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CUTTING PARAMETERS IN THE MINIMUM QUANTITY LUBRICANT (MQL) MACHINING PROCESS OF A GEARBOX

J. Antonio Travieso-Rodríguez, Giovanni Gómez-Gras, Silvia García-Vilana, Ferran Mainau-Noguer
Escola Universitària d'Enginyeria Tècnica Industrial de Barcelona. Universitat Politècnica de Catalunya. Mechanical Engineering Department.
C/ Comte d'Urgell, 187, Barcelona
Spain

ABSTRACT
Today one of the top priorities in the machining industry is to increase or retain the profit margin through cost reduction. In addition, consumers are becoming increasingly aware of the impact that the life cycle of products has on the environment, at the time of their choice. So companies are required to research and develop sustainable processes or adapt existing ones. This research has been commissioned by a company that had conducted a feasibility study showing the need to replace the machining process based on cutting fluids in their production lines with the MQL lubrication system. This paper aims to find the key process parameters for machining different parts of an automobile gearbox. It particularly focuses on the definition of appropriate cutting parameters for machining under the new condition (MQL); through a statistical method of Design of Experiments (DOE). With recommended parameters significant improvements in the surface roughness of different machined parts are shown. Production costs are also reduced by decreasing spending on lubricants and by optimizing the cycle time that is reached under the new cutting conditions..
Keywords: gearbox, aluminium, MQL, DOE, cutting parameters

1. INTRODUCTION
The process of material cutting plays a key role in the development of parts. It is often conclusive to match the requirements that them must fulfill before being installed on mechanisms and machines.
Machining is not always successfully developed because there are multiple factors involved that determine the expected outcome in terms of part quality; thus increasing the number of rejected workpieces, and rising production costs. One of the factors that play a major role is the tool wear, which is accelerated by an increased temperature in the cutting area. The heat effect can be reduced by using a cutting fluid that functions as a coolant and/or lubricant. Nowadays, the use of these fluids in the machining industry is a cause for concern due to their high costs. Other drawbacks include the formation of bacteria that are harmful to the human health, the poor stability of fluids during the process execution, the high oil consumption, other consumable items required during the use of fluids, the water consumption for cleaning deposits and filters etc.
A solution to prevent the use of large quantities of cutting fluids is the minimum quantity lubrication (MQL). This system allows a faster chip evacuation compared with conventional cutting fluids [1], since pressurized air is used along with a small quantity of lubricant. Chips absorb most of the heat generated during the cutting process. Dhar, N.R. et al [2], showed that with MQL better surface roughness results are obtained, as compared to those reported by conventional processes with cutting fluids. In another study on this topic, Jiang, F. et al. [3] analyzed the effect of cutting parameters on the average surface roughness (Ra) under different cooling and lubrication conditions including MQL cutting, cutting fluid and dry cutting. These authors concluded that the surface roughness under MQL cutting conditions was the best one, whereas the surface roughness under dry cutting conditions was the worst one. Under the three cooling and lubrication conditions mentioned above, the study showed

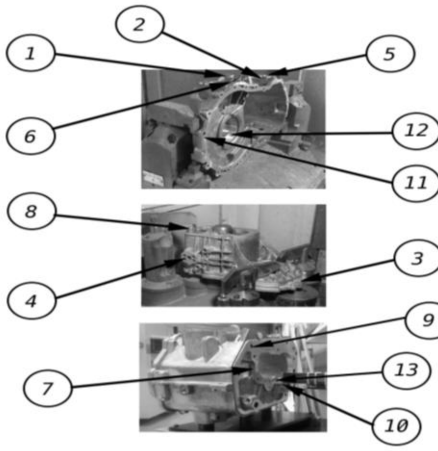
that the roughness Ra is sensitive to both the feed per tooth and the axial depth of cut – on the contrary, it is not sensitive to the cutting speed, nor to the radial depth of cut.

Braghini, A. et al. [4] studied the wear and lifetime of the tool, particularly in end milling of UNS S15500 stainless steel under different lubrication and cooling conditions. Based on the results obtained in this work, they reached some conclusions on how to mill the study steel, using coated carbide inserts under the cutting conditions assessed in the study. Firstly, cutting with pure oil allowed a longer lifetime of the tool than using an emulsion or dry cutting. But dry cutting showed a longer lifetime that emulsion cutting. Therefore, in this type of process, the tool cooling should be minimized and lubrication should be promoted. Secondly, the combination of adhesion and abrasion was the wear mechanism that led to the end of the tool life in the three cases. However, there are some differences in the way in which these mechanisms worked under each cooling/lubrication condition. When MQL was used, the pure oil helped to reduce the influence of this wear mechanism, and the lifetime of the tool was longer than in dry cutting.

As seen in all the aforementioned studies, the use of MQL is a good alternative to machining with cutting fluids or dry cutting. It is important to note that the cutting regime parameters and the way in which MQL is used produce an effect on the workpiece quality obtained. According to the parameter values, different results are obtained in terms of surface roughness and residual stress. Therefore, to establish a system based on the MQL machining, it is necessary to decide which are the main parameter values to be used during the machining process itself, since manufacturers of the tools used, do not provide these data in their catalogues. Hence the industrial relevance of the study that is developed in this paper. After all the analysis, the main purpose of this paper is to study the appropriate cutting parameter values to be used in the machining operations of different parts of an automobile gearbox with the MQL lubrication system. So far these operations were performed using a conventional lubrication system. Through a feasibility study, the gearbox manufacturer decided to replace it with a MQL System. For this study, a series of experiments aimed at obtaining the best results on each surface during specific operations were performed. The Design of Experiments (DOE) Box-Behnken technique was used to try to minimize the required number of tests to be run. Suitable values for each process parameter were eventually obtained.

2. METHODOLOGY

The gearbox whose manufacturing process was studied in this work, is shown in Figure 1. The first step in undertaking this study was the selection of the operations that have a greater impact on the machining process, mainly due to their duration. They are all milling and drilling operations. These operations are listed in Figure 1. Parameters under consideration were then determined; their variation might affect the results of the cutting quality. In this case, we decided to analyze them as variables; cutting speed *Vc*, tool feed rate *f* and oil pressure *P*.



Op.	Process
1	Milling 11F28
2	Milling 54°
3	Drilling Ø10H7
4	Milling Ø20H8
5	Contoured with Ø57H7mill
6	Drilling Ø8.5
7	Milling Ø20
8	Plan with 3 lips Ø12mi
9	Milling Ø7.1
10	Drilling Ø6.5

Figure 1. View of the gearbox and list of the machining operations selected for the study

For the three above-mentioned variables, minimum, mean, and maximum values were selected to carry out the experiments. In Table 1, an example of the selected values to conduct the experiments in operations 3and 5 is shown. The operations were: Operation 3: Drilling, done by a ø10H7 drill. The hole requires roughness to be Ra≤6μm. Operation 5: Contouring of a cylindrical surface, done by a Ø57H7 mill. In this case, specifications require roughness to be Ra≤6μm.

Table 1. Range selection for each parameter in operations 3 and 5

	Operation 3			Operation 5		
	Low	**Central**	**High**	**Low**	**Central**	**High**
***Vc* (m/min)**	226.4	254.7	383	537	644	751.8
***f* (mm/min)**	5000	6000	7000	600	720	840
***P* (bar)**	6	8	10	6	8	10

With both this parameter definition and the DOE technique, Box-Benhken for each study operation, experiments to be performed were planned. Using the Minitab software and combining parameters, an experimental design which consisted in performing 15 experiments for each operation, was developed. To evaluate the surface quality of experiments, the surface roughness Ra in a direction parallel to the milling feed rate was measured. Results were entered into the aforesaid software and the statistical accuracy of experiments was then analyzed, resulting in 95% confidence level. Results for operations 3 and 5, for example, can be seen in Tables 2 and 3.

Table 2. Results obtained in each experiment op. 3

Exp.	*Vc* m/min	*f* mm/min	*P* bar	*Ra* µm
1	226.4	5000	8	0.390
2	283	5000	8	0.508
3	226.4	7000	8	0.542
4	283	7000	8	0.369
5	226.4	6000	6	0.392
6	283	6000	6	0.493
7	226.4	6000	10	0.217
8	283	6000	10	0.296
9	254.7	5000	6	0.155
10	254.7	7000	6	0.231
11	254.7	5000	10	0.306
12	254.7	7000	10	0.202
13	254.7	6000	8	0.274
14	254.7	6000	8	0.231
15	254.7	6000	8	0.257

Table 3. Results obtained in each experiment op.5

Exp.	*Vc* m/min	*f* mm/min	*P* bar	*Ra* µm
1	537	600	8	1.154
2	751.8	600	8	1.156
3	537	840	8	1.061
4	751.8	840	8	1.024
5	537	720	6	1.166
6	751.8	720	6	1.471
7	537	720	10	1.033
8	751.8	720	10	1.200
9	644	600	6	0.909
10	644	840	6	1.145
11	644	600	10	0.933
12	644	840	10	0.891
13	644	720	8	0.890
14	644	720	8	0.996
15	644	720	8	1.228

Fitting of data obtained with surface roughness measurements for each experiment was analyzed via the R^2adj parameter. From the previous analysis a polynomial equation for each experiment was obtained. The curve has the shape of equation (1). The analysis carried out using the Minitab software allowed to determine which parameters are statistically significant in each study operation. For the four operations detailed so far (3 and 5), cutting speed *Vc* and feed rate *f* are generally parameters whose variation has some influence on results of the surface roughness Ra measured. Pressure *P* was only significant in operation 3. For example, in the case of operation 5 shown in Figure 2B, with increasing feed rate, the surface roughness worsened as expected. On the other hand, with higher lubricant pressure roughness results improved because this contributed to a better lubricated surface of interaction between the workpiece and the tool, and it helped to evacuate chips. After analyzing the variables whose behavior influenced the surface roughness results obtained, and how this variation affected Ra (Figure 2), it was possible to determine the recommended parameter values to be used, Table 4.

Table 4. Recommendations on machining process parameters to be used with the MQL system

Op	*Vc* m/min	*f* mm/min	*P* bar
1	2375	15000	8
2	2375	11520	6
3	314	1812.5	6
4	440	1680	6
5	1253	1680	6
6	205	2450	10
7	1759	11200	6
8	452	5760	10
9	268	975	10
10	225	2750	10
11	2375	15000	6
12	811	768	6
13	1696	1562.5	6

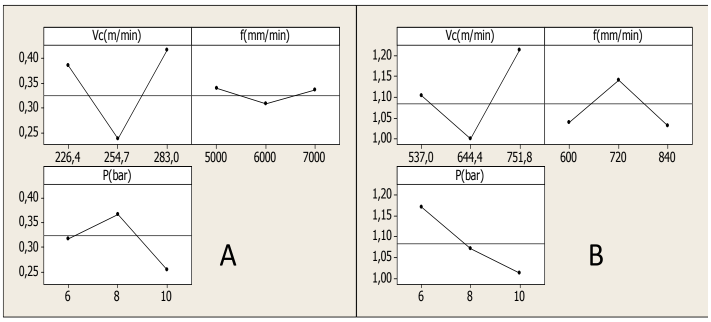


Figure 2. Summary graph of the influence of experimental parameters on the index of measured Ra in: A-Operation 3, B-Operation 5

In addition, it was also possible to analyze changes in cutting parameter values in different operations with MQL machining, compared to dry machining. In Figures 3 and 4 variation proposals in terms of speed and feed rates, under MQL and dry machining conditions respectively, are shown.

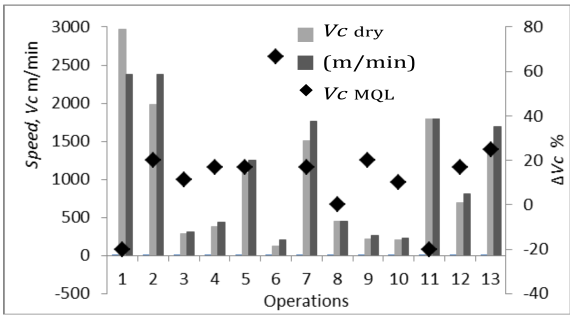


Figure 3. Changes in cutting speed values in MQL refer to dry machining processes

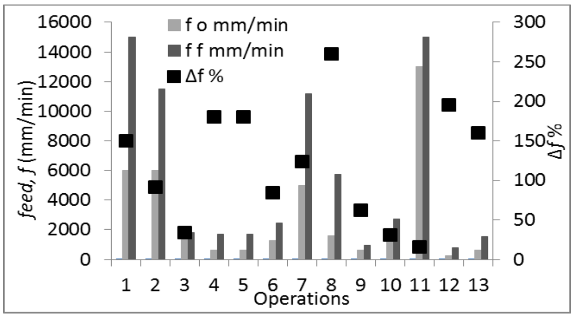


Figure 4. Changes in feed rate values in MQL refer to dry machining processes

3. RESULTS DISCUSSION

From the above-mentioned results it was interesting to analyze the variations which different process parameters experienced, as compared to the values that they showed when these operations were performed using the machining process based on cutting fluids. This comparison helps to conclude whether machining with the MQL lubrication system is convenient or not. In general, there was a significant increase in feed rate (for example, Operation 8 showed an increase of 260% and eight of the operations exceeded 90% increases). Our aim was to maximize this particular variable, since it has a direct effect on the cycle time, so results obtained are beneficial. In any case, an increased feed rate causes a reduction in cycle time. With the new process parameters and the MQL lubrication system, roughness values below those required in the technical documentation of the workpiece were obtained. This is a positive development, since this is precisely the key quality indicator that must be controlled in each part to be machined.

An increased cutting speed in eleven of the thirteen operations minimized not only the surface roughness, but also the feed rate per tooth. This is the philosophy of high speed machining (HSM), which aims to reduce the contact time between chips and the tool. Results show a great deal of improvement since the roughness values obtained are lower than those required in the plan, and the decreased machining time is remarkable, as compared to the conventional process. In general, the lifetime of tools was not significantly affected by varying cutting parameters.

5. CONCLUSIONS

After performing each experiment for the 13 machining operations of different parts of the study gearbox, we arrive to some conclusions. Through the use of DOE techniques, a minimum number of experiments to determine the optimum values of process parameters were performed. The feed rate was maximized in all experiments, which has a direct effect on the duration of the cycle time and helps to minimize machining times. The surface roughness Ra decreases using new cutting parameters and the MQL lubrication system. It was proved that the MQL lubrication system was feasible for the various operations on this gearbox, and a new study to continue defining cutting conditions for the remaining operations is needed.

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