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ENERGY CONSUMPTION EVALUATION IN MACHINING CENTERS ADAPTED FOR MQL

Augusto Dttmann
Jefferson de Oliveira Gomes
Aeronautics Institute of Technology
augusto.dttmann@gmail.com
gomes@ita.br

Abstract. *The MQL (minimum amount of lubricant) is always an alternative to flooding when looking for reduction of oil consumption. There are authors who defend the improvement of machining force, increase tool life and decrease energy consumption due to the withdrawal of the high pressure pump from the flood system, although there are divergences. A literature review has shown that many predictive models of machine tool power consumption do not consider the consumption of the required air compressor in MQL. These models are based on a study carried out in 2006 at MIT. Withal, they are still under development with some calculations oversized, while others ignore components of the machining center. This paper's motivation was the divergent points analysis and test models to predict the energy consumption of machine tools using MQL and flooding. These tests were performed in a comparative manner between the two techniques in a machining center adapted for MQL. Tool life and cutting forces were also measured. The machining process chosen was the through-hole in gray cast iron. It was found that the amount of energy consumed in the cutting is lower when compared to the consumption of basic components of the machine tool. Using the MQL, the tool life showed a decrease. However, it allows the feed to increase and reduces the energy consumption.*

Keywords: *MQL, energy consumption, machining, tool life*

1. INTRODUCTION

Machining stands out as being one of the main discrete manufacturing process in the industry. This process consumes a large amount of water and energy, necessary for the assembly of cutting fluids. MQL shows to be a possible solution to reduce the consumption of these resources. However, this reduction must be analyzed with criteria, since the withdrawal of the centrifugal pumps in the MQL conflicts with the necessity of the use of compressors for the production of fog when studying the energy consumption.

It is also noted that water and energy are two concerns for both, private and public sectors. In Brazil, these two factors, in addition to being linked during manufacture, are coexistent due to the water energy base.

According to the Ministry of Mines and Energy, Brazilian industry currently consumes 115 TWh, which only 25 TWh are self-produced and responsible for 20% of installed water resources consumption. There is also a forecast of the increase in electricity consumption for large industries of 191.9 TWh, with a self-production of 60.1 TWh by the year 2050 (Ministry of Mines and Energy, Energy Research Company, 2013).

According to researchers from the last decade, the application of MQL, when compared to the flood method, presents some advantages, such as the considerable reduction in the components of shear forces, reduction of the discard volume, cleaner chips, reduction of the cost of process and cleaning. However, these statements are conflicting among authors. According to PUSAVEC (2010), the cutting tool life can be compromised due to a more pronounced wear. Another conflicting factor is the fog generated in the application, which can be considered as an undesirable by-product, contributing to the pollutant content in the air, plus the smoke from the burning oil and the cost of the implantation/adaptation of a compressed air system (RAHMAN et al., 2002).

The divergence between the studies occurs on talking about the machining forces reduction, improvement of tool life and energy consumption analysis (Liao and Lin, 2007; Dhar et al., 2006; Weinert et al., 2004; Meena and Mansori, 2011). Therefore, this paper seeks to study the divergent points, which were raised from a synoptic review, having as motivation the lack of relationship between the key terms of the research.

2. MATERIALS AND METHODS

The material used for testing was gray cast iron DIN GG 25 with 182 HB, this material is used in the manufacture of motors and gears.

All specimens were milled to 380x240x37mm dimensions to ensure perpendicularity to the machine axis. Drilling operations were carried out with carbide drills, 13.5 mm diameter, 140º tip angle and TiAlN coated by Mapal.

In order to define machining parameters for drilling operation, dry tests were performed on the Romi D800. The strength and power data collection were taken simultaneously to the tool life test to compare these effects. Figure **1** illustrates the test´s flowchart.

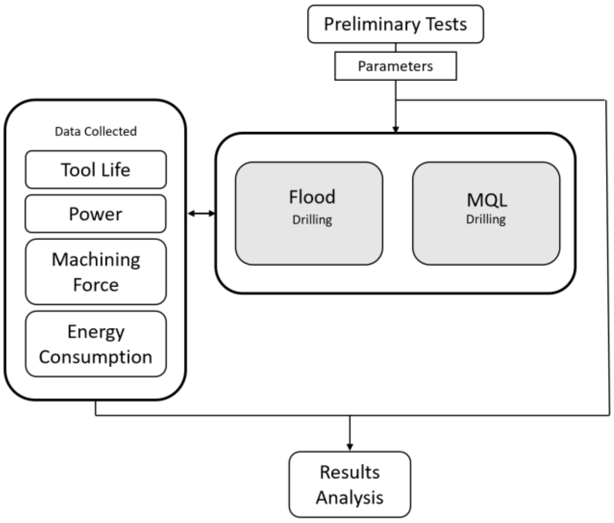


Figure 1. Flowchart test.

Figure 2. MQL system used in adaptation.

For the tests with MQL, the Romi D800 machining center was adapted using Bielomatik's 1-channel system. This system was chosen since it is easy to adapt.

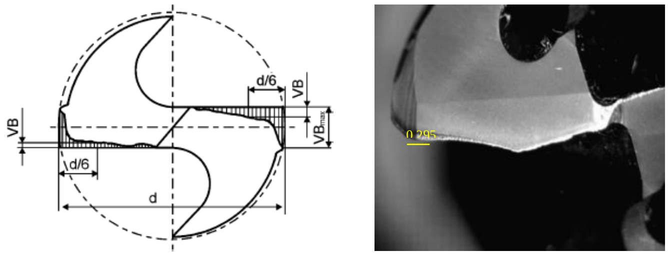
The final test cutting parameters were defined based on the supplier's technical recommendation and preliminary tests. The selected conditions are described in tab. 1.

Table 1. Cutting speed and feed rate used in each setup.

	1	2	3	4
Vc [m/min]	110	110	140	140
f [mm/rot]	0.3	0.4	0.3	0.4

2.1 Tool Life

The end-of-life tool criteria used in the tests was established in ISO 3685/93, VB = 0.3 mm for regular flank wear for drilling, Fig. 3. This value, although, can vary according to the convenience of each industry, since it depends on the machine tool rigidity, precision required, among other factors.



(a) (b)

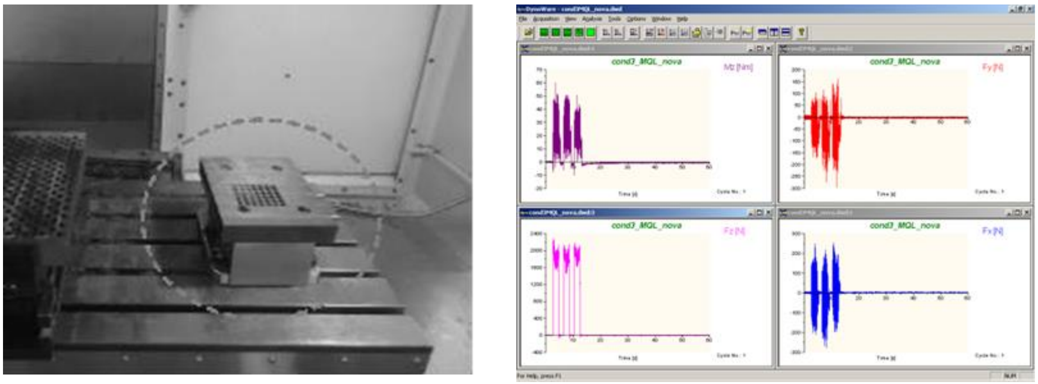
Figure 3. Measurement method of flank wear (a) and measured flank wear (b). Adapted from Dolinsek, Sustarsic & Kopac (2001)

All drills were photographed in the new state and every specimen were machined. The images were captured with a JVC TK-C1380 video camera coupled to a Wild M3C Type-S microscope.

Each drill was tagged to identify the edges. The wear on both flanks was measurement.

2.2 Machining Force

During machining, the momentum and the machining forces were measured by using Kistler's piezoelectric platform, Fig. 4. For the acquisition of the machining force the datas were collected with the platform while three holes were made. In order to monitor the increase in machining force with the tool wear, the force measurements were performed at each stop of wear measurement and compared with the force measured with the drills in new state. These measurements were taken every 30 holes. For each acquisition round, a new file was created in the system's interface software (Dynoware Type 2825-D-02). To ensure a wide range of different load intensities, all acquisitions were performed with a measuring range of 4000 N per amplifier channel.



(a) (b)

Figure 4. (a) Piezoelectric platform for measuring the machining force installed in the machine tool. (b) DynoWare software interface for machining force data collection and treatment.

The measured data were compared with the calculated values. The cutting force and momentum can be calculated by Eq. (1) and Eq. (2), as found in the literature, respectively.

$$F_c = k_c.\left(\frac{f.D}{4}\right) \quad (1)$$

$$M_t = \frac{F_c.D}{2000} = k_c.\left(\frac{f.D^2}{8000}\right) \quad (2)$$

Where:
D = drill diameter [mm];
f = feed [mm/rot];
k_c = specific cutting pressure [N/mm²];

2.3 Energy Consumption

The required power demand was measured by using a Mult-K 120 KRON power meter and a digital magnitude transducer. LabView, which was developed in the laboratory, was used to read and organize the collected data.

The models evaluated for energy consumption are listed in Table 1.

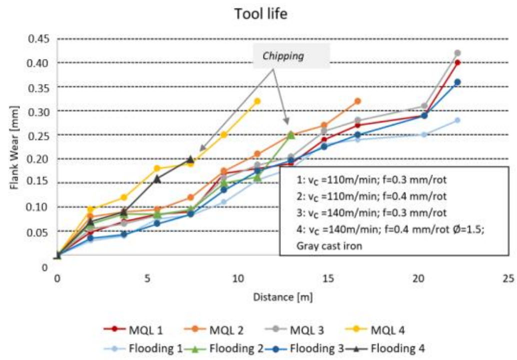
Table 1. Energy consumption models

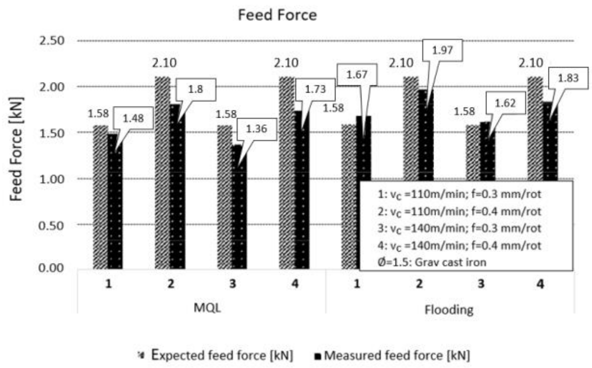
Author	Model
Mori et al. (2011)	$\boldsymbol{E = P_1(T_1 + T_2) + P_2T_2 + P_3T_3}$
	E = total energy consumption [Wh]; P_1, P_2, P_3 *= constant power, idle and cut [W], respectively;* T_1, T_2, T_3 *= corresponding time of the powers.*
Diaz et al. (2011)	$\boldsymbol{E = P.\ \Delta t = (P_{cut} + P_{air}).\ \Delta t}$
	E = total energy consumption [Wh];P = total power demand [W]; Δt *= machining time [h];*P_{cut} *= cut power [W];*P_{empty} *= power demand operating on empty [W]*
He et al. (2012)	$\boldsymbol{E = E_{spindle} + E_{feed} + E_{tool} + E_{cool} + E_{set}}$ $\boldsymbol{E = \int_{tsf}^{tsi} P_m dt + \int_{tcf}^{tci} P_c dt + \sum_{i=1}^{m} \int_{tff}^{tfi} P_i dt + P_{tool} t_{tool} + P_{cool} \Delta t_{cool} + (P_{servo} + P_{air}) \Delta t}$ *(16)*
	P_c *= cut power [W];* P_f *= feed power [W];*P_{tool} *= tool change power [W];* P_{cool} *= power of the cooling pump [W];* P_{servo} *= servo power [W];* P_{air} *= air power [W];* t_{si} *e* t_{sf} *= incial and final spindle time [h];* t_{ci} *e* t_{cf} *= inicial and final cut time [h];*Δt_{pump} *= pump dirve range;*
Balogun & Mativenga (2013)	$\boldsymbol{E = P_b t_b + (P_b + P_r) t_r + P_{air} t_{air} + (P_b + P_r + P_{ref} + k\dot{v}) t_c}$
	E = total energy consumed [W]; P_b *= constant power demand [W];* P_r *= power demand in standby mode (door closed) [W];* P_{empty} *= cutting power operating in empty [W];* P_{cool} *= power of the cooling system; tb = machine time [h]; tr = time of machine to be machined [h]; tar = empty operating time [h]; tc = cutting time [h];k = specific energy required, tabulated value according to the material [kJ/cm³];* $\dot{v}$ *= material remove rate [mm³/s].*
Aramcharoen & Mativenga (2014)	$\boldsymbol{ETotal = Eilde + Etool + Espindle + Ecut + Efeed + Efluid}$
	E_{idle} *= Energy consumed by the machine in the on state without splindle and feed movement;* E_{tool} *= Energy consumed in tool change;* $E_{spindle}$ *= Energy consumed by spindle movement;* E_{cut} *= Energy consumed in the cut;* E_{feed} *= Energy consumed when moving the table or cutter;* E_{pump} *= Energy consumed by the cutting fluid pump.*

3. RESULTS AND DISCUSSION

3.1 Tool Life and Force

The tool life curves, during the operations, presented smoother behavior when applied to the flood technique, Figure 4.1. The researcher PUSAVEC (2010) obtained a similar result to this, where it was observed the decrease of tool life with the use of MQL. However, using the flood technique, the tool tends to flake due to increased feed.





(a) (b)

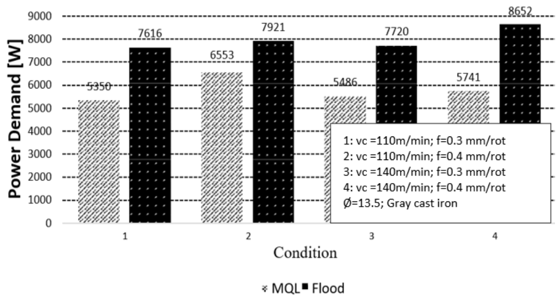
Figure 5. (a) Tool life for each parameter set. (b) Feed Force for each parameter set.

First analyzing the graph, there is a decrease tendency in the force in the order of 200 N. However, when applying the test of Tukey in the measured data, it is noticed that there is no significant difference between the forces. In the literature it is common to find studies describing a considerable decrease in strength with the application of MQL (Tasdelen & T. Wikblom, 2008).

3.2 Energy

The energy consumption forecast models are closer when using the flood technique. None of the models presents the compressed air portion to the MQL, even in machining center where they are designed for this technique use.

In order to compare the operation energy consumption with the two techniques, the machining center power demand and air compressor were measured when using MQL.



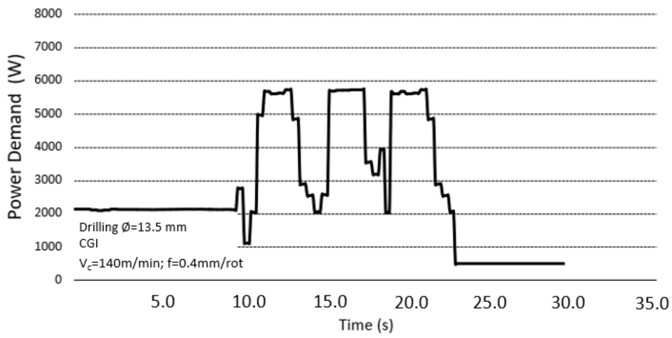


Figure 6. Machine tool active power demand for different cutting conditions in drilling operation (Ø = 13.5) in gray cast iron.

Figure 7. Power demand curve in drilling operation for condition 4 with the flood technique.

Figure 6 represents the active power demands according to the cutting condition and cutting fluid application technique. There was a 30%, 17%, 29% and 34% reduction for conditions 1, 2, 3 and 4, respectively, when using MQL. It is also possible to observe that the cutting conditions variations do not exert a great influence on the power demand, even when the removal rate is increased by 69.69%, as shown in condition 1 to condition 2.

The Figure 7 describes the machining center power demand curve for the drilling operation in gray cast iron using flooding. The peaks represented in the curve correspond to three holes machined during the energy and force acquisition.

When operating at no load, the machining center power demand corresponds to 57.79% of the power consumption compared to the drilling operation.

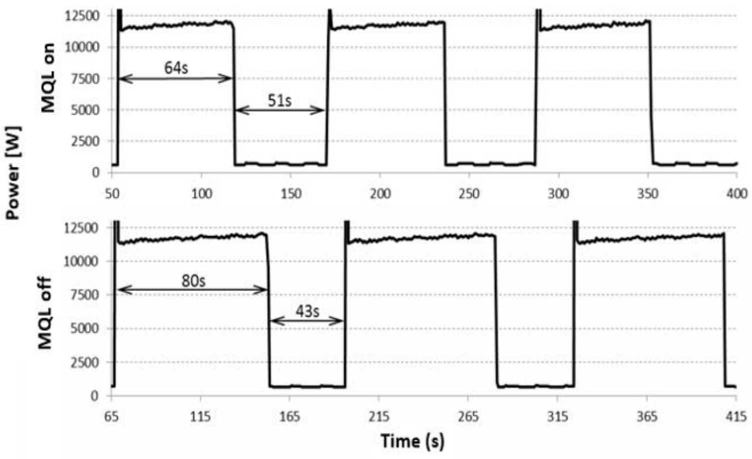
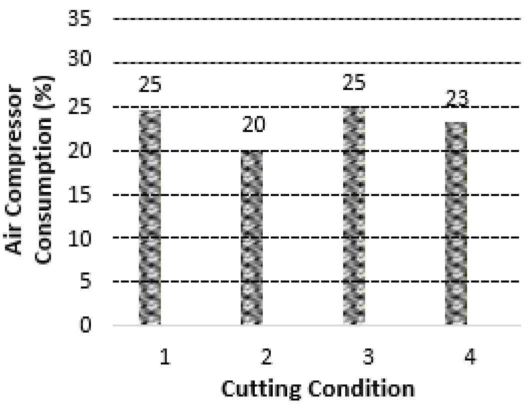


Figure 8. Compressed air system power curve, with MQL on and off.

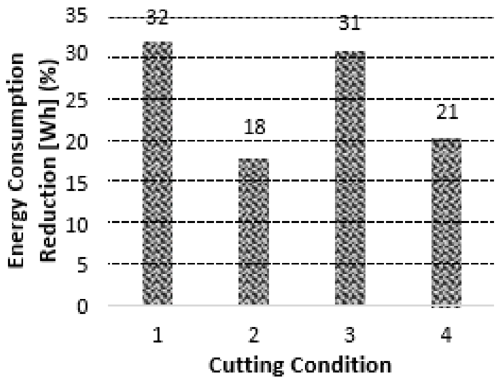
Air compressor operation is intermittent even with MQL system off. In order to have the compressed air power demand, it was necessary to measure the network air consumption with the system turned on and subtract it with the system turned off. The Figure 8 describes the lab network´s power demand curve when MQL is turned off and when it is powered on. Before start-up, the compressor keeps on for 64 seconds and off for 51 seconds. Increased compressed air demand implies on increased time with it on and decreased time when it is off. With the MQL system active, the compressor increases to 80 seconds the time on and decreases to 43 seconds the time off. Thus, the compressed air network without using the MQL system has a compressor drive 56% of the time. When the MQL system is powered on, the compressor's on-time is 66%.

Comparing the power demand represented in Figure 6 for the machining conditions using MQL and flooding, the difference between the active power demands for the two cutting fluid application methods is verified. In condition 4 there was a reduction from 8,652 W to 5,741 W, equivalent to 34%.

Low cutting parameters provide low demand, in the other hand, they imply a longer machining time, leading to higher final energy consumption. The portion of energy dedicated to the cut is low when compared to the total consumption, representing an average of 15%. Most are consumed by the so-called machine basic consumption, which is responsible for lighting, computers, ventilation, etc.



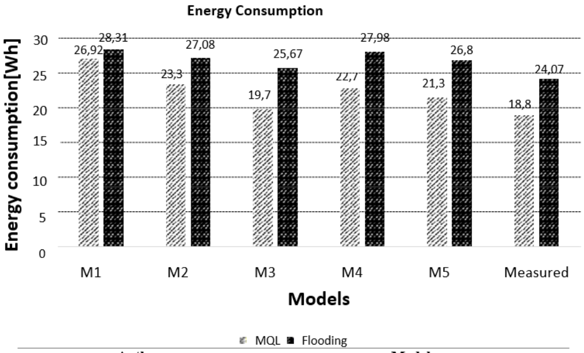
(a)



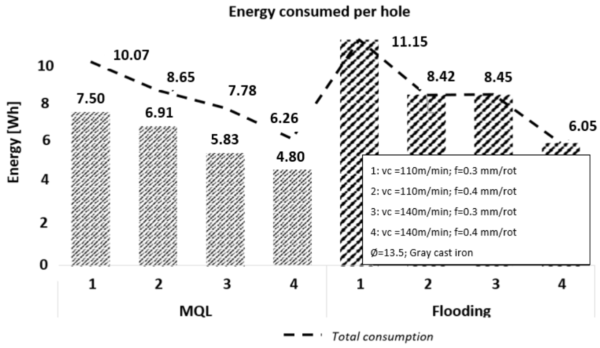
(b)

Figure 9. a) portion consumed by the air compressor in relation to the total consumption of MQL machining; (b) reduction of energy use with MQL.

With the MQL it is possible to reduce the energy consumption, however, this reduction should not be analyzed only from the power demand. According to the data of Figure 9.a, it is possible to verify that the compressed air consumption maintains stability in relation to consumption of the machine tool when using MQL. The consumption corresponds to an average of 23.25% of total consumption per hole with this technique. The reduction in energy consumption is equivalent to an energy demand, this similarity is already expected due to the machining times being equal.



Authr	Model
Mori et al. (2011)	*M1*
Diaz et al. (2011)	*M2*
He et al. (2012)	*M3*
Balogun & Mativenga (2013)	*M4*
Aramcharoen & Mativenga (2014)	*M5*



(a) (b)

Figure 10. Energy consumed according to each model evaluated. (b) Energy consumed in each hole for each set of parameters.

The best comparison is by energy consumption per hole. The calculation of energy consumption can be performed by determining the integral of the power demand curve over time.

As the integral is the area under the curve of a function, the machining center power consumption and the compressor can be determined by calculating the area of their respective curves.

The bars in Figure 4.b represents the energy consumption per hole considering only the machining center consumption and the dotted line reports the total consumption, including compressed air consumption. The coincidence of total consumption with the machine consumption bars for the flooding method is due to the non-use of additional compressed air.

The models presented in Tab. 1 for the energy calculation were tested for the MQL and flooding method. The selected condition was 4 to perform the calculation from the model due to presenting the highest removal rate. The model 5 presented the smallest difference between the calculated value and the measured value (5.23%).

4. CONCLUSIONS

Analyzing the results, it is possible to find the following conclusions for each observed point:

Force

- Machining forces have a decrease with the MQL use. It is possible that this decrease occurs due to the higher oils lubricity employed with this technique. There was a decrease for both torsional moment and forward force.
- The force with the MQL technique kept an average of 200 N below the average found in the flooding. The reason for the decrease in force is different when compared to some studies found, however the materials also different from each other.
- The results are consistent with studies found in the last ten years. These claim a decrease in machining force with the MQL use, however the decrease obtained was not in the same proportion.

Tool Life

- The tool life resulting from the MQL use in drilling gray cast iron differs from the improvement exposed by some work.
- For smaller feeds, the tool life curve is slightly steeper. However, by using MQL it is possible to increase feed without major losses in tool life, which is not the case with flooding.
- With flooding, increased feed rate tends to chip the tool. As MQL oil is more viscous and has a higher lubricity level, it is possible that the unbroken cutting pressure range of the film will be larger.

Energy Consumption

- Power demand using MQL is lower compared to flooding. This can be attributed to the high pressure pump removal, required by the flooding.

- Much overlooked by some authors, air compressor consumption is significant and should be considered. The use of this system corresponds to 23% of total energy consumption when using MQL.

- With the MQL use a reduction in energy consumption is possible, however this should not be analyzed from the power demand only. Low cutting parameters provides low demand, which in turn implies longer machining time, which can lead to higher power consumption at the end.
- The share of energy devoted to cutting is low compared to total consumption, representing an average of 15%. Most of it is consumed by the basic consumption of the machine, which is responsible for lighting, computers, ventilation, etc.
- Power consumption forecasting models are closer when flooding is used, but none of them shows the share of compressed air for MQL
- The tested models provided different results from the measured ones. It is possible that this happened due to the difference between the machining center characteristics of the work presented here and the articles used as reference.

5. ACKNOWLEDGEMENTS:

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