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THE MQL'S ATMOSPHERIC AIR TEMPERATURE INFLUENCE IN SAE 4340 STEEL CYLINDRICAL GRINDING USING CBN GRINDING WHEEL

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Abstract. Grinding is a process that has the objective to improve the surface roughness decreasing distances between peaks and valleys on the surface of the workpiece. The tool used is the grinding wheel which consists of grains of very hard materials, known as abrasives, compacted and circularly joined by a binder which may be vegetable or mineral.

Given that grinding is an attrition process its use of energy is very high. Most common way to remove the generated heat is the flood application system that allows best surface roughness and the reuse of the fluid. The greatest problem of this cooling system is a generation of a toxic mist that is highly harmful to the operator. In addition, the wrong disposal of the fluid causes a contamination of groundwater and a consequent contamination of the living beings that depend on this water. Therefore, to reduce the consumption of oil, one of the components of the cutting fluid, was created the MQL (minimum amount of lubricant) technology, which uses low-oil spray in high speed to create a layer between wheel surface and workpiece ones. The paper looks for the use of a vortex tube in order to cool MQL at low temperatures in order to reach better results.

Better results were found in CAMQL (Cold Air MQL) in comparison to MQL simple system for different feed rates and now it's expected to improve this method with the objective to reach industrial uses.

1. INTRODUCTION

Grinding is a machining process that generates great amounts of heat due to the wear of the grain's cutting edges and a consequent increase in the contact area between the tool and the workpiece (BELENTANI, 2013), which may cause damages to the surface of the workpiece such as cracks, dimensional and shape distortions and residual stresses.

Such as the possible damages at workpiece's surface, productivity is also affected by the generated heat. The temperature is the limiting factor in this case.

The use of flood coolant system may offer a great lubrication and heat removal rates (SANCHEZ *et al.*, 2013)., however its processing costs and potential environmental damages are serious problems to be considered. In other hand, in machining processes with insufficient quantity of coolants it can occurs thermal damages and dimensional inaccuracy at workpiece's surface compromising its use in industrial applications.

In the search for a greener coolant technology allied to the necessity of high dimensional precision, the MQL's system has been developed. It consists in create an oil-mist by mixing oil (it can be mineral, vegetable, semi synthetic, synthetic oils and even an emulsion) with a high pressure air flow (DHAR *et al*, 2006).

If it's considered an aerodynamic barrier created in the grinding wheel's surface it'd be necessary a great quantity of coolant to break this barrier and get to the grinding contact between the wheel and the workpiece. The MQL's secret is to use air instead of fluid to break this barrier and a tiny quantity of oil that will create a layer at the contact, decreasing the sliding friction coefficient in comparison to conventional coolant system (ESTEVES *et al*, 2006) and, consequently, the cutting forces.

Saberi et al. (2016) verified the application of cold air combined with MQL (CAMQL) for surface grinding of CK45 steel using aluminum oxide grinding wheels compared to conventional and dry grinding. It was analyzed the shear forces and the surface quality of the workpieces. The grinding forces were smaller for the CAMQL condition; however CAMQL presentd the highest coefficient of heat transfer and the worst finishing of the evaluated methods. The authors concluded that the CAMQL technique may be applicable for fine grinding of soft steels.

The temperature of the air flow used in the experiments will influence the removal rate of the heat generated by the process. Better results should be reached using air at lowers temperatures and that's what this research is about.

1.1 Objectives

Evaluate the influence of air temperature on MQL cooling system for the external cylindrical plunge grinding of ABNT 4340 steel using a CBN wheel. For comparison, tests will be carried out under the same conditions also with flood cooling and with MQL using compressed air at without refrigeration and using or not a nozzle to clean the surface of the grinding wheel.

2. MATERIAL AND METHODS

All the tests were conducted in the Abrasion Machining Laboratory (LUA), Faculty of Engineering – UNESP – Bauru, using a grinder model RUAP515H from Sulmecânica, equipped with CNC controls from Fagor in order to access the X-axis. Two CNC programs were created; one for the machining of the test pieces and one another for the printing of wheel's surface to measure its wear.

For grinding, a SNB151Q12VR2 Boron Cubic Nitride grinding wheel (CBN) from Nikkon was used. It consists of a vitrified bond with CBN grains, with an external diameter of 350 mm and a thickness of 19 mm. Figure 1 shows the microstructure of the wheel with a zoom of 200x. The conditions for grinding experiments of ABNT are shown at Table 1.
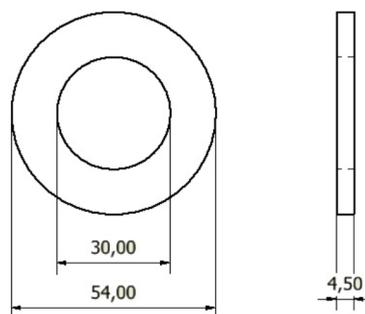

Figure 2. SAE 4340 steel workpiece

The workpieces used for the experiments were of SAE 4340 steel, quenched and tempered, with a hardness of 653 HV and its dimensions are shown at Fig. 2.
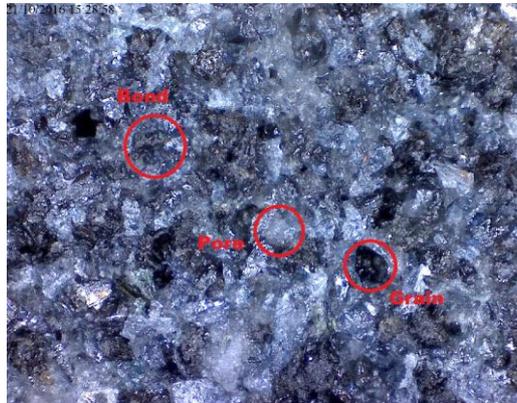

Figure 1. CBN wheel's microstructure

Table 1. Cutting conditions in experiments

Grinding process	External cylindrical plunge
Gringing wheel	Cubic Boron Nitride grains
Grinding wheel speed (v_s – m/s)	$v_s = 30$ m/s
Radial feed v_f – mm/min	0.25, 0.50, 0.75
Workpiece speed (v_w)	$v_w = 0.58$ m/s
Cooling parameters	Conventional (flood) e MQL
Flood cutting fluid	QUIMATIC ME-1, emulsion with semi-synthetic vegetable-based oil at a concentration of 3%
Fluid for the MQL	Accu-Lube® LB-1100, vegetable based product, biodegradable, viscosity 32 to 39 cSt (40° C)
MQL oil flow	120 ml/h
Air Pressure in MQL	0.7 MPa
Workpiece material	AISI 4340 steel, quenched e tempered (58 +/- 2 HRc)
Dresser	Diamond Conglomerate - dimensions 15 mm $\times$ 8 mm $\times$ 10 mm
Dressing depth (a_d)	$a_d = 0.040$ mm (20 cycles – 0,002 mm each)
Sparkout (t_s)	$t_s = 7.50$ s
Dressing speed (v_d)	$v_d = 740$ mm/min

Experiments were taken using 4 different coolant system: MQL, MQL with a cleaning nozzle [4], flood and CAMQL. Using feed rates of 0,25, 0,5 e 0,75 mm/min the table 2 could be mounted.

Table 2. Experiments order

Number of experiment	Type of coolant system
1-9	MQL+CA
10-18	Conventional
19-27	MQL
28-36	MQL+C

2.1 Flood cooling system

The flood (conventional) cutting fluid application system belong to the grinder itself and consists of two circular nozzles of 6.3 mm in diameter each. The hoses are flexible and are easy to position them in each of the tests.

A hydraulic pump with a flow of 550 L/h is responsible to send the cutting fluid towards the cutting zone.

Due to the lack of information about the optimum direction of the cutting fluid flow in cylindrical grinding, the nozzles were positioned directly toward the cutting zone.

2.2 MQL cooling system

The MQL device, shown at Fig. 3 consists in two pneumatic pumps with adjustment, a little tank (300mL), a gauge, a frequency generator to induce oil inside air flow and a metallic box to mount the equipment inside it.

It works by sending drops of oil to an air flow in order to atomize them, providing the oil with a maximum contact area with the surface to be cooled.

Two nozzles were used with MQL. The first one, for common MQL applications is shown by (Kamira *el al*, 2017) and the second, for CAMQL was specially built to provide a mixture between the pre-mixed oil and air with the cold air flow. This choice was made to obtain the highest thermal efficiency.

Figure 3. LUA's MQL Device

The cold air of the CAMQL system was cooled to a temperature of approximately 0 ° C by a vortex tube supplied by Emugue-Frank Company with a pressure of 6 bar.
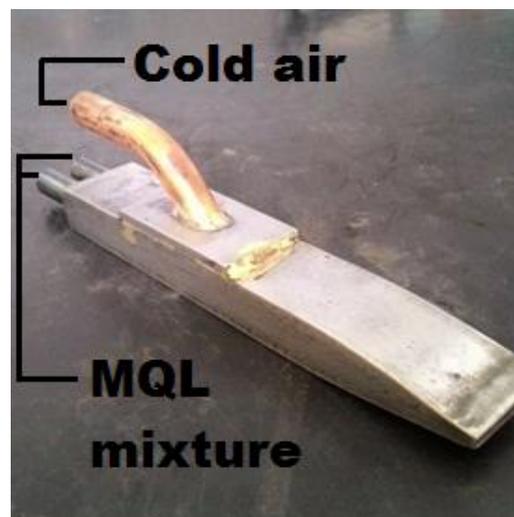

Figure 4. Nozzle developed to the experimentation

2.3 Roughness

The average arithmetic roughness (Ra) was chosen for the analysis of the surface quality of the pieces obtained through the tests performed with different machining conditions. The quantification of this parameter was performed using a Surtronic 3+ Rugosimeter from Taylor Hobson, available at the Abrasion Machining Laboratory (LUA) of the Faculty of Engineering of Bauru.

2.4 Data analysis

Three types of Data were collected: Cutting Power, Acoustic Emission and the vibration produced by the grinding machine.

The LUA's data acquisition system was built by Data Acquisition and Signal Processing Laboratory, from UNESP Bauru, and can acquire acoustic emission, cutting power and vibration data. The analysis began with a .dat file were the measured values were saved for each time interval of 0.1 s. A MATLAB code was written to process the data to obtain only the one inside the steady state. For each test three files were created (EA.dat, PT.dat and VB.dat). The MATLAB code used is show on fig. 5. Files also create files with decimal values of 2048th point of the original data file.

```
1 -     clear all
2 -     clc
3
4 -     arq=fopen('EA.dat','r','ieee-be.164');
5 -     EA=fread(arq,inf,'float64');
6 -     EAD=decimate(EA, 2048);
7 -     save EAD.txt EAD -ASCII
8 -     plot(EAD)
9 -     [x]=ginput(2)
10 -    EA2=EAD(x(1):x(2));
11 -    mean(EA2)
12
13 -    arq=fopen('VB.dat','r','ieee-be.164');
14 -    VB=fread(arq,inf,'float64');
15 -    VBD=decimate(VB, 2048);
16 -    save VBD.txt VBD -ASCII
17 -    plot(VBD)
18 -    [x]=ginput(2)
19 -    VB2=VBD(x(1):x(2));
20 -    mean(VB2)

21
22 -    arq=fopen('PT.dat','r','ieee-be.164');
23 -    PT=fread(arq,inf,'float64');
24 -    PTD=decimate(PT, 2048);
25 -    save PTD.txt PTD -ASCII
26 -    plot(PTD)
27 -    [x]=ginput(2)
28 -    PT2=PTD(x(1):x(2));
29 -    mean(PT2)
```

Figure 5. MATLAB routine for data analysis

2.5 Vickers Hardness

After the prepared samples, the microhardness measurement was performed using a Mitutoyo microdurometer, model HM-200. The equipment counts with both the indenter for measuring Knoop hardness and Vickers hardness. It also features objective lenses of 10 and 50x of magnification. The measurement was carried out according to ASTM E92 using a load of 300 g.

3. RESULTS

The combination of high heat generation at the interface between the workpiece and the wheel with accumulation of chips on the cutting surface of the grinding wheel favors the wear of its grains and, consequently, the decrease of the surface quality.

The CAMQL technique aims to solve the heat accumulation problem of the traditional MQL system, thus promoting the cooling of the cutting zone, which improves the superficial quality with the application of this process when compared to the traditional MQL. It can be seen in Fig. 7 where at feed rates of 0,5 and 0,75 mm/min the difference reached 0,08 µm.

In an overall analyzis, conventional system has gone the best and it is possible to credit the performance of MQL+C system to the high superficial wheel cleaning quality, exposing the grains to all workpiece's surface and

preventing the formation of a draft at cutting zone. This is the place to enforce the importance of dressing. Fig.6. shows how the wheel surface is after grinding and then after dressing. It's possible to notice the light area at (A) represents spaces occupied by fluid and chip, compromising the quality of the process.

Conventional cooling system provides better results for the surface finish, since the emulsion oil and water has a higher density than air, which leads to better cooling, since I know specific heat and thermal conductivity are higher (Saberi et al., 2016),.
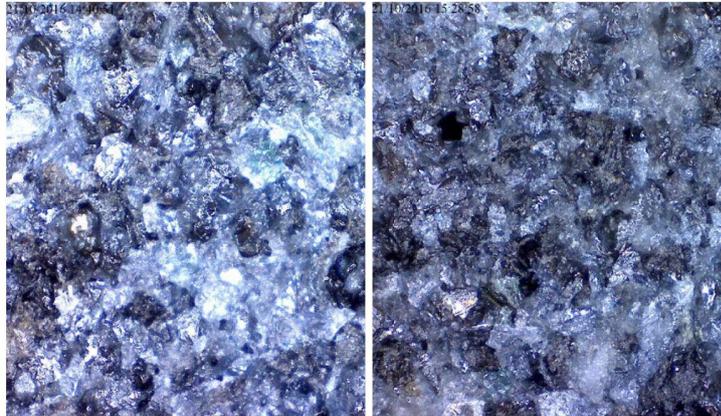
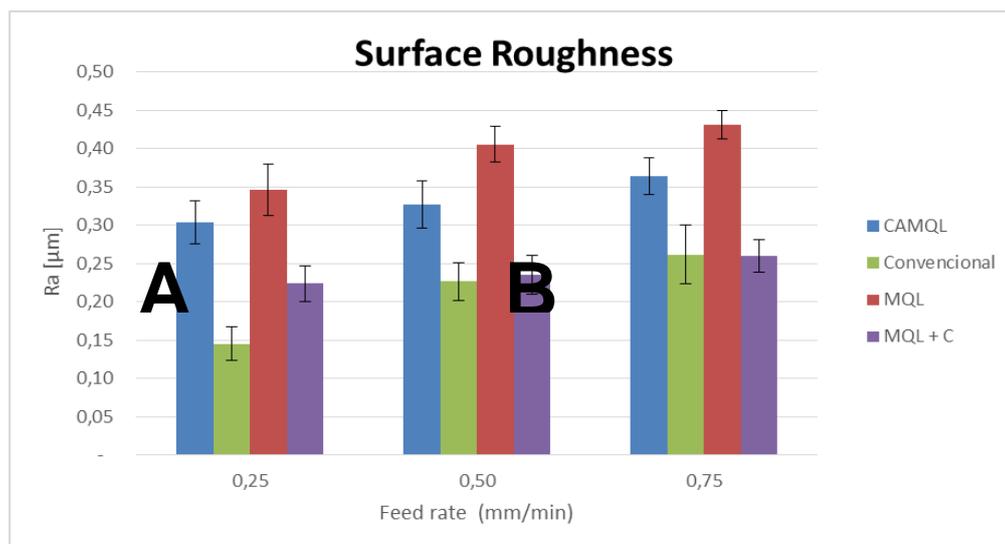Figure 6. The importance of dressing

Figure 7. Surface roughness comparison between processes

Other output data used for comparison proposals it is the workpiece's Vickers Microhardness next to the machined surface. Figure 8 shows that processes using a feed rate of 0,25 mm/min could retain the original hardness of the workpiece, in special the one with CAMQL cooling system. At higher feed rates the MQL+C system achieved better results but comparable to CAMQL's ones.

In Fig. 9 the Cutting Power results were becoming higher as the Feed Rate increased. This extra required power comes due to an increase in the material removal rate, and consequently the process becomes more severe, with a higher heat generated,

Also, the starting point, the process which our experiments want to achieve, the conventional cooling system (flood) reached the best results when talking about the Cutting Power. The results of the CAMQL cooling system were better than those of the common MQL system but presented worse ones when compared with MQL + C system. This can be explained since the application of MQL, whether it is the traditional method or with cold air, presents a mist using compressed air and oil, which has as one of the main functions to remove chip from the cut region. However, the MQL process reduces the porosity of the wheel by formation of sludge decreasing its cutting capacity (Belentani et al., 2014).
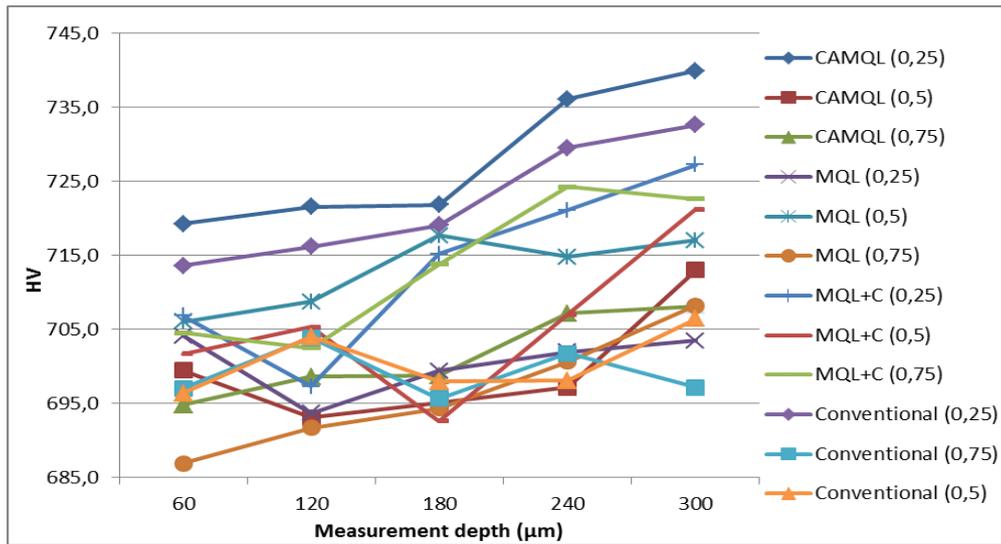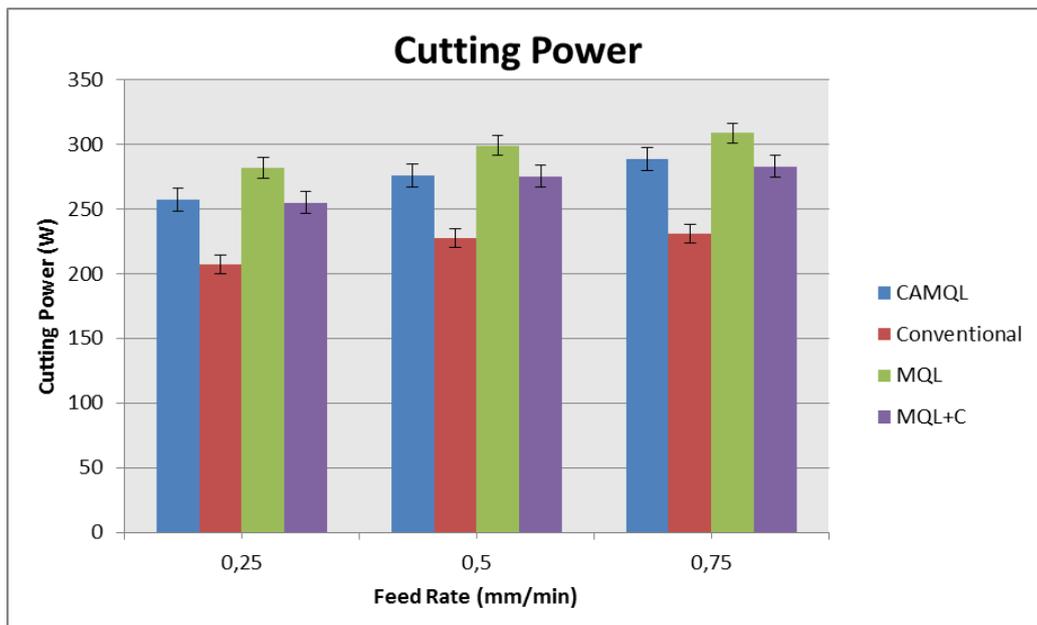
Figure 8. Vickers Microhardnes

Figure 9. Cutting Power vs. Feed Rate

Acoustic Emission and Vibration are two related outputs. They are connected with part of the amount of energy lost in machining. Therefore when higher of these results are obtained it means that more energy is required to machine the same amount of material.

It is important to comment that the Acoustic Emission and Vibration outputs are only qualitative, not quantitative since the values are given in Volts by the sensors.

Knowing that the acoustic emission in the grinding process consist in the characteristics of some phenomena of this process such as chip formation, friction, bond and grain fracture and the thermomechanical transition phase (Babel et al., 2013), Fig. 10 is presented. In it, CAMQL and Conventional system presented very similar results to a Feed Rate of 0,25 mm/min, while for common MQL and with cleaning the results were higher for the same Feed Rate. For 0,5 and 0,75 mm/min, Conventional system performed the best for as much as CAMQL were better than common MQL and with cleaning. MQL got the worst results in both Feed Rates.
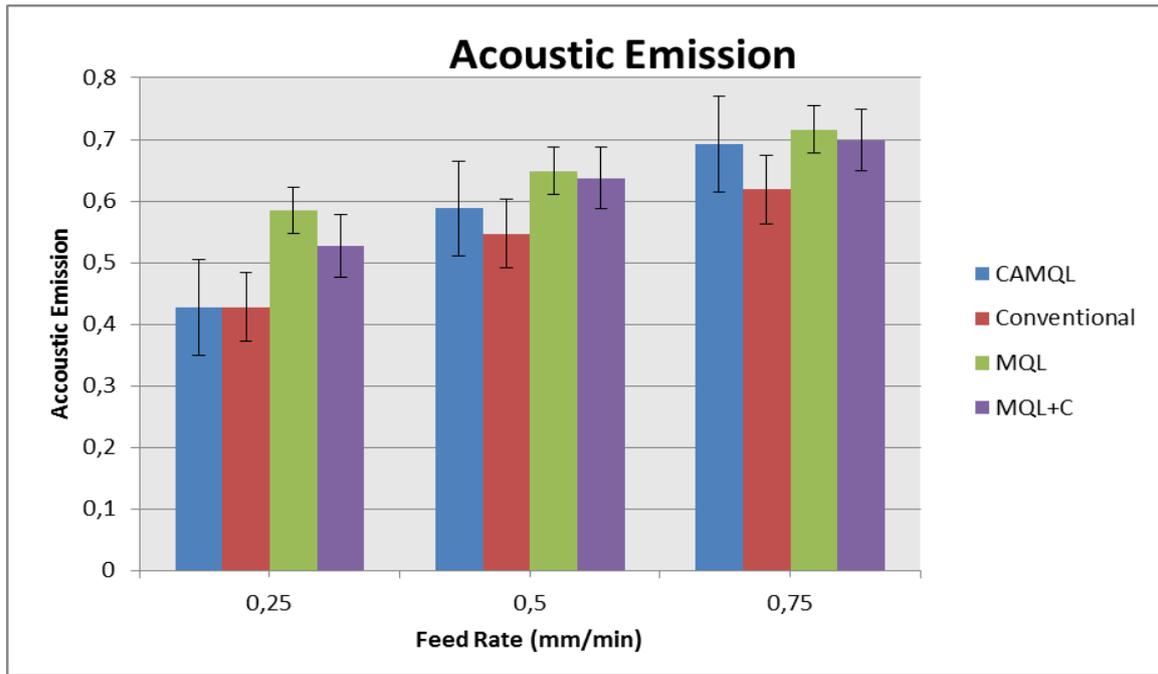
Figure 10. Acoustic Emission vs. Feed Rate

The Vibration Data shows that Conventional cooling system still are the best in terms of Vibration. In all three Feed Rates used it performed better than the other three cooling systems. When using a Feed Rate of 0,25 mm/min, CAMQL performed better than both the common and with cleaning MQL. When considering the Feed Rates of 0.5 e 0,75 mm/min, MQL+C obtained better results than CAMQL. As in all other parameters, common MQL system had the worst results.
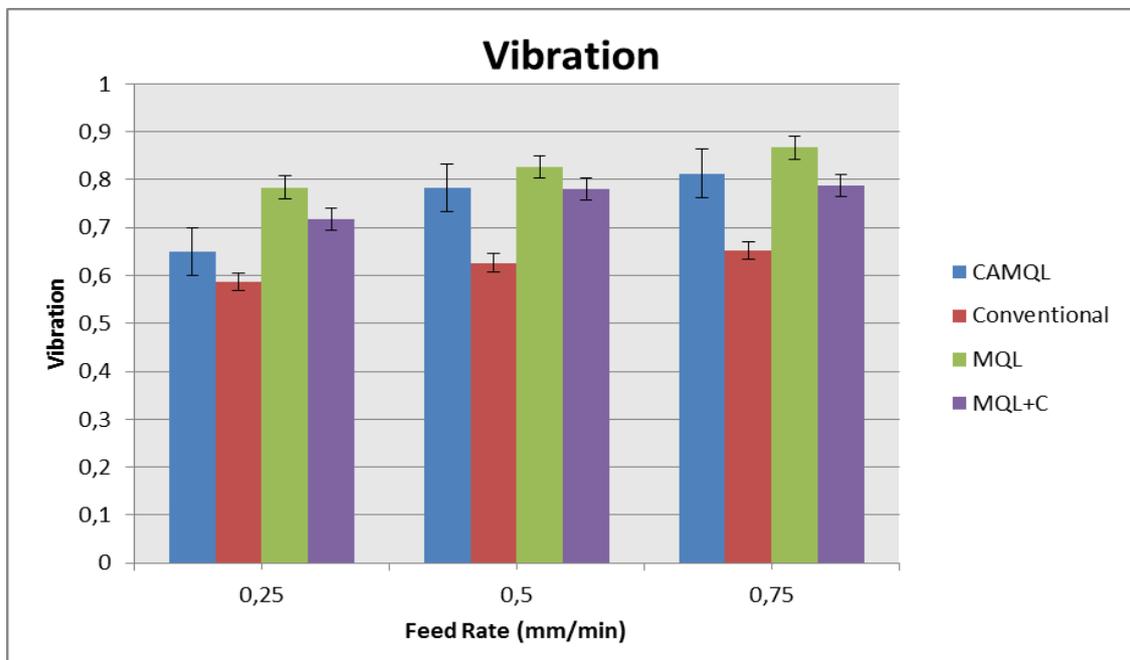

Figure 11. Vibration vs. Feed Rate

It is possible to organize the current conclusions around this paper into topic. The topics are in the following.

1. The conventional lubrication-cooling method (flood) presented the best results for the almost all parameters analyzed. At all three speeds, the parameters remained lower than the other in the proposed conditions;

2. The MQL technique with cold air, named here as CAMQL has potential in terms of the parameters analyzed in the present study when compared to the common MQL technique. This happens because the proposed technique

improves the cooling aspect of the process, consequently improving all variables influenced by the excess heat present in the grinding process, such as shape distortions and residual stresses;

3. All mean roughness values (Ra) were below 0.45 μm. For the conventional lubrication-refrigeration technique, the values were below 0.30 μm, for the MQL technique, below 0.45 μm and for CAMQL below 0.40 μm;

4. Microhardness values have experienced an increase, probably followed by the emergence of compressive residual stress;

5. Considering the Hardeness of 4340 Steel in its conditions, all the methods have succeeded, specially the proposed CAMQL technique, which is superior to common MQL without any extra of energy required;

6. The search for a more sustainable and economical machining can be achieved with CAMQL technique, and this method can also indicate the viable path for the application of MQL in the industry.

4. ACKNOWLEDGEMENTS

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