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# NUMERICAL STUDY OF THE INFLUENCE OF THE OIL MIST PARTICLE SIZES USED IN MQL BY INTERNAL CANALIZATIONS ON A SURFACING OPERATION

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**Abstract.** This paper proposed a numerical study of the Minimum Quantity Lubrication (MQL) design parameters effects outside a rotating tool. Parameters as particle sizes for different oil mist input device parameters (inlet pressures) as function of different canalization geometries have been determinate on a previous experimental part, which are not presented here. The parameters thus identified were integrated as boundary conditions for the numerical simulation of a rotating tool during three milling surfacing processes (three different cutting velocities) with different canalization orientations. The chip removal is not considered here. Only the numerical effectiveness of the minimum quantity lubrication is taken into account. The main goal of the oil mist is to spray the cutting edge to ensure a good lubrication on the tool-chip contact area and to determinate the optimal cutting parameters. The simulations highlighted the impingement of the different oil particle sizes on the tool carbide inserts. A volume per unit area and a mean distance of the oil scatter from droplet impingements relative to a global virtual area from tool/chip interface were considered. The global virtual area was taken as function of the feed rate, for three cutting velocities. The Taguchi method is applied in order to optimize numerical design parameters in finishing conditions as function of those different parameters. The minimum quantity lubrication design parameters evaluated are canalization orientations, inlet pressure, feed rate and particle sizes in cutting velocities. The analysis shows that Taguchi method is suitable to solve this numerical problem. The results shows that the optimal combination for a high lubrication performance at high cutting speed is based on high feed rate, with high canalization orientations and mean particle sizes.

## 1 INTRODUCTION

Finishing process in milling is the most important operation to ensure steady state quality, especially on surface roughness. At High Speed Machining (HSM), the chip was subjected to strong elastoplastic strains. The local stresses obtained on the cutting edge, increased the temperature and enable the sticking phenomena. [1]. Some experimental studies have advocated the use of the minimal fluid process and have underlined its benefits. Lubrication has a significant effect on these machined surface characteristics. The two-phase "air + oil" mixture has significant influence on the work piece versus carbide tool thermo mechanical behaviour. The pressurized oil mist sprayed on the cutting edge avoids the sticking phenomena highlighted by [2]. Temperature decreasing during machining, really good finishing surface and exceptional tool life time were largely obtained with minimal fluid coolant compared with dry or flood lubrication process [3-5]. All these parameters ensured with the minimal fluid process lead to high production rate.

All studies to date have focused on external minimal fluid coolant process. Some authors showed the influence of the minimum quantity lubrication cooling with external nozzles in milling [6], in drilling [7] or in turning process [8]. Tool elaboration with inner canalizations answered to large-scale industries production request. The geometry of the inner canalizations depends on different parameters (inlet pressures, cutting speed) and is not easy to determinate as the external spray nozzles. Several phenomena appear during the tool rotation and the small particle size of the oil mist has to be preserved [9,10]. Moreover, the lubrication is only efficient for oil included on the tool/chip interface calls "cutting area". The objective is to optimize parameters to have the maximum of oil quantity in the defined-cutting area and this volume has to be the closest to the cutting edge. To the complexity to reach the right conditions of micro spray efficiency because of the large amount of parameters, Taguchi method is used in this study. This method is largely used for reducing time for experimental investigation and investigating the effects of multiple factors on performance [11]. But this method is exceptionally used here in this numerical study.

This paper presents a study of the effectiveness of the minimal lubrication coolant in a numerical surfacing milling machining simulation in different cutting velocities. A first step of numerical simulation with a specific surfacing tool is presented. Different inner canalization orientations, inlet pressures and contact area depending on feed rates as function of the cutting velocities which have significant effects on micro spray efficiency on the cutting edge have been considered. Moreover, different particle sizes found in previous studies, which have significant effects, are considered [9]. All these parameters are taken into consideration to find a combination of milling parameters to achieve high micro spray performance based on oil mist quantity and the mean distance of the micro spray to the cutting edge. The chip removal is not considered because of its complex physic. Only the contact area is considered to simulate the chip removal. Taguchi method is used, in a second step, in order to optimize the cutting design parameters. The main objective is to find combination of cutting design parameters to reach a large volume per unit area of oil and small mean distance of the mist impingement to the cutting edge.

## 2 SIMULATION TECHNIQUES

All the simulations were in steady state conditions. The flow motion is ensured by the continuity and momentum equations with the standard $k$-$\varepsilon$ turbulent transport equation, for the two-phase flow. The Lagrangian multiphase flow is used to simulate the particle tracks of the oil mist [9]. Finally, a Motion Reference Frame (MRF) is used in the steady state condition to ensure the rotation of the milling tool and the diphasic mixture. An in-place interface is defined to separate the motion area (milling tool) and the outlet area. The motion modeling affects the continuum transport equations as a body force due to the system rotation in the momentum equations, depending on the rotational velocity. Boundary conditions are taken from experimental part: i.e. inlet pressures oil mist characteristics, particle sizes and oil flow rates. Initial conditions are a relative external atmospheric outlet pressure ($P_o = 0.1\ MPa$) and different cutting velocities (*Vc = 1256, 2513 and 5026 m/min*). The wall boundary interaction mode for the Lagrangian phase is set to rebound. The surface roughness for the wall region is taken as smooth. The main goal of this section is to define optimize parameters, such as: inlet pressures, canalization orientations, and cutting area from the feed rates at different cutting velocities, with the effect of the particle size. This section gives the parameter values and the tool-chip contact areas to collect data which are analyzed for the Taguchi optimization process.

### 2.1 Numerical milling prototype

Figure 1 showed the studied tool. It is consisted of seven carbide inserts with a diameter *D= 80 mm*.

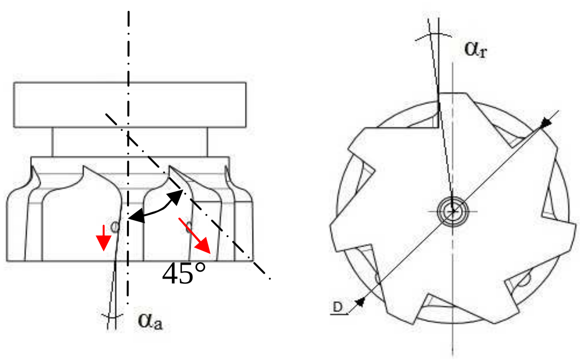


**Figure 1:** Illustration of the milling prototype and its geometric parameters.

The main goal of this prototype is to be used in a minimum quantity lubrication production line. A main canalization was drilled in the center of the tool as well as small canalizations (ramifications) in the sides to ensure the oil mist spray on each insert cutting edge (red arrows on figure 1 show the direction of the spray). The secondary canalizations (ramifications) were oriented at *45°* relative to the vertical axis (Figure 1). As the canalization orientation is a significant parameter, *45°*, *60°* and *75°* oriented canalizations are considered, for further calculations.

## 2.2 Surface areas

The tool chip contact area is determined by the cutting depth (*Ap*) and contact length ($l_c$) as the chip slide on the carbide tool. [1] summarized the different contact length models as function of work piece material and the cutting speed.

Thus, the studies of [12] allowed calculating the contact length with the following equation (Eq 1):

$$a = t_1\left[t_2\left(\frac{1-\tan\alpha_a}{t_1}\right)+\frac{1}{\cos\alpha_a}\right] \tag{1}$$

where $t_1$ is the undeformed chip thickness, $a = t_2$, $t_2$ is the chip thickness and $\alpha_a$ the rake angle. For tungsten carbide tools, Stephenson [13] proposed the following relation (Eq 2)

$$l_c = 1.75\, t_2 \tag{2}$$

The chip formation is created by successive tooth passes, in milling process. The chip size is evaluated as function of the tooth position, but whatever the rotation compared to the work piece, a maximal chip is created. Thus, the remove material configuration is considered as continue (as in turning process). Equations *1* and *2* can be used to have the contact length. The rake angle $\alpha_a$ is usually used for turning configuration, but the radial rake angle $\alpha_r$ has to be considered here, in milling process (see on figure 1).

## 2.3 Cutting parameters

Feed rate $f_z$ (*mm/rev*) and thus cutting areas $S_i$ (*mm²)* are variables for specific cutting velocities. Due to its large range of use, three cutting velocities were considered such as *Vc = 1256, 2513 and 5026 m/min*. These cutting speeds show the use of the surfacing tool on a wide range of materials. For this kind of surfacing tool, and the different finishing configurations, the cutting depth ($A_p$) is set to *0.5mm*. Inlet pressures and particle sizes were taken from previous experimental study, which consisted on characterizing the oil mist [14].

The following table 1 summarises data of the different variables used in this study:

**Table 1:** Variable data used for the analysis of the optimization.

| *Vc (m/min)* | $P_{inlet}$ *(MPa)* | *Fz (mm/rev)* | *Contact area (mm²)* | *Canalization orientations (deg°)* | *Particle diameters (µm)* |
|---|---|---|---|---|---|
| *1256* | *0.03* | *0.05* | $S_1$*=0.739* | *45°* | *1* |
| *2513* | *0.077* | *0.01* | $S_2$*=1.479* | *60°* | *10* |
| *5026* | *0.1* | *0.015* | $S_3$*=2.217* | *75°* | *100* |

However in this study a full factorial design is used to study the influence of minimum quantity lubrication coolant design parameters (Canalization orientations, Particle diameters and Inlet pressure) on milling process finishing (feed rates and cutting speeds) like an average length and an oil quantity volume per unite area.

## 2.4 Numerical results

Numerical simulations were carried out for each feed rate, inlet pressures, canalization orientations and each cutting velocity, which represent, respectively, *3x3x3x3 = 81* simulation runs.

Figure 2 shows an example of the particle impingements on the insert for *Vc = 5026 m/min*, *0.03 MPa* inlet pressure and *45°* oriented canalization. The "x" axis represents the total insert width. The insert height is represented by the *"y"* axis. Linear regression is done from the scatter plot to have the trend of the main flux for each particle size impingements (straight lines on figure 2).

Figure 2 shows also details about the contact areas *S1*, *S2* and *S3* considered for this study. They depend of the cutting depth *Ap* and the calculated contact length *lc* from each feed rate (section 2.2). The two evaluated parameters taken into consideration are: (i) an average length and (ii) an oil amount volume per unite area.

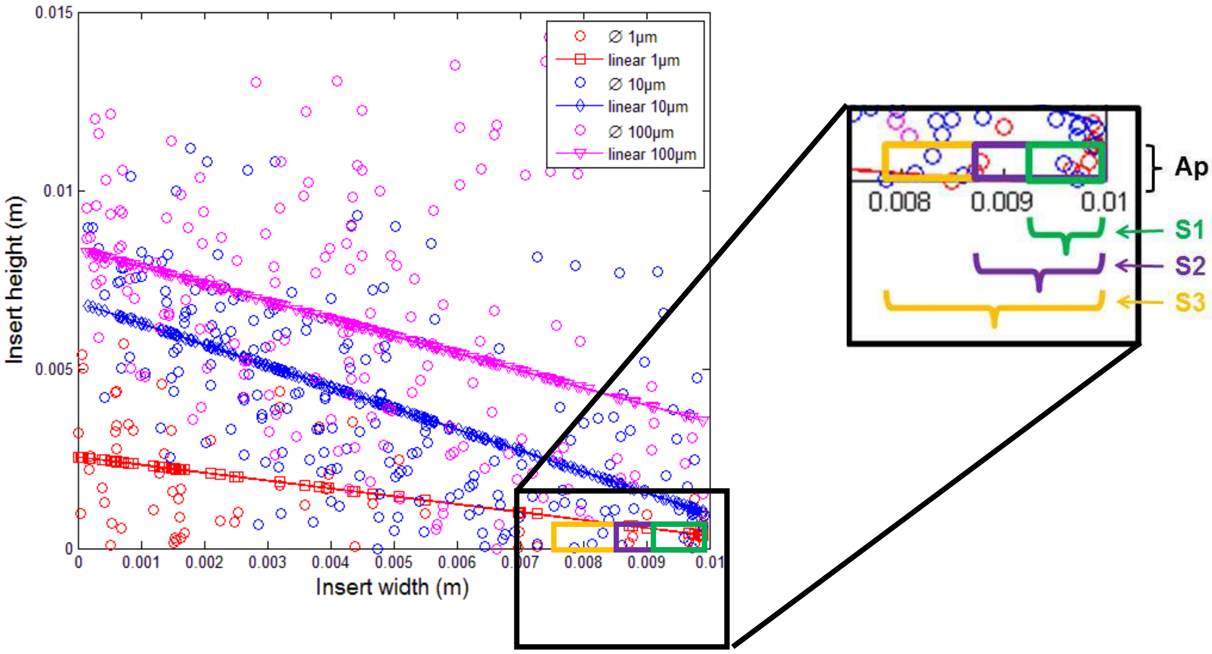


**Figure 2:** Example of the results showing the particle impingement a) on the insert and b) on the different tool-chip contact areas ($S_1$, $S_2$, $S_3$), for *Vc = 5026 m/min* and $P_{inlet}$ *= 0.1 MPa* inlet pressure, for 45° canalization orientation.

For the first one, it is important to know where the particle impingement is and then an average particle is calculated in each area. The distance from this average particle and the cutting edge (insert width=*0.01m* and insert height = *0m*) is measured. More the distance closes to zero, better the results.

For the second one, oil amount is recommended for good lubrication efficiency. Then, the number of particle is counted in each contact area. More the volume of oil per unite surface is important, better the results.

## 3 LINEAR REGRESSION AND ANOVA ANALYSIS

In many experimental conditions, it is possible to represent independent factors in quantitative form as given by Eq. (3). Then these factors can be represented of as having a functional relationship or response as follows:

$$Y = \Phi(x_1, x_2, \ ..., x) \pm e_r \tag{3}$$

Between the response $Y$ and $x_1, x_2, \ldots, x_k$ of $k$ quantitative factors, the function "$\Phi$" is called response function. The residual "$e_r$" measures the experimental errors. For a given set of independent variables, a characteristic function is responded. When the mathematical form of "$\Phi$" is unknown, it can be approximated satisfactorily within the experimental region by a polynomial function. In the present investigation, a linear regression has been applied for developing the mathematical model in the form of multiple regression equations for chosen parameters. In applying the regression the independent variable was viewed as a function to which a mathematical model is fitted. The Multiple Linear Regression method is the most informative method of analysis of the result of a factorial experiment. The second order polynomial (regression) equation with interaction used to represent the response surface $Y$ is given by [15]:

$$Y = b_0 + \sum b_i x_i + \sum b_{ij} x_i x_j + e_r \tag{4}$$

where $b_0$, $b_1$, $b_2$, etc., are the linear term coefficient and $b_{ij}$ the interaction term coefficient to be estimated by the method of least squares. The resolution of this full factorial design allows us to estimate all the main effects and interactions. Note that run orders are used randomly during the experiments.

In order to ensure the goodness of fit of the models obtained in this study, the adequacy of the model was tested using the analysis of variance (ANOVA) technique. The test for significance on individual model coefficients was performed, the calculated F-ratio of the model does not exceed the standard value and the calculated R-ratio of the model is above the standard value for a desired *95%* level of confidence.

**Table 2 :** Parameters and levels used in the study.

| *Parameters* | *Unit* | *Levels* | | |
|---|---|---|---|---|
| *Canalization orientations (Co)* | *degree* | *45* | *60* | *75* |
| *Inlet pressure (Ip)* | *MPa* | *0,03* | *0,077* | *0.1* |
| *Particle diameters (dp)* | *µm* | *1* | *10* | *100* |
| *Feed rate (fz)* | *mm/rev* | *0.05* | *0.01* | *0.015* |
| *Cutting velocity (N)* | *m/min* | *1256* | *2513* | *5026* |

# 4 RESULTS AND ANALYSIS

The objective of the ANOVA technique is to find parameters which have significant effects on design geometry for optimizing micro spray effects. In this perspective, the average length and the oil amount volume per unit area are analyzed. The actual data for the average length and the volume per unite area is summarized in *81* numerical runs, considered 243 values with considering the three particle sizes.

## 4.1 Influence on average length ($L_{average}$)

The second-order empirical model of selected minimum quantity lubrication design parameters on average length was calculated. The second order model can be expressed as a function of cutting and design parameters (*Co, Ip, dp fz* and *N*) with their regression coefficients presented in table 3.

The direct and the interaction effects were analyzed and by selecting the backward elimination procedure to automatically reduce the terms that are not significant, the resulting ANOVA analysis for the reduced second-order model for response ($L_{average}$) is given in Fig. 3 as histogram representation.

**Table 3:** Variable interactions with their regression coefficients, for the length average.

| *Variables* | *Coefficients* |
|---|---|
| *Constante* | *-3242695,49* |
| *N* | *137,6223* |
| *fz* | *24772019* |
| *Co* | *82573,3706* |
| *Ip* | *4650151,07* |
| *dp* | *17515,5568* |
| *N * fz* | *5308,2883* |
| *N * Co* | *17,6943* |
| *N * Ip* | *646,3352* |
| *N * dp* | *5,5793* |
| *fz * Aci* | *2477201,22* |
| *fz * Ip* | *90486926* |
| *fz * dp* | *781099,493* |
| *Co*Ip* | *301623,1* |
| *Co*dp* | *2603,665* |
| *Ip*dp* | *95106,3848* |
| *N * fz * Co* | *530,8288* |
| *N *fz * Ip* | *19390,0552* |
| *N * f *dp* | *167,3785* |
| *N *Co *Ip* | *64,6335* |
| *N * Co * dp* | *0,5579* |
| *N * Ip * dp* | *20,3799* |
| *fz *Co * Ip* | *9048692,59* |
| *fz *Co * dp* | *78109,949* |
| *fz *Ip * dp* | *2853191,43* |
| *Co * Ip * dp* | *9510,638* |
| *N * fz* Co *Ip* | *1939,0055* |
| *N * fz *Co* dp* | *16,7378* |
| *N *fz *Ip * dp* | *611,3982* |
| *N *Co *Ip *dp* | *2,038* |
| *fz * Co * Ip * dp* | *285319,139* |
| $N^2$ | *0,0165* |
| $fz^2$ | *495440261* |
| $Co^2$ | *5504,8925* |
| $Ip^2$ | *14366428* |
| $dp^2$ | *278,0251* |

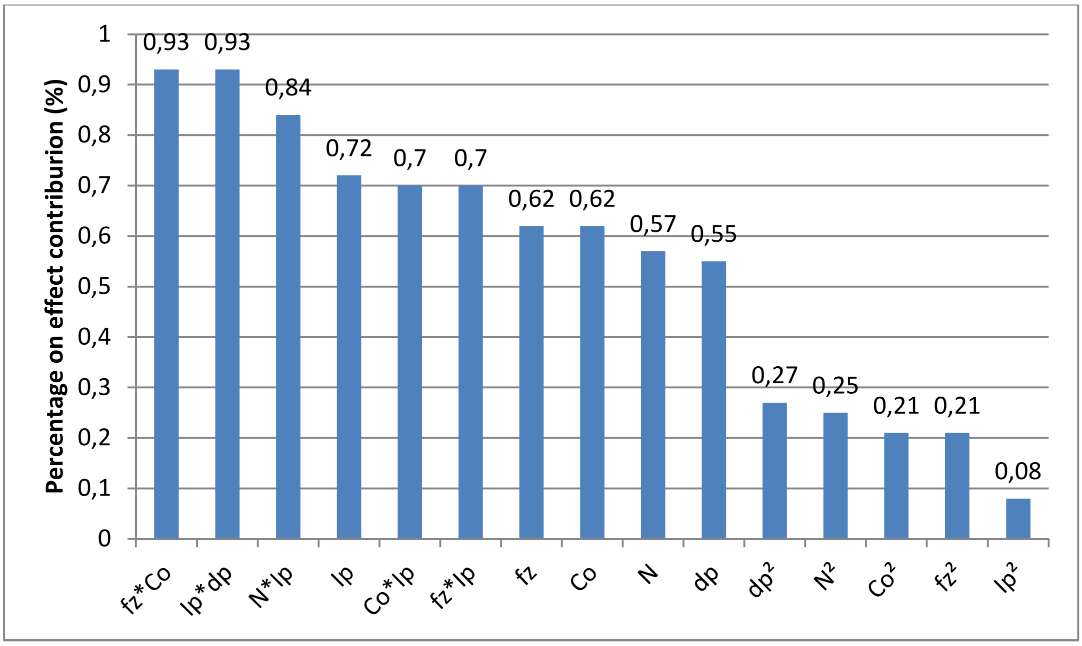


**Figure 3:** Histogram of the contribution of the effects for the average length.

The analysis of the contribution of the effects of the minimum quantity lubrication design parameters shows that the average length is more important with all parameters separately.

The contribution of the effects on average length must be taken carefully. Since the average length must be as small as possible, the study of figure 3 shows the contributions of some parameter effects which have minor impact on the average length. Thus, inlet pressure (*Ip*), canalization orientations (*Co*), the rotation speed (*N*) and the feed rate (*fz*) from the contact area have an inverse significant effects on the average length. Indeed, large particles are heavier and are sprayed far away from the secondary canalizations. The large canalization orientations (*Co*) make easier the oil mist spray away from the canalizations. Another important point is the feed rate or the contact area. The analysis seems to show that particles impinge mostly in large feed rate (*fz*) (large contact area).

## 4.2 Influence on oil amount volume per unite area (*Vs*)

The second-order empirical model of selected minimum quantity lubrication design parameters on oil amount volume per unite area was calculated. The second order model can be expressed as a function of design parameters (*Co*, *Ip*, *dp*, *fz* and *N*) with their regression coefficients presented in table 4.

The direct and the interaction effects were analyzed and by selecting the backward elimination procedure to automatically reduce the terms that are not significant, the resulting ANOVA analysis for the reduced second-order model for response ($V_s$) is represented on figure 4.

The analysis of the contribution of the effects of the minimum quantity lubrication design parameters shows that the oil amount volume per unite area is more important with large particles (*dp*).

**Table 4:** Variable interactions with their regression coefficients, for the oil amount volume per unite area.

| Variables | Coefficients |
|---|---|
| *Constante* | *0,0005* |
| *N* | *0* |
| *fz* | *-0,0037* |
| *Co* | *0* |
| *Ip* | *-0,0006* |
| *dp* | *0* |
| *N * fz* | *0* |
| *N * Co* | *0* |
| *N * Ip* | *0* |
| *N * dp* | *0* |
| *fz * Co* | *0,0002* |
| *fz * Ip* | *0,0028* |
| *fz * dp* | *-0,0001* |
| *Co*Ip* | *0* |
| *Co*dp* | *0* |
| *Ip*dp* | *0* |
| *N * fz * Co* | *0* |
| *N *fz *Ip* | *0* |
| *N * f *dia* | *0* |
| *N *Co *Ip* | *0* |
| *N * Co * dp* | *0* |
| *N * Ip * dp* | *0* |
| *fz *Co * Ip* | *0,0003* |
| *fz *Co * dp* | *0* |
| *fz *Ip * dp* | *0,0001* |
| *Co * Ip * dp* | *0* |
| *N * fz* Co *Ip* | *0* |
| *N * fz *Co* dp* | *0* |
| *N *fz *Ip * dp* | *0* |
| *N *Co *Ip *dp* | *0* |
| *fz * Co * Ip * dp* | *0* |
| $N^2$ | *0* |
| $fz^2$ | *0,082* |
| $Co^2$ | *0* |
| $Ip^2$ | *-0,0026* |
| $dp^2$ | *0* |

Contrary to the average length, the contribution of the effects has to been taken in the right sense Indeed, the maximum radius is *Ø100µm* and the calculated volume is raised with exponential three (cubic meter). The analysis of the effects suggests that the feed rate (*fz*) and more particularly the couple feed rate/oriented canalization have some effects on the oil amount volume.

High oriented canalization increases the particle spray efficiency on the carbide insert. Most of the particles impinge more precisely on the direction of the main flux on the insert. Whereas the feed rate or the contact area either the feed rate/particle diameter or the cutting velocity have no significant contribution of the effect on the oil amount volume per unite area.

In the above case studies, two contributions of the effects of the minimum quantity lubrication design parameters have been analyzed for the average length and the oil amount volume per unite area.

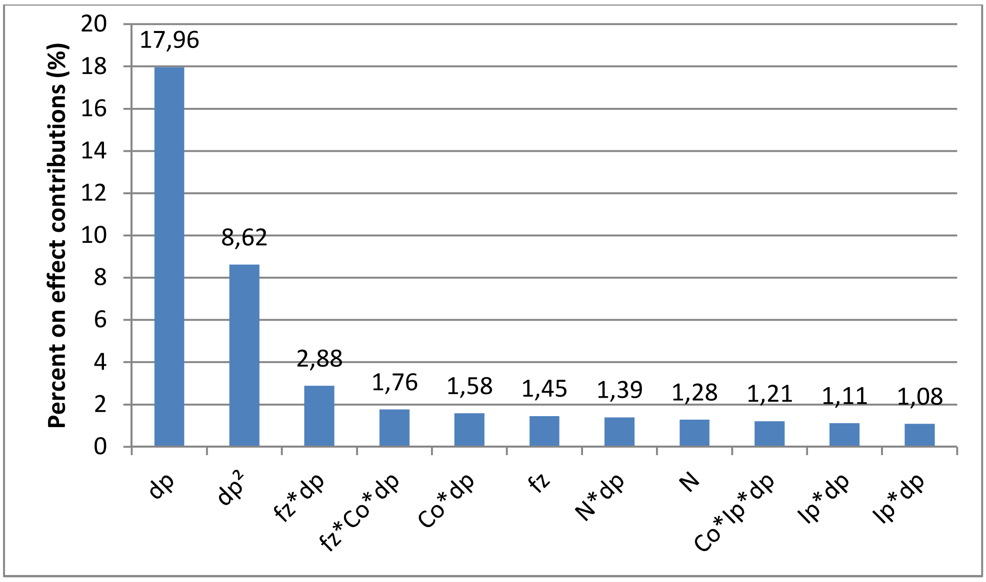


**Figure 4**: Histogram of the contribution of the effects for the oil amount volume per unite area.

The effects of the average length are taken as inverse function to have the minimum contributions of the parameters for the average length. The effect consists in having the smaller average length. This seems to be consistent since the inlet pressure (*Ip*) sprayed greater than *Ø10µm* particles closer to the cutting edge because of inertial effect [9]. In the same way the particles are sprayed far away from the output canalizations as the secondary canalizations orientation (*Co*) is more horizontal (about *75°*). This contribution is coupled with the increased cutting speed (*N*) which decreased the average length by spraying the particles closer to the cutting edge. The feed rate (*fz*) contribution consists in having larger contact area. Large particles are more likely to be in the highest contact area. Indeed, these particles increased their impingement close to the cutting edge thanks to the inertia initiated by the cutting speed (*N*) and the inlet pressure (*Ip*).

Whereas, the contribution of the effects for the oil amount volume per unite area is taken as the right interpretation. Particle diameter seems to be the most important parameter for the both effects. The increased feed rate (*fz*) coupled with the particle size (*dp*) increased the oil amount. The effect of the canalization orientation (*Co*) has an effect with the contribution of particle size and feed rate. All others parameters have too small effects before the particle sizes.

The analysis based on empirical functions allowed also getting optimal parameters. Thus, optimal predicted values are obtained for both criteria $L_{average}$ *and* $V_s$ as showed in table 5. Expectation values are given from the analysis. The cutting speed (*N*) and the orientation of the canalizations (*Co*) have to be larger, respectively *12000 m/min* and *60°* for both calculated values. Thus, the particle sizes have to be larger (closed to *Ø40µm*), which contributes to the efficient spray due to the inertia phenomena.

Whereas, the analysis of the feed rate (*fz*) and the inlet pressure (*Ip*) parameters gave dispersed values as from *0.16* to *0.05 mm/rev* and from *0.1* to *0.054 Mpa*, respectively.

**Table 5:** Predicted values for the study parameters from the ANOVA analysis.

| *Parameters* | *Calculated values for $L_{average}$* | *Calculated values for $V_S$* |
|---|---|---|
| *fz* | *0.16* | *0.05* |
| *Co* | *60.17* | *59.96* |
| *Ip* | *0.1* | *0.054* |
| *dp* | *42.52* | *37* |
| *N* | *12000* | *11666* |

## 5 CONCLUSION AND FUTURE WORKS

This paper has presented a numerical influence analysis of the minimum quantity lubrication design parameters in milling finishing process, with a Tagushi method.

A numerical rotating of a milling prototype has been considered in finishing configuration with minimum quantity lubrication process by inner canalizations, for different cutting speeds. The numerical simulation produced a scatter plot from the impingement of the different particle size on the carbide inserts. The average length (*mm*) and the oil amount per unit area ($\mu m^3/mm^2$) effects have been realized.

The study of the minimum quantity lubrication process optimization has been done as functions of different parameters:

- ✓ the canalization orientations (*Co*)
- ✓ the particle diameters (*dp*)
- ✓ the inlet pressure (*Ip*)
- ✓ the feed rate (*fz*) or the tool/chip contact area.
- ✓ the cutting velocity (*N*)

The main conditions for the analysis are the following:

- ✓ the particle impingement has to be close to the cutting edge (small average length)
- ✓ the oil amount has to be necessary in the tool/chip contact area (important oil amount volume per unite area).

The Tagushi analysis allowed determining the most influence parameters, the maximized parameters and the following conclusions are:

- ✓ the canalization orientation has to be high enough. This high orientation is wanted to improve the spray direction.
- ✓ the inlet pressure has to be high enough to make easy the oil mist spray on the cutting edge, because of cutting speed and the aerodynamic effect of the rotating tool.
- ✓ an average particle size gave by the analysis has to be closed to Ø40µm to facilitate the reach of the oil mist to the cutting edge due to their inertia.
- ✓ the cutting speed gas to be high enough, which is hope in high speed machining.

- ✓ the feed rate can be largely used, whatever the configuration. But small feed rate is better in High Speed Machining which limited the cutting forces and cutting temperature.

Parameter as cutting depth has to be considered, on future works. This numerical parameter optimization has to be taken carefully because the chip removal is not considered. The fluid/structure will be considered in future works which will represent the real machining conditions.

## REFERENCES


[1] Iqbal S. A., Mativenga P. T., Sheikh M. A., A comparative study of the tool-chip contact length in turning of two engineering alloys for a wide range of cutting speeds, *Int. J Adv Manuf Tech* (2009) **42**: 30-40.

[2] Bouzid Saï W., Ben Salah N., Lebrun J.L., Influence of machining by finishing milling on surface characteristics, *Int. J. of Mach. Tools and Manuf.* (2001) **41**: 443-450.

[3] Dhar N. R., Islam M. W., Mithu M. A. H., The influence of minimum quantity of lubrication (MQL) on cutting temperature, chip and dimensional accuracy in turning AISI 1040 steel, *J. Mat Proc Tech* (2006) **171**: 93-99.

[4] Lopez de Lacalle L. N., Angulo C., Lamikiz A., Sanchez J. A., Experimental and numerical investigation on the effect of spray cutting fluids in high speed milling, *J. Mat Proc Tech.* (2006) **172**: 11-15.

[5] Kalita P., Malshe A. P., Kumar S. A., Yognath V. G., Gurumurthy T., Study os specific energy and friction coefficient in minimum quantity lubirication ginding using oil-based nanolubricants, *J. Manuf. Proc.* (2012) **14**: 160-166.

[6] Rahman M., Senthil Kumar A., Salam M.U., Experimental evaluation on the effect of minimal quantities of lubricant in milling, *Int. J. Mach. Tools Manuf*. (2002) **42**: 539-547.

[7] Zeilmann R. P., Weingaertner W. L., Analysis of temperature during drilling of Ti6A14V with minimal quantity of lubricant, *Int. J. Mach. Tools Manuf.* (2006) **179**: 124-127.

[8] Kamata Y., Obikawa T., High speed MQL finish turning of Inconel 718 with different coated tools, *J. Mat Proc Tech.* (2007) **192**: 281–286.

[9] Duchosal A., Serra R., Leroy R., Static numerical simulation of oil mist particle size effects on a range of internal channel geometries of a cutting tool used in MQL strategy, Int. J. Eng. Sc. Inno. Tech. (2012) **1** (2): 43-59.

[10] Aoyama T., Development of a mixture supply system for machining with minimal quantity lubrication, CIRP Annals – Manuf. Tech. (2002) **51**: 289-292.

[11] Ghani J. A., Choudhury I. A., Hassan H H., Application of Taguchi method in the optimization of end milling parameters, *J. Mat Proc Tech.* (2004) **145**: 84-92.

[12] Bahi S., Nouari M., Moufki A., El Monsori M., Molinari A., A new friction law for sticking and sliding contacts in machining, Trib. Int. (2011) **44**: 764-771.

[13] Stephenson D. A., Assessement of steady-state metal cutting temperature models based on simultaneous infrared and thermocouple data, J. Eng. Ind. (1991) **113**: 121-128.

[14] Duchosal A., Leroy R., Vecellio L., Louste C., Ranganathan N., An experimental investigation on oil mist characterization used in MQL milling process, Int. J. Adv. Manuf. Tech., (2013) **66**: 1003–1014.

[15] Cochran W. G., Cox G., “Experimental design”, Asia Publishing House, 1962.