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ACOUSTIC EMISSION AND SURFACE QUALITY IN THE MILLING OF HARDENED SAE 4340 STEEL WITH MINIMAL QUANTITY OF FLUID

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Abstract. *The decreased use of lubricating and cooler fluids in milling processes is being sought by many industries due to the high cost of maintenance and discard of these fluids, in addition to the severe damage they bring to the health of workers and the environment. In this paper we analyzed the acoustic emission in the SAE 4340 steel milling using minimal quantity of fluid (MQF) at different flow rates compared to conventional lubrication (abundant) in the concordant and discordant machine for carbide tools, with coating. For different machining conditions was checked the surface quality of machined parts. The steel used was the SAE 4340 hardened and tempered, with high industrial use in mechanical components that receive dynamic forces. The project was developed in Machining Studies Laboratory at Unesp-Guaratinguetá, using a CNC Machining Center. An appropriate statistical analysis (analysis of variance) of results in order to understand the effects of the MQF in milling of chosen steel and correlate the output variables was performed. As a result, we intend to know the effects of the MQF in milling concordant and discordant process of SAE 4340 hardened steel with carbide tools.*

Keywords: *MQF, SAE 4340 steel, acoustic emission, roughness, milling.*

1. INTRODUCTION

Currently, many research and industries are looking for a more economical solution to the issue of lubrication and cutting fluids in the machining process. Besides the economic factor, the coolers agents can also cause serious damage to the environment and to humans who operate them, and this justifies the search for new ways of cooling and lubrication, as the technique of minimal quantity of fluid, to effectively reduce the heat energy in order to improve the tool life and surface roughness, in a ecological and economic better way (Rakurty et al. 2013). However, concerning to SAE 4340 hardened steel, little is known about its milling with the technical minimum quantity of fluid (MQF).

The SAE 4340 steel is a high hardenability and good forgeability steel of great industrial use. The aerospace industry is widely used because of its high strength and toughness, from parts used in the assembly of the aircraft as well as in tools that are used for construction and assembly of aircraft (Torres, 2002).

The milling process is a process widely used in the metalworking industry, because with it is achieved to obtain parts with simple geometry as much as complex. However the development of alternative and sustainable machining technologies is needed, in search to save more energy and materials in industry (Simunovic, 2015).

By having the interrupted cut, the use of MQF in milling has been a viable alternative as it provides a cooling in the period in which the cutting edge does not touch the part. Based on these factors, milling tests were run on hardened SAE 4340 steel using the conventional lubrication and cooling system (fluid in abundance), and later with the MQF technique in order to compare the results, and pursue their feasibility.

2. OBJECTIVE

This project seeks to analyze the output variable acoustic emission, for the SAE 4340 tempered steel milling, using carbide cutters, and under the conditions of conventional lubrication and MQF technique.

It is also intended, in order to better understand the results for these techniques, analyze the surface quality of machined parts by roughness.

From these analyzes, it is hoped to find the best parameters in order that implementation of the MQF is possible for this process. Thus, also examine the carbide tools behavior, with coating in the milling process with different cutting fluid application systems at different flow rates, and compare the concordant and discordant cutting conditions.

3. LITERATURE REVIEW

The following is a brief literature review of the main issues and technical concepts needed to understand this work.

3.1 Milling process

According to Costa (2006), the machining is an operation which aims to generate size, shape and finish, or a combination of these characteristics in one piece producing chips (portion of material removed from the piece).

The milling is a machining process which is performed to remove material from a given piece of non-continuous manner, by rotary motion of a multi-cutting tool, with several cutting teeth, thus obtaining surfaces of different shapes (Stemmer 1992).

According to Souza Júnior (2001), cutting conditions that directly influence the quality part are:

- Cutting speed (m/min) is the tangential speed at which the outer diameter of the cutter traverses the workpiece, and this diameter is measured between the opposite edges of cuts linearly;
- Table feed rate (mm/min) is the relationship between the distance traveled by the piece in a minute in relation to the tool;
- Feed per revolution (mm/rev) is the distance the piece (table) travel for each rotation of the cutter;
- Feed per tooth (mm/z) is the distance traveled by the work table for each rotation, divided by number of teeth of the cutter;
- Cutting depth (mm): is the width of penetration of the tool in the workpiece, measured in a direction perpendicular to the work plan;
- Work Penetration (mm): the penetration of the tool relative to the workpiece, measured in the work plan and a direction perpendicular to the forward direction;
- Forward Penetration (mm): is the tool penetration measurement in the work plan and in the forward direction.

3.2 Concordant and discordant milling

In discordant cutting, direction of forward movement is contrary to the direction of movement of the cutter and the cutting depth increases progressively from zero to a maximum value. At the beginning of the cut, when the tool touches the part, this is forced into the workpiece, causing friction, which causes plastic deformation at this location instead the chip formation, and high temperatures.

In the concordant milling, forward movement has the same direction as the rotational movement of the tool. In this type of milling, the vertical component of machining has the same direction around the cut, that is, pushing the workpiece toward the table. This reduces several drawbacks compared to the discordant milling, however, as the beginning of the cutting occurs tearing the maximum cross-cutting section, much strength is dispensed at the beginning of the cut, a fact that is magnified in hard materials machining, which may promote breakage and decreased tool life. Furthermore, this effect is favored cutting the occurrence of mechanical vibrations (Diniz et al., 2013).

3.3 Cutting fluids

According to Hryniewicz *et al* (2000), the main features of cutting fluids are:

- The part and tool cooling, reducing the cutting temperature;
- Lubrication, reducing the friction between the workpiece and the tool, facilitating start-up and transport chips and thus improving the surface quality of the workpiece;
- Possibility to use higher cutting speed and penetration rate.

However, there are a high maintenance cost and treatment, implying that costs can reach up to 20% of the total production price. Moreover, disposal, incorrect handling and transport can cause serious ecological damage. And yet, there may be health problems, either through skin contact or by inhalation and ingestion of fluid droplets, causing problems in the respiratory and digestive systems (Howell et al., 2006, Rakurty et al. 2013).

3.4 Miminum quantity of fluid technique

The application of cutting fluid in abundance in machining processes is the most common procedure when you need lubrication and cooling, however, in order to reduce the economic and environmental problems caused by the use and disposal of cutting fluids, is being sought alternative techniques. An alternative is the use of MQF, which is already widely used in other machining processes (Uysala, 2015).

The MQF technique is to apply a small amount of cutting fluid mixed with compressed air to form an aerosol by promoting: lubricating the workpiece-tool contact zone reducing friction and the temperature, transforming the heat for vaporization (of the fluid) and driving the air flow (Shokrani, 2012).

This is an alternative to conventional refrigeration, especially when dry cutting is not applicable and do not want to use the flood, and has some advantages, such as fluids are used in smaller quantity; fewer problems with storage, treatment and disposal of the fluid; and diminution or absence of problems with bacteria and fungi.

3.5 SAE 4340 steel

The steel used in this research will be the SAE 4340. This steel is high hardenability for parts of large thicknesses and high strength.

It is often used in various mechanical equipment under the action of dynamic stresses in the aerospace, automotive and machinery and equipment, mainly for its high mechanical strength, and the homogeneity of hardness by its cross section.

4. OUTPUT VARIABLES IN THE MILLING PROCESS

The output variables listed below will be analyzed in research seeking to understand the effects of MQF in milling.

4.1 Acoustic emission

Acoustic emission is the spread of a vibrational wave in the mesh of crystalline materials due to rearrangement of the internal structure of the material (Williams, 1968). When a deformation occurs in the material (modified by cutting, abrasion, crack etc.) occurs a breakdown of the structure of the material which tends to rearrange them, these rearrangements that generates vibrational waves traveling speed of sound, hence the name acoustic emission. These signals are captured by a piezoelectric sensor to convert mechanical signals into electrical signals.

Sales et al. (2009) stated that in machining, the acoustic emission is dependent on basic discordance mechanisms such as dislocation of this discordances, grain slips and void coalescence. The piece-tool interaction piece generates a characteristic acoustic emission signal that increases its range due to several aspects.

According Mechefske et al. (2002) and Maia (2009), the study of the wear phenomena by monitoring the acoustic emission has a high correlation, being the acoustic emissions generated in a material being machined, thus providing indications of the physical condition of the piece.

4.2 Roughness

Due to the withdrawal mechanism of material used in conventional machining processes, and the imposed shear and vibration generated by the process and equipment, makes the piece presents an uneven surface.

Most machining studies that aim to analyze the quality of the parts produced, analyze the imperfections and the topography left these parts. This topography of the parts produced is called roughness and is characterized as micro-geometrics errors being a result of the machining process (Agostinho, 1981).

4.2.1 Avarege roughness (Ra)

One of the oldest parameters still in use these days is the average roughness (Ra). Its use is attributed to the ease way to obtaining it because of the simplicity of its formulation. Its definition can be expressed as the mean deviation of profile of its average line. According Rossi (2008), average surface roughness can be defined as the average distance of a profile from its mean line, measured over a length.

The midline is a line arranged parallel to the direction of the profile within the measuring path *lm*, so that the sum of the upper areas is exactly equal to the sum of the lower areas (Novaski, 1994).

4.2.2 Total roughness (Rt)

The total roughness is given by the difference between the highest peak and the lowest depression in the considered length, irrespective of the partial roughness values. It may be a good indicator of the occurrence of failures in the manufacturing process.

Rt parameter gives greater stiffness results, as regards the sample length to the evaluation length.

5. METHODOLOGY

The research project was carried out through experimentation, starting from preliminary tests to determine the parameters and variables more appropriate to research as cutting speed, feed rate, feed per tooth, cutting depth, the conventional system and lubrication MQF system flows rate, cutting fluids, etc.

5.1 Equipaments and lubrication systems

The work was developed in the Machining Laboratory in Unesp- Guaratinguetá, using a machining center, brand DMG model DMU50ECO series DMG Ecoline, Fig. (1), for which it was developed and assembled an acquisition of acoustic emission data system.

Figure 1. Machining Center, brand DMG model DMU50ECO series DMG Ecoline.

To carry out the project were used the Machining Center own conventional lubrication systems (fluid in abundance) and an MQF system (compressed air and fluid) from Machining Studies Laboratory. The fluid used in the MQF was the ACCU-LUBE LB-1100 lubricant from ITW Chemical, it is suitable for machining using minimal quantity of fluid, since it is indicated for operations that generate a lot of heat and machining operations of hardened metal, and has no chlorine. For conventional machining was used lubricant BLASER VASCO 1000.

The data acquisition comprising a computer system with a data acquisition board, a channel module and a connecting cable between the board and the channel module has been implemented and allows obtaining any variables measured in real time as acoustic emission. Integrating this data acquisition system is the acoustic emission sensor piezoelectric, with an output signal amplifier RMS (Root Mean Square) rectified, PHYSICAL ACOUSTICS CORPORATION brand, model R15A, and amplifier signal model 1272- 1000.

For subsequent measurement of roughness value, it was used rugosimeter Mahr brand, MarSurf M300 model. For the roughness the parameter analyzed was the average value "Ra" and "Rt" for best fit the surface finish studies, as found in the literature review. The sampling length was set at 0.250 mm (cut-off). The measuring travel (*lm*) for cut-off of 1.25 mm is 0.250 mm, resulting in the average of 5 values acquired by measurement.

They were held in total 3 roughness measures and in each sequence of machining, all specified in micrometers.

5.2 Milling tools and test specimen

A partnership with Seco Tools company, based in Sorocaba was held, in which was achieved the donation of tools for conducting the tests. As them, the MP16-16019R08Z3-M05 with 3 cutting edges (Z3), MP16-16019R04Z6-M04 with 6 cutting edges (Z6) and the 2 edges wafer LOEX080408TR-M08 and the 4 edges XOMX10T308TR-ME07.

All tools used have a coating of titanium aluminum nitride (TiAlN). The main advantage of using hard metal cutting tools with this coating, called tinal is that hardness is maintained under extremes cutting temperature, surpassing the 700 °C.

Figure 2. Tools Z6, Z3, ME07 (upper) e M08 (lower), respectively.

Was used as a specimen the SAE 4340 steel whose dimensions were defined (25x70x100mm). These dimensions also are due to the reason that they can be attached to a support to the specimen where the acoustic emission sensor was placed. After this specification the samples were quenched and tempered in the Company Proterm in São José dos Campos getting to the final hardness of 56 HRc.

5.3 Trials

First tests were conducted with a conventional lubricant, which uses cutting fluid in abundance for the concordant and discordant directions, varying all the tools, running 3 replicates for each test conditions.

Later tests were conducted with the technique minimal quantity of fluid, again varying the direction of cutting tools and cutting fluid flows. The flow rates used were 120, 40 and 12 ml/h, again performing 3 trials for each condition to the machining direction concordant and discordant test and wear.

The cutting parameters used were: Cutting speed = 200m / min; Feed rate: 0.04 mm / tooth; RPM: 2609

6. RESULTS AND DISCUSSION

To better understand the experiment was done a statistical analysis of the data obtained experimentally. It was developed the experiment design study for full factorial, with the determination of three main factors (lubrication, milling type and cutting direction) that directly influence on the data obtained and the necessary amount of levels for each factor, totaling 96 combinations to 3 factors and subsequent levels.

The analysis was performed using the Minitab statistical software, providing tables, with their coefficient of determination, degree of freedom, P-values and F-values, in addition to the main effects graphics. The analysis was done considering a 5% significance level.

6.1 Avarege roughness (Ra)

Table 1. Analysis of variance for Ra.

FACTORS	*GL*	*F*	*Pvalue*
Lubrication	3	3,07	0,034
Milling type	3	9,00	0,000
Cutting direction	1	7,94	0,006
Lubrication* Milling type	9	4,17	0,000
Lubrication* Cutting direction	3	1,75	0,166
Milling type * Cutting direction	3	9,76	0,000
Lubrication * Milling type * Cutting direction	9	2,40	0,021
Error	64	#	#
Coefficient of Determination	R-Sq(adj) =52,93%		

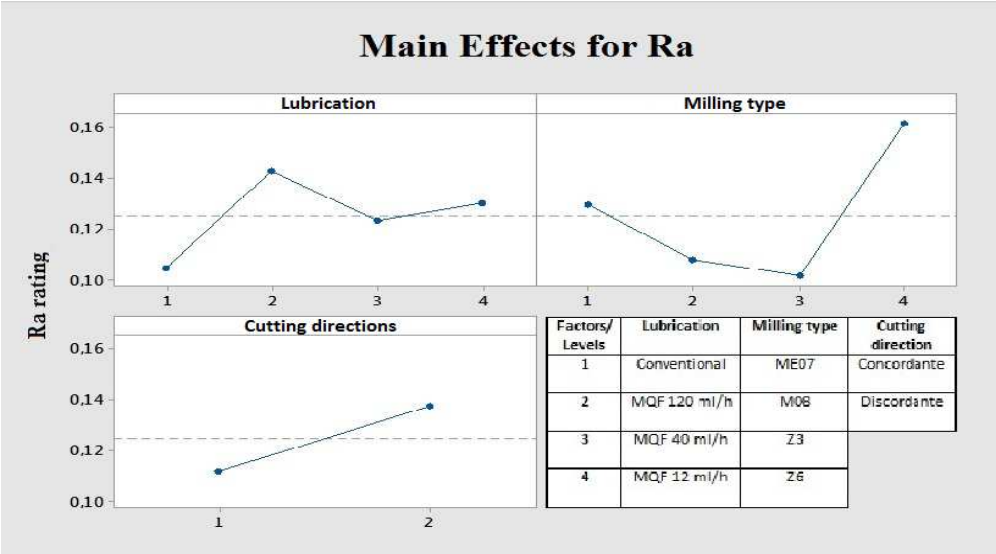

Figure 3. Main effects diagram for Ra.

For the table, most of the P values value indicated that the experiments were significant because the P-value was less than the significance level of 5%, except the interaction of lubrication with cutting direction. As the value of P can be hard to find, we can use the value of F, and a statistical table to through interpolation error of the degree of freedom with the factor, estimate the value of F critical. Thus, measured values F, which are numerically greater than the critical F indicate experimental significance. The R2 value (set) indicates that the line average Ra of points found by the not fully explain the data, with a correspondence of only 52.93% of the values.

For the lubrication factor, the value obtained from Ra with lubrication was too low, on the order of 0.1 microns and may even replace the grinding process. The flow rate of 40 ml/h showed the best results of roughness for the MQF as the increase of only 0.02, approximately.

Regarding the tools, the M08 showed best values of Ra than ME07, because of having four cutting edges, attacking least the specimen at every step. For the tangential milling, as the surface area of interest attacked is larger, the roughness increases, as can be seen for Z6 tool. The cutting direction discordant resulted in higher mean roughness values, as expected, since in that case the direction of forward movement contrary to the direction of cutter movement.

6.2 Total roughness (Rt)

Table 2. Analysis of variance for Rt.

FACTORS	*GL*	*F*	*Pvalue*
Lubrication	3	8,85	0,000
Milling type	3	14,55	0,000
Cutting direction	1	8,38	0,005
Lubrication* Milling type	9	3,23	0,003
Lubrication* Cutting direction	3	1,52	0,219
Milling type * Cutting direction	3	7,60	0,000
Lubrication * Milling type * Cutting direction	9	2,04	0,049
Error	64	#	#
Coefficient of Determination	R-Sq(adj) =56,30%		

To Rt only a P value yielded no significant only for interaction of the cutting direction with. The R^2 value indicates that the average line found by the points of Rt, does not explain fully the data, only 56.30% of the values.

For lubrication levels the chart followed the same trend of Ra chart, but without the sharp drop in the lubrication of 40ml/h, confirming the expected higher roughness values for least amount of cutting fluid.

The tangential milling with Z3 and Z6 tools was more critical as to Ra, and the sense of discordant court also. It is also important to note that the Rt values were more specific and gave smaller than those of Ra, which features a very satisfactory result.

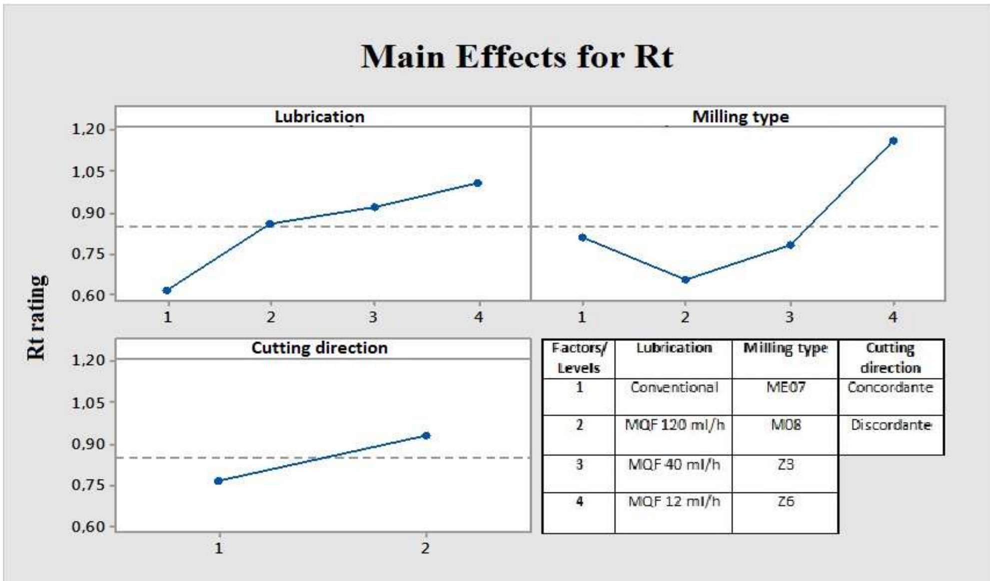

Figure 4. Main effects diagram for Rt.

6.3 Acoustic emission

Table 3. Analysis of variance for acoustic emission.

FACTORS	*GL*	*F*	*Pvalue*
Lubrication	3	623,89	0,000
Milling type	3	111,73	0,000
Cutting direction	1	0,18	0,674
Lubrication* Milling type	9	133,63	0,000
Lubrication* Cutting direction	3	17,01	0,000
Milling type * Cutting direction	3	3,77	0,015
Lubrication * Milling type * Cutting direction	9	4,22	0,000
Error	64	#	#
Coefficient of Determination	R-Sq(adj) = 97,34%		

In the analysis of variance for the noise emission levels, we can see, by P values, which only the cutting direction factor is not significant, and therefore all the other factors, and combinations between them should influence the noise emission values. For the R2 value also see that the average from these values straight explains almost completely covering more than 97% of the data.

Because the cutting direction have not given significant, can be seen in the acoustic emission average chart that does not occur change the value of the acoustic emission to vary between concordant or discordant. However, assessing the lubrication factors and type of milling, we can say that the most interesting were the MQF lubrication, the flow 40 ml/h and face milling with the M08 tool, respectively, provided for smaller acoustic emission values.

The highest acoustic emission, which was provided with conventional lubrication factor, was not expected, since the conventional lubricating should best results. However this can be attributed to the interaction of the cutting fluid that is applied in abundance during the process, and the acoustic emission sensor.

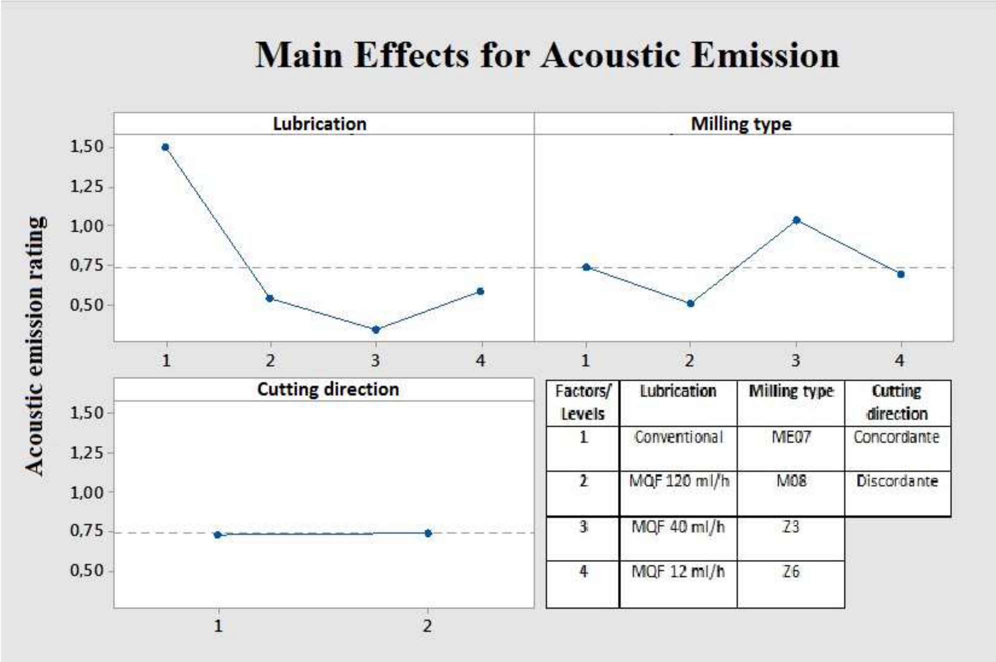

Figure 5. Main effects diagram for acoustic emission.

7. CONCLUSION

After the analysis and evaluation of parameters was possible to verify the importance of studies of the tables with P and F values, as the charts show only tendencies, closed between limits. Also is encouraged a more detailed statistical analysis of interactions between process factors in order to find the best conditions for the implementation of MQF.

From the study of the Ra and Rt values, good surface quality data have been found and can even infer that this process MQF technique studied can get to replace the rectifying process. Meanwhile, with the data acquired from acoustic emission it is possible to estimate trends and create models of behavior, which can be used in further assays so as to monitor in real time the tool wear and part quality.

We observed, through the graphs generated acoustic emission during trials, the end of the cut is well defined by peaks, mainly for the sense of discordant court. In concordant sense, we can see the presence of transient signals the beginning of the court. Both facts are due to aggressive interaction of the tools with the piece, or chip impacts, so the start and end of CDP form the greater part of the wear zones.

With this study was possible to better understand the milling with coating hard metal tools, of SAE 4340 hardened steel, using the minimum quantity of fluid technique. Furthermore, the vast majority of the analyzed results occurred with satisfactory values, bringing best results, at least equivalents, the process abundant lubrication.

Finally, the feasibility of using MQF in milling machining center for SAE 4340 steel hardened been confirmed, favoring the largest study of milling conditions with MQF technique for future application in the industry, bringing many economic and sustainable benefits.

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