Influence of the cooling liquid on surface quality characteristics in milling

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Abstract. Cooling system and cooling liquid characteristics are among the main factors influencing surface quality and tool wear. The aim of this study is to analyse the effect of the cooling liquid, used in different concentrations and at different temperatures, on the quality of the surface layer processed by milling. In order to make this analysis a Minimum Quantity Lubrication (MQL) cooling device is used. Three different volumetric ratios were used to modify the concentration of the cooling fluid (25% water to 75% emulsion, 50% water to 50% emulsion, 75% water to 25% emulsion) and three different temperatures. The studies revealed that surface roughness can be correlated with the variation of the cooling liquid temperature while surface flatness can be correlated to both, cooling liquid temperature and concentration.

1. Introduction

Cooling and lubrication during machining operations are important factors that can determine the surface quality of the processed part. The cooling and lubrication liquids have the tasks: to lower the temperature of both the tool and the part during the machining process, and also to reduce the friction between the surfaces of the tool and the part. They represent also a means of transport for the evacuation of the chips.

A synthetic review of the role of the cutting fluids in machining operations is presented in [1]. The paper presents a model for the formation of fluid mist during machining and discusses its associated health problems. Comparisons are made between dry and wet cutting for different operations, and some strategies for the reduction or elimination of cutting fluids from several processes are presented.

In an effort to address the problems raised by the use of cooling fluids, a new cooling and lubrication method has gained a relatively large interest: minimum quantity lubrication (MQL). This method uses a flow of pressurized air to spray the cooling liquid in the form of fine droplets in the cutting area. An early investigation MQL of performance is presented in [2]. The study revealed, by comparison to the classic method of flood cooling, that although the consumption of lubricant is drastically reduced, the tool wear is comparable, surface roughness is equivalent, there is no significant difference between the cutting forces.

The effects and the mechanisms in (MQL) are examined by the means of an intermittent turning process in [3, 4]. The friction forces between the tool and the newly machined surface was measured. Different types of lubricants were used: synthetic ester and vegetable oil. The study has revealed the existence of a transition temperature, above which the lubricity disappears. In the case of vegetable oil the transition temperature is approximately 200°C.

A comparative study presents in [5] the effect of different cooling conditions in the machining of
an aluminum alloy by taking into consideration the cutting forces, surface roughness and tool wear. It was concluded that MQL can replace flood cooling in certain conditions, but a special attention must be drawn to the liquid constituents.

The effect of cutting parameters and cooling technique on surface roughness in milling is experimentally investigated in [6]. The study reveals that surface roughness is influenced by the volumetric concentration of the cutting fluid used in MQL, and that MQL is more effective than flood cooling at higher cutting speeds by decreasing the roughness.

The aim of the present study is to analyze the effect of cooling liquid used in different mixture ratios with water, at different temperatures, on the quality of the surface layer processed by milling, when MQL is deployed.

2. Experimental Procedure
The experiments were conducted on a CNC vertical milling center Rapimill 700 (figure 1). The workpieces made of Al 6061-T6 aluminum alloy were machined with a 50 mm diameter Sandvik CoroMill equipped with 5 uncoated carbide inserts. 6061-T6 is a high strength and high corrosion resistance aluminum alloy with a good workability, which makes it suitable for applications in aircraft and automotive industries, consumer electronics, and numerous others. The mechanical properties are as follows: the modulus of elasticity (Young) of 68.9 GPa, yield strength of 276 MPa, tensile strength 310 MPa, hardness of 107 HV. The chemical composition of the material is presented in table 1.

| Component   | Content [%] | Component   | Content [%] | Component   | Content [%] |
|-------------|-------------|-------------|-------------|-------------|-------------|
| Magnesium   | 0.8-1.2     | Silicon     | 0.4-0.8     | Zinc        | max. 0.25   |
| Copper      | 0.15-0.4    | Ferrum      | max. 0.7    | Titanium    | max. 0.15   |
| Chromium    | 0.04-0.35   | Manganese   | max. 0.15   | Aluminum    | 95.8-98.6   |

In order to assess the influence of the cooling conditions, cutting parameters were kept constant throughout the experiments, with the following values: the cutting speed $v_c$ of 314 m/min corresponding to a spindle speed $n$ of 2000 rpm, the feed rate $f$ of 900 mm/min, and the depth of cut $a$ of 0.15 mm.

The cooling fluid was applied using a SKF MQL system. A synthetic water miscible emulsion TS 30 PT was used for cooling. Three mixture ratios were used for the cooling fluid: 25% water with 75%
emulsion (liquid L1), 50% water with 50% emulsion (liquid L2), and 75% water with 25% emulsion (liquid L3). The cooling fluid was conditioned for three temperatures: 6°C, 12°C, and room temperature (20°C).

The temperatures during machining were monitored using a FLIR® A655 sc thermal vision camera and the Research IR® software. A TR-220 Innovatest® was used for surface roughness (Ra) measurement. The measurements were made parallel to the cutting direction and the results presented in this study represent the averages of three readings for each surface. Hardness was determined using a Ultramatic 2 ultrasonic hardness tester from Innovatest®, while flatness deviation was measured on a Tesa® micro-hite 3D machine.

A run with dry machining at room temperature serves for benchmarking the results of the other tests.

3. Experimental Results and Discussion

Surface quality was examined from the perspective of three parameters: surface roughness $R_a$, hardness (HV), and surface flatness deviation.

3.1. Surface roughness

Surface roughness affects the functionality of components and it can influence the resistance to corrosion, fatigue resistance, etc. The surface roughness values resulted from the tests are presented in table 2 and graphically illustrated in figure 2. The dotted line represents the value of surface roughness measured for the benchmark part, obtained from milling the aluminum alloy under dry cutting conditions at room temperature. A multiple regression analysis carried in Minitab® software has revealed that the variation of surface roughness cannot be correlated with the concentration of the cooling liquid, but only with the temperature of the liquid (figure 3). Surface roughness values decrease with the increase of cooling liquid temperature. An explanation of this result might be given by the fact that at higher temperatures, the coolant is less viscous so the cooling effect is more effective. A less viscous liquid is capable of a better penetration into the areas where the rake face and the flank face of the tool interact with the material reducing the friction forces.

![Figure 2. Surface hardness.](image)

3.2. Surface hardness

Surface hardness can improve wear resistance of the parts. The measurements of surface hardness are presented in table 3, while a graphical illustration is in figure 4. The dotted line represents the value of surface hardness that was obtained in the benchmark test. In most of the cases the hardness is over the level of the dotted line. The regression analysis has revealed that a correlation cannot be established between the variation of surface hardness and the two input parameters (the temperature of the cooling liquid and the concentration of the liquid).
Table 2. Surface roughness [μm].

| Cooling liquid mixture ratio       | Cooling liquid temperature [ºC] |
|-----------------------------------|---------------------------------|
| L1 (25% water, 75% emulsion)     | 0.32 0.34 0.23                  |
| L2 (50% water, 50% emulsion)     | 0.36 0.31 0.28                  |
| L3 (75% water, 25% emulsion)     | 0.32 0.31 0.23                  |
| Benchmark (dry cutting, 20ºC)    | 0.32                            |

Figure 3. Regression report.

Figure 4. Surface hardness.

Table 3. Surface hardness [HV].

| Cooling liquid mixture ratio       | Cooling liquid temperature [ºC] |
|-----------------------------------|---------------------------------|
| L1 (25% water, 75% emulsion)     | 148 122 108                     |
| L2 (50% water, 50% emulsion)     | 149 175 144                     |
| L3 (75% water, 25% emulsion)     | 185 109 138                     |
| Benchmark (dry cutting, 20ºC)    | 123                             |
3.3. Flatness deviation

Precision is an important feature for the quality of a part, therefore it should be carefully taken into consideration when cutting conditions are established. The present study has revealed that dry cutting used in the benchmark test produces the largest deviation from the flat shape of the surface. This can result from the fact that during dry cutting, the largest amount of the heat developed in the cutting zone is transferred to the part and the tool, but when MQL is deployed the heat is more efficiently eliminated. This is more obvious especially in the case where the cooling liquid was brought to lower temperatures. The recorded values of deviation are presented in Table 4 and illustrated in figure 6. The regression analysis showed that the deviation values are correlated with both, the cooling liquid temperature and the concentration of the liquid (figure 7).

| Table 4. Surface flatness deviation [µm]. |
|------------------------------------------|
| Cooling liquid mixture ratio | Cooling liquid temperature [°C] |
| L1 (25% water, 75% emulsion) | 6 | 2 | 2 | 3 |
| L2 (50% water, 50% emulsion) | 1 | 3 | 5 |
| L3 (75% water, 25% emulsion) | 4 | 1 | 3 |
| Benchmark | | 10 |
| (dry cutting, 20°C) | | | |

**Figure 5.** Regression report for surface hardness.

**Figure 6.** Flatness deviation.
4. Conclusions
The present experimental study has analysed the effect of the cooling liquids used in MQL on surface quality resulted from milling a 6061-T6 aluminum alloy. For this, three different concentrations were used for the cooling liquid by modifying the volumetric ratio between the emulsion and the water. Another studied parameter was the temperature of the cooling liquid, case where the liquid was brought to three different temperatures: 6°C, 12°C, and 20°C (room temperature). The results were also compared with the ones resulted from the dry cutting.

The following conclusions can be formulated:

- Surface roughness variation can be correlated with the variation of the cooling liquid temperature. As the temperature of the liquid increases, the surface roughness decreases.
- No correlation was discovered between surface hardness and the concentration of the cooling liquid or its temperature.
- Deviation from surface flatness can be correlated to both, cooling liquid temperature and cooling liquid concentration. The lowest values of deviation were found for the lower liquid temperatures.
- Generally, the quality of the surfaces resulted when milling is done with MQL is superior to dry cutting. This is because MQL assures a better heat dissipation and the reduction of friction between the surfaces of the tool and the processed material.

The study can be continued for different cutting parameters and also for different materials.

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