their chemical composition, once a part of the liquid has been evaporated, which has been in contact with the hot area, a significant amount of gases can be released that can harm the environment. These liquids that remain in the processing area are also difficult to remove after the process is finished. Also, recycling is expensive. The gases emitted from the processing process can cause skin irritation and also lung disease to operators due to air pollution [2].

Due to these negative effects and strict environmental laws and policies, a research line has been developed to minimize the amount of liquid used, if it cannot be completely eliminated (due to its processing advantages). Costs related to the use of cutting fluids and recycling are often higher than labor costs [3].

Even if we were to pursue economic studies, dry processing without a cooling liquid is the most advantageous in terms of production costs and environmental impact, however, the frictional forces
and the heat generated in the manufacturing process can cause significant dimensional errors in the machined part, as well as the accelerated wear of the cutting tool [4].

A compromise would be widely accepted in the industry to use with minimum quantity lubrication (MQL). The cutting fluid for an MQL system should be selected not only on the basis of the main characteristics related to the cooling performance in the cutting process, but also on the basis of its secondary properties, such as biodegradability, oxidation stability and storage possibilities. Cutting processes that require the use of minimal amounts of liquid are those processes where the friction forces are high [5].

The MQL system proposes the use of cooling liquids for a minimum period of time, which are generally three or four times less quantitative than those used in flooded lubrication conditions [6].

There are documents that indicate that the MQL process is more efficient in a final cutting process. The advantage of this system is that the lubricant can reach faster and with higher pressure in the cutting area, in milling operations, compared to other classical methods [7].

The MQL system can use an air-oil mixture that can be used in low-power processing. This is because the film formed on the surface of the boundary instrument is not thick enough to support too large friction forces, but the oil MQL systems mixed with water droplets showed better lubrication performance under the same cutting conditions [8].

2. MQL cooling systems of machine tools

As was said before, the MQL systems were introduced in the processing processes to obtain safety, economic and environmental benefits, by reducing the use of cooling liquids or lubricants when cutting metals. As we can find in the literature, in general the cost of the cooling fluids relative to the total processing cost varies between 7 and 17%, while cost of the cutting tool is between 2 and 4% [9].

The MQL system, due to the reduction of the amount of lubricant used in metal cutting processes, significantly reduces the processing costs. Figure 1(a) show the way in which the cooling is performed during the cutting process and the way in which the nozzles with mixed cooling liquid are positioned. Figure 1(b) illustrates how the milling machine works.

![Figure 1. MQL type cooling device: (a) the cutting process, (b) cutting pattern.](image)

The MQL system uses very small lubricant flows, of the order ml/h instead of l/min, as in the case of conventional systems. At the same time, an MQL system ensures a good air / lubricant or water / lubricant mixture to be sent with pressure on the cutting surface. Generally, two different methods of mixing are used: mixing inside the nozzle and external mixing of the nozzle.

Using the mixing device inside the nozzle, the pressurized air and lubricant are mixed in the nozzle by a mixing device. The lubrication is obtained by using the lubricant, the liquid jet being sent accurately and the wet area being minimal, at the same time being the area with high temperatures [9].
Due to this method we observe the following advantages: sending the lubricant jet with precision and its distribution only in the problem area, the quantity of dangerous vapors is reduced, and the adjustment of the mixture is very easy to control. Method by mixing liquids outside the nozzle: the mixture is obtained in a mixing device positioned in a specific reservoir, in this case the lubrication between the workpiece and the tools can be achieved, the mixing method being not so important for the process itself just from the point of design view of the MQL system. Figure 2 shows an MQL system in which the liquid mixture is carried out inside the nozzle, the liquid used to be an air-oil mixture.

![Figure 2. Cooling systems of machine tools.](image)

A nozzle device is located before the flank of the cutting nozzle and another after that device in areas where is observed a high friction between tool and workpiece. For how can be lubricate this processed area depends on the correctness of the system used and the resulting processed surface. Height adjustable nozzles are used to be the best possible coverage area for further processing workpiece geometries.

3. Results and discussion

The flow generator and fluid feeding system are developed depending of jet flow parameters: pressure, flow rate and cooling distance (it is the distance between nozzle and cutting zone) are controllable. 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 steel St52-3 at different cutting depths, the chemical composition is presented in table 1.

![Table 1. Chemical composition (%) of steel St52-3.](image)

From the analysis of these graphs from figure 3 we can see that when are use a cooling system MQL type composed from emulsion of two fluids that oil and air is a noticeable improvement of all graphics processing analysis. The experimental installation consists of a universal milling machine. The extremely small amount of coolant was supplied by the MQL system during the 5-bar pressure experiment. The MQL system generates in the cutting area a fine oil particle, an oil-air mixture that is sprayed through an exhaust nozzle discharging the cutting oil to a level of 600 ml/h. The working material (50 × 70 × 12 mm) was made of St52-3 steel. The experiment was performed at the cutting speed of 225 RPM, at a constant feed rate and the cutting depth between 0.05 and 0.3. A completely water-soluble coolant was used as an emulsion in a volumetric concentration of 1:10.

Can be observe 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. 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.

Figure 3. Comparison between different cutting parameters: (a) Friction coefficient; (b) Cutting temperature; (c) Traction force; (d) Surface roughness.

The cutting temperature was measured using thermocouple and it was found to increase with an increase in the depth of cut, the cutting fluid mainly depends on heat convection to reduce the cutting temperature. 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.

4. Thermal Analysis with Solidworks

The two mechanisms of heat generated are friction and plastic deformation in the workpiece. The heat generated in the milling zone during MQL is transferred into the chip, the oil mist, the tool, and the workpiece. In the model, heat will be assumed to be generated at the tool-workpiece interface (global scale) and in the grain wear flat-workpiece interface (local scale). The average heat flux $q_t$, in the contact zone can be expressed as [8]:

$$ q_t = \frac{F_t V_c}{b l_c} $$

(1)

where: $F_t$ [N] is the processing force, $V_c$ [m/s] processing speed, $b$ [mm] thickness, $l_c$ [mm] the length of the heat affected area.

For this moving heat source model, the temperature rise in the workpiece is analyzed with Solidworks Thermal Simulation. Total heat flux can be expressed as:

$$ R = \frac{q_w}{q_t} $$

(2)
The heat flux that remains in the workpiece is denoted as \( q_w \).

The variation and calculation of convection heat transfer coefficients in the leading edge \( (h_l = h_a) \), contact zone \( (h_c) \) and trailing edge \( (h_t = h_b) \) are calculated from the derived equations.

In figure 4 is presented the geometrical dimensions and thermal model for the workpiece.

![Figure 4. Workpiece dimensions and thermal model.](image)

From a thermal simulation point of view, the material has the following thermal properties: thermal expansion coefficient 1.3 × 10⁻⁵ /K, thermal conductivity 200 W/m·K and specific heat 900 J/kg·K. The average temperature for an MQL system is 300°C.

The model was built by defining the nodes and elements of Solidworks. The advantage of such a finite element model of a solid model to help programming is that the loading step of the thermal analysis, figure 5 [10].

![Figure 5. Thermal analysis of the model.](image)

The graphs explain that at low processing depths the MQL system is not necessarily necessary, and an air- or water-cooling system can be used, but with the increase of the cutting depth an MQL system is better. At greater depths of cuts more heat is generated due to the higher frictional forces during processing, therefore large increases in temperature are recorded at the chip-tool interface. With simulations made in Solidworks this shows that an MQL system is much better to consider with increasing cutting depth, with greater efficiency than the other two classical systems under analysis.

This study was the influence thermal cutting tool on the workpiece. In front of the head of the cutting tool additional heat is generated which is transmitted by conduction workpiece material. When this heat is above a certain limit, as mentioned earlier, it can be harmful to the cutting process.

By the method of the finite element realized in the specialized program Solidworks it was possible to simulate and analyze the model from the thermal point of view, figure 5 showing an image of the temperature distribution in the piece. For a proper view, a section of it was made. This analysis was
performed when the tool is fully working, inside the edges of the workpiece, because then the maximum heat is released.

This heating in the contact area between the tool and the part can be controlled from a value point of view using an MQL type lubrication cooling system, namely the type of the one studied in the work with liquid mixture. In figure 6 the temperature diagram in the section area of the workpiece was captured.

5. Conclusions
As can be seen from the study has been demonstrated that the use of an MQL system is advantageous in several ways. A smaller amount of fluid is important in terms of the economy lubricant, however using MQL system can be advantageous in milling processes and not only. Due to launch velocity the fluid jet can 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.

From the thermal analysis is made in SolidWorks conclude that the cutting forces have a great influence in the entire process, the heat is diffused in the workpiece, which can have undesired effects without achieving an appropriate cooling. 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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