Sustainable machining of molds for tile industry by minimum quantity lubrication

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Abstract

Nowadays, to reduce water pollution, soil contamination, and human health hazards, the environmental legislation is forcing manufacturing companies to avoid the use of metalworking fluids. Thus, the adoption of the dry machining and minimum quantity lubrication (MQL) techniques is becoming essential. However, small and medium companies are having difficulties and are skeptical about the adoption of these new techniques.

In this study, a methodology is proposed to implement an MQL system for sustainable machining with a step-by-step procedure that facilitates its industrial application. The methodology is divided into three steps: i) MQL configuration to verify its effect on surface roughness, considering the effective flow rates and nozzle position; ii) process modeling based on the Box–Behnken design of experiments (DoE) to model surface roughness, power consumption, and tool life; and iii) process optimization for minimizing cost and environmental impact in terms of water usage and kg of CO_2 equivalent.

The methodology is applied in the manufacturing process of a component of a mold for the tile industry. Different alternatives are analyzed and the best alternative in both economic and environmental aspects is the use of the MQL system with optimal cutting parameters and an early tool change strategy that ensures part quality without subsequent grinding operations.

Keywords: Sustainable machining, minimum quantity lubrication, surface roughness, tool wear, milling, grinding.

1. Introduction

Nowadays, manufacturing process optimization requires the setup of process parameters not only to obtain a minimum manufacturing cost but also a minimum environmental impact. The awareness of customers and current environmental legislation in the EU and US is forcing manufacturing companies to strive for developing environmentally friendly manufacturing processes. In machining systems, the use of metalworking fluids (MWFs) is required owing to its positive effect on heat elimination, lubrication of the chip–tool interface, and chip removal (Stephenson and Agapiou, 2016). In many cases, the use of MWFs is mandatory to avoid or minimize the built-up edge (BUE) phenomenon that produces a deficient surface roughness and low tool life due to the adhesion of the workpiece material on the cutting tool (López De Lacalle et al., 2006). However, MWFs entail important environmental issues, especially at the disposal stage, such as hazardous metal carry-off, hazardous chemical constituents, oxygen depletion, oil content, and nutrient loading, which may produce water pollution and soil contamination (Lawal et al., 2013). Besides their negative impact on the environment, MWFs are hazardous substances that can be dangerous for shop-floor operators. Health hazards can range from irritation of the skin, eyes, throat, and lungs, to more severe conditions such as chronic bronchitis, asthma, or even a variety of cancers (Greaves, 1997; Kumar et al., 2014). In terms of economic cost, the use of MWFs may represent from 7% to 17% of the total cost of the machining process, whereas tool costs may represent from 2% to 4%. Thus, the impact of MWFs is not negligible, and they are a factor to take into account in the manufacturer's budget (Klocke and Eisenblaetter, 1997).

For these reasons, dry or near-dry machining strategies have been investigated with promising results, and some of these techniques have been successfully applied in the industry (Debnath et al., 2014; Goindi and Sarkar, 2017; Jawahir et al., 2016; Lawal et al., 2013; Weinert et al., 2004). With the advances in cutting tool technology, dry machining has been a feasible alternative to conventional wet machining operations, and current research in the area of dry machining has moved towards internal cooling (Sun et al., 2012) and heat pipe technology (Liang and Quan, 2013). However, in many cases, dry techniques produce high wear rates of the cutting tools or deficient surface roughness, which encourages the research on near-dry techniques. Among the near-dry techniques, cryogenic cooling is the most promising field of research. Still in an early stage of development, cryogenic cooling uses liquid nitrogen in the cutting zone to reduce the temperature during machining. This technique is an environmentally safe alternative to conventional emulsion cooling because nitrogen evaporates harmlessly into the air, and thus, there is no MWF to dispose of. Furthermore, the generated chips have no residual oil on them and can be recycled as scrap metal (Wang and Rajurkar, 2000). Several research works have proved the effectiveness of the cryogenic cooling technique in terms of better product quality (Dhar and Kamruzzaman, 2007), productivity (Sharma et al., 2009), and reduction of tool wear (Dhar and Kamruzzaman, 2007). However, the initial high cost of the equipment and the limitation of its effectiveness mainly at low cutting speed hinder its industrial implementation (Dhar et al., 2002). Another near-dry technique is the solid lubricant technique, which consists of using as lubricant small solid particles dispersed in an oil base. Depending on the working conditions, this method can be effective for reducing friction between two surfaces in contact. However, this method is complex to use as it requires the selection of the right solid lubricant for each specific application. Some of the applied solid lubricants are graphite (Moura et al., 2015; Nageswara Rao and Vamsi Krishna, 2008) and molybdenum disulphide (Moura et al., 2015; Suresh Kumar Reddy and Nouari, 2011) in powder with SAE 20 oil in various proportions.

Unlike the cryogenic cooling and solid lubricant techniques, the minimum quantity lubrication (MQL) is a near-dry technique that has been widely studied and validated with important benefits with respect to conventional techniques. The MQL technique provides the cutting zone with a small amount of lubricant atomized in a compressed air flow. The lubrication function is carried out by the lubricant oil, which reduces the friction coefficient between the chip and the rake face of the tool, whereas the compressed air provides the cooling function and facilitates chip removal. Although the oil consumption is minimum owing to the small droplets of oil used, it is enough to diminish the tendency of adhesion, improve the surface roughness, and increase the life of the cutting tool. In previous studies, Qin et al. (2016) investigated the turning performance of TC11 titanium alloy using the MQL system with different tool coatings. The obtained surface roughness and tool life improvement were identified for all coatings, and the use of the Al2O3/TiAlN-coated tool proved to be the most suitable for MQL as it increased the tool life by 88.4%. The experimentation showed the importance of using the correct coating to take the advantage of using the MQL technique. Machado and Wallbank (1997) showed that the impact of MQL on surface roughness after turning high and medium carbon steel is noticeable at low cutting speeds; however, at high cutting speeds the influence is of less importance because the formation of the BUE at high speeds is reduced. The effect of dry machining, MQL, and flooded coolant conditions was also analyzed with respect to cutting forces, surface roughness, and tool wear by Sreejith (2008). In the experimentation, it was found that MQL provides a good alternative to the flooded coolant/lubricant conditions as it improves the surface roughness and tool life. Similarly, Wu et al. (2009) studied the influence of different lubrication techniques such as dry machining, flood lubricant, high pressure-air, and MQL with different flow rates on milling operations and different steels. Flank wear evolution, surface roughness, cutting forces, and temperatures were measured, and the main findings were that MQL produces the best surface roughness with lower cutting forces and the distance of the MQL nozzle is a critical setup factor for the MQL performance.

Unlike flood machining, where the base stock of MWFs are mineral oils or polyalkylene glycol, with poor biodegrability and an important environmental impact, MQL uses biodegradable lubricants, such as vegetable oils or synthetic esters. The use of biodegradable lubricants in MWFs has been previously studied. In previous works, Lawal et al. (2012) analyzed the use of different vegetable oils, such as coconut, palm, and sunflower oils, during machining of ferrous metals. The authors stated that the use of vegetable oil-based MWFs could be an environmentally friendly mode of machining, and it obtains a similar performance to that of mineral oil-based MWFs. Similar conclusions were drawn by Cetin et al. (2011), where sunflower and canola fluids with extreme pressure additives performed better for cutting and feed forces than conventional cutting fluids. In MQL, vegetable oil and three different polyol esters were compared and different performance evaluations such as cutting performance, biodegradability, oxidation stability, and storage stability were conducted (Suda et al., 2002). In terms of biodegradability and oxidation and storage stability, synthetic polyol esters showed better performance, and the observed cutting performance was equivalent to that of conventional water-soluble coolants. Therefore, biodegradable lubricants for MQL have proved to be at least as effective as common MWFs based on mineral oils, with much less environmental impact.

Near-dry techniques are usually focused on machining processes such as turning, milling, or drilling. Other processes such as grinding with geometrically undefined cutting edges require high energy density and the inaccessibility of the cutting zone makes it very difficult to reduce the supply of conventional cooling lubricants (Weinert et al., 2004). The implementation of near-dry techniques in grinding processes is still under investigation, although some studies have pointed out some interesting findings (Manimaran et al., 2014). However, if the part quality requirements are not very demanding, the use of near-dry techniques in combination with adequate process modeling and optimization algorithms may produce parts within specifications without additional grinding operations, thus shortening the manufacturing process with minimum cost and environmental impact. Even if a final grinding operation is required, previous machining operations need to ensure a minimum surface roughness to facilitate and economize the grinding operation.

In this paper, a methodology is proposed to evaluate the feasibility of implementing a MQL system that improves the manufacturing process by controlling the surface roughness in milling operations and reducing/removing subsequent grinding operations. The low-cost investment in the MQL equipment and the maturity of this technology, tested through a large body of research, enable the implementation of these sustainable machining processes. The methodology deals with the MQL configuration, the steps required for modeling the machining process, the equations to estimate the economic and environmental impact of the manufacturing process, and the optimization procedure to minimize them. The methodology is applied in the manufacturing process of a component of a mold for the tile industry and the efficiency of the MQL is validated in terms of cost and environmental impact.

The paper is organized as follows. Section 2 provides an overview of the methodology applied in the research. Section 3 shows the experimental setup with the equipment used and the MQL system applied. Section 4 shows the experimental results for each step of the methodology, identifying the MQL parameters, modeling the machining process, and conducting the optimization and sustainability analysis for different production alternatives. Finally, Section 5 presents the main conclusions of the work.

2. Methodology

To replace the costly and non-environmentally friendly grinding operations with conventional milling operations using MQL techniques, it is necessary to understand the milling process and evaluate the feasibility of controlling the process throughout the cutting tool life. The use of MQL in milling may reduce the surface roughness (Qin et al., 2016; Sreejith, 2008) and increase the cutting tool life by four fold compared to dry machining in some cases (Marksberry and Jawahir, 2008), although an increase of 20–25% in tool life has been always reported in the literature (Campatelli, 2009). These machining improvements enable the possibility of controlling the cutting parameters to keep the surface roughness values within specifications for a longer period of time. However, the feasibility of replacing grinding operations with milling operations when the surface roughness specifications are not very demanding requires a comprehensive study of the milling process to find out the optimal milling conditions and to estimate if the resulting machining cost and environmental impact is significantly reduced. For this purpose, the 3-step methodology is proposed as shown in Figure 1. This methodology is defined as follows:

- Step 1: Analysis of MQL parameters. The first step is to analyze the effect of MQL parameters on the machining process. Parameters such as nozzle position or flow rate are critical factors in the performance of MQL. For instance, Lacalle (2006) found an important influence of the relative position between the nozzle and tool feed direction on machining performance. Other authors have studied parameters such as air flow rate, air pressure, and nozzle diameter (Cai et al., 2012; Hwang and Lee, 2010). In this methodology, and according to results reported in the literature, only the nozzle position and flow rate are studied. Additionally, it is critical to evaluate the minimum quantity of lubrication that has a significant impact on the cutting process. Previous studies suggest that a very small quantity of MQL is enough to improve the cutting performance (López De Lacalle et al., 2006); however, a short machining experimentation should be conducted to evaluate this minimum value. Finally, the possible interaction between cutting speed and flow rate should be considered as high cutting speeds reduce the formation of the BUE. Thus, the effect of MQL may only be appreciable at low cutting speeds, whereas at high speeds the benefit of using MQL in terms of surface roughness improvement may be limited (Machado and Wallbank, 1997). After this step, the MQL system has been correctly setup (nozzle position, minimum flow rate to operate) and it has been verified whether its influence on surface roughness is significant at all cutting speeds for the application under study.

- Step 2: Process modeling. In this step, the behavior of the process should be modeled for a later optimization procedure. The variables to be modeled are surface roughness, tool life, power consumption, and runout effect. Surface roughness and power consumption can be modeled according to the design of experiments (DoE). As the main cutting parameters are cutting speed and feed rate (the axial and radial depth of cut are usually predefined), a Box–Behnken DoE can be applied given that it is the most efficient DoE in terms of number of runs within surface response models (NIST/SEMATECH, 2012). The tool life is modeled considering the well-known Taylor equation and experimental data is used to estimate the Taylor coefficients. The runout effect is not directly modeled but is quantified to add this factor into the surface roughness model. Finally, the effect of tool wear on surface roughness is added. Although the influence of tool wear may vary (some researchers have shown that at the first stage of wear, surface roughness may improve (Barber et al., 2001)), a conservative approach is adopted considering that surface roughness linearly increases from new to worn out tool states.

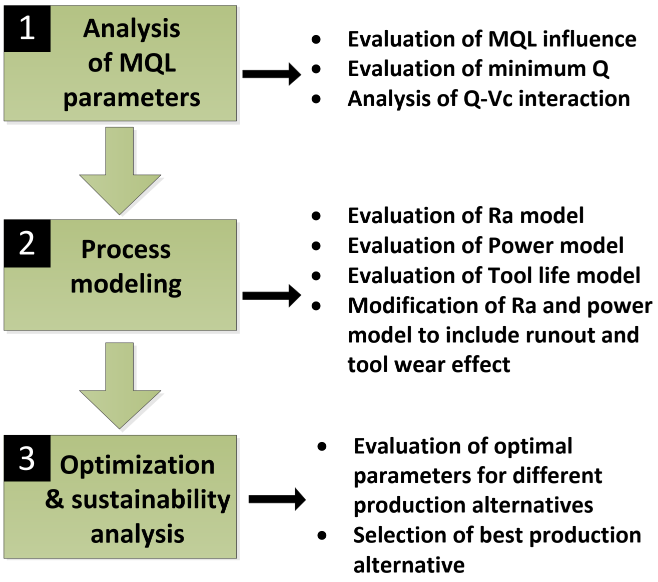

Figure 1. Methodology to analyze and implement MQL systems for sustainable machining processes.

- Step 3: Optimization and sustainability analysis. In the last step, the optimal cutting conditions are evaluated under different production alternatives to minimize the operation cost. For this purpose, the following cost factors are considered: machining center usage cost, grinding center usage cost, cutting tool costs, and coolant cost. The optimization procedure, which is a non-linear optimization problem, is subjected to the maximum surface roughness value owing to part quality requirements. After optimization, the total cost and the environmental impact of each alternative are analyzed and are compared to current practices. The considered environmental factors are water use and kg of CO_2 equivalent. According to the results, one can decide if the MQL approach with optimum cutting parameters can replace efficiently the grinding operation or other alternatives are preferred. Note that the optimization can also be conducted in terms of minimal environmental impact instead of cost, although for most companies the cost optimization procedure with an environmental comparison of the approaches to confirm the environmental improvement is a preferred strategy.

3. Experimental setup

In the tile industry, molds are required to press and shape the ceramic powder before the tile enters in the dryer and kiln for the sintering process. A typical mold is shown in

Figure 2, which is composed of different parts such as upper and lower plates, frame, hydraulic pistons, blocks, and punches. The part under study is the punch, made of DIN C45 steel, whose manufacturing routing sheet is face milling, drilling, tapping, welding the edges for increasing the hardness and wear resistance, and grinding. The operation under study is the milling and grinding operation of the upper surface of the punch, which requires a surface roughness of less than 1.5 µm according to the assembly requirements of blocks and punches. Currently, the milling operation is conducted with a round face cutter mill and compressed air cooling. Compressed air is used instead of MWFs in milling to avoid a thermal shock to carbide tools. The surface is later grinded 0.2 mm in depth using mineral oil as lubricant. Grinding is a non-environmentally friendly operation with high power consumption and expensive cutting tools. Therefore, the manufacturer is interested in estimating the feasibility of using MQL with optimum cutting conditions to avoid the grinding stage, thus improving the manufacturing cost and reducing the environmental impact.

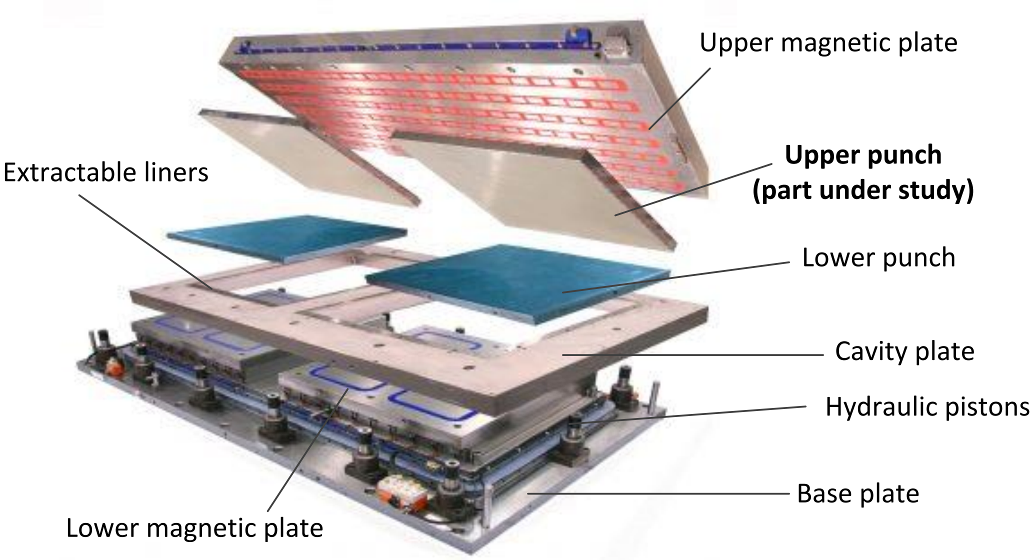

Figure 2. a) Typical mold for manufacturing tiles. Courtesy of MACER S.L.

The experimental setup reproduces the machining operation conducted by the mold manufacturer at the laboratory level. The part under study is the punch, with average dimensions of 700 x 700 x 30 mm. All surfaces are machined, and the upper part of the punch is grinded with a grinding wheel of aluminum oxide to ensure a surface roughness lower than 1.5 µm.

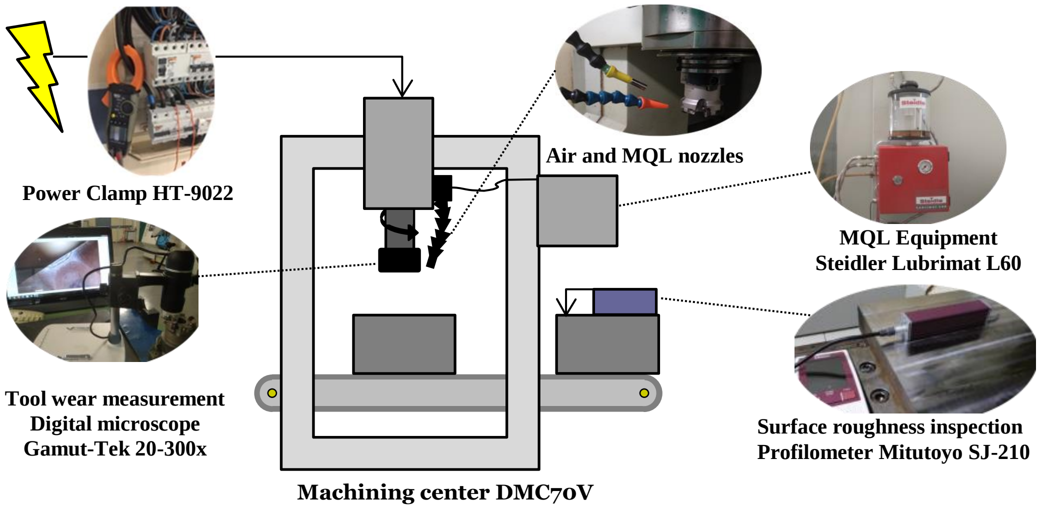

Figure 3. Equipment used for the experimentation.

The machining center used for the experimentation is a Deckel Maho machining center model DMC 70V and the external MQL system is a Steidle Lubrimat L60 with the lubricant Lubrimax Edel C. This lubricant is a high-grade vegetable oil having extreme-pressure additives with a viscosity of 88 mm^2/s (20 °C) and 43 mm^2/s (40 °C), density of 0.93 g/cm^3 (15 °C), and flash point at 200 °C. The used cutting tool is a Sumitomo toolholder WRCX 12052 RS, which is 52 mm in diameter, and 5 octagonal/round carbide inserts, reference QPMT 120440 PPEN-H, which are 12 mm in diameter. During the machining process, the power consumption is measured by a HT9022 power clamp connected to the electrical panel and the power is sampled every second. To measure the tool wear of the inserts, a digital microscope Gamut-Tek 20–300x is used with an amplification set to x50 and 5 Mpixels of resolution. The tool wear is measured according to the ISO norm 8688-1:1989 (ISO, 1989) and the cutting tool flank wear, Vb, is recorded. The surface roughness after machining is measured by a Mitutoyo SJ-210 profilometer with the parameters configured to a cut off length of 0.8 and 5 sampling lengths. Figure 3 shows the equipment used in the experimentation.

4. Experimental results

The proposed methodology is applied for manufacturing the punches of a standard mold in the tile industry. The results at each step are presented below.

4.1 Study of MQL parameters

Before studying the MQL parameters and their influence on surface roughness, a short experimentation is conducted to confirm the benefit of applying MQL with respect to air cooling, the current method used in the company. For a cutting speed (V_c) and feed per tooth (f_z) of 125 m/min and 0.1 mm/tooth, respectively, two longitudinal cutting passes, henceforth runs, are conducted using MQL and air cooling. Additionally, two runs for dry machining are added for comparison purposes. For each run, 10 surface roughness measurements with the profilometer are registered. MQL systems are commonly used with flow rates (Q) less than 50 ml/h and little or no benefit is reported when using higher values (Liao et al., 2017; Sreejith, 2008). Thus, for this experimentation the flow rate of MQL is adjusted to 50 ml/h to ensure sufficient lubrication. The MQL nozzle is mounted at 135° from the tool feed and 100 mm from the cutter inserts, according to other researchers and vendors' recommendations (López De Lacalle et al., 2006; Walker, 2013), see Figure 4. The results from this experimentation are presented in Figure 5, and they clearly show the effectiveness of MQL on the surface roughness quality. The test of the hypothesis shows that the MQL lubrication produces a lower surface roughness value than the dry and air-cooling techniques, with a p-value less than 0.001.

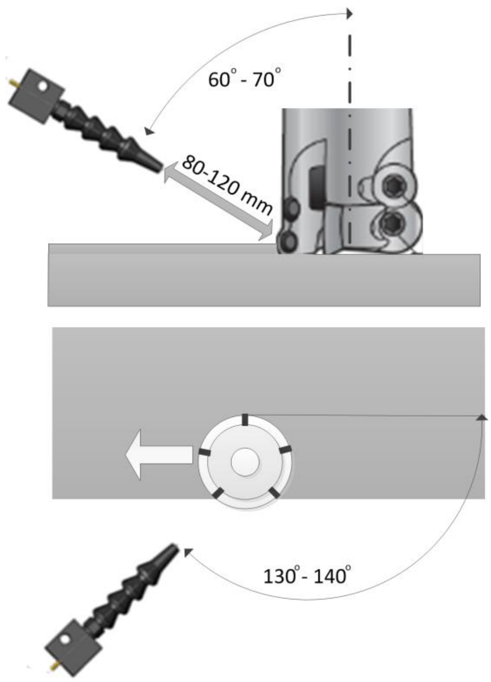

Figure 4. Nozzle setup for the MQL system.

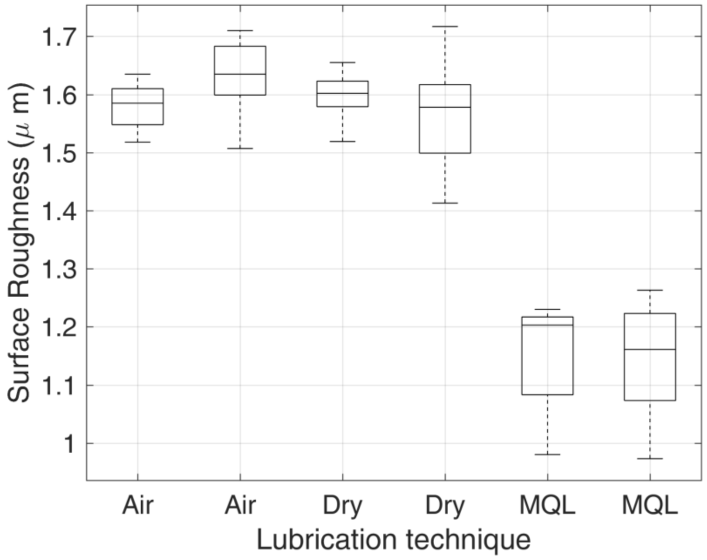

Figure 5. Surface roughness for dry, air cooling and MQL techniques. Cutting conditions: V_c= 125 m/min, f_z = 0.1 mm /tooth. If MQL is used, Q = 50 ml/h.

To evaluate the influence of MQL parameters (flow rate and nozzle position) on the surface roughness, two DoE are conducted: the first DoE varies the flow rate from 5 to 50 ml/h, and the second DoE analyzes the influence of nozzle position, from 0° to 180°. For each MQL set of parameters, two experimental replicates are conducted and 10 surface roughness measurements are obtained at each run. The results are shown in Figure 6, where the influence of the MQL flow rate and the nozzle position on the surface roughness value is clearly observed. According to the hypothesis test, the MQL flow rate of 5 ml/h is statistically different from the 15, 30, and 50 ml/h flow rates, whereas there is no difference between the 15, 30, and 50 ml/h rates. A p-value less than 0.05 shows differences between the samples, suggesting that a minimum MQL value is required to improve the surface roughness, in this case 15 ml/h or higher. The hypothesis test for the nozzle position gives a p-value of 0.433, which means that there is no difference between the nozzle positions. Although other studies recommend the nozzle position at 135° (López De Lacalle et al., 2006; Walker, 2013), according to the results, the orientations of 45°, 90°, 135°, and 180° provide similar surface roughness values for this application.

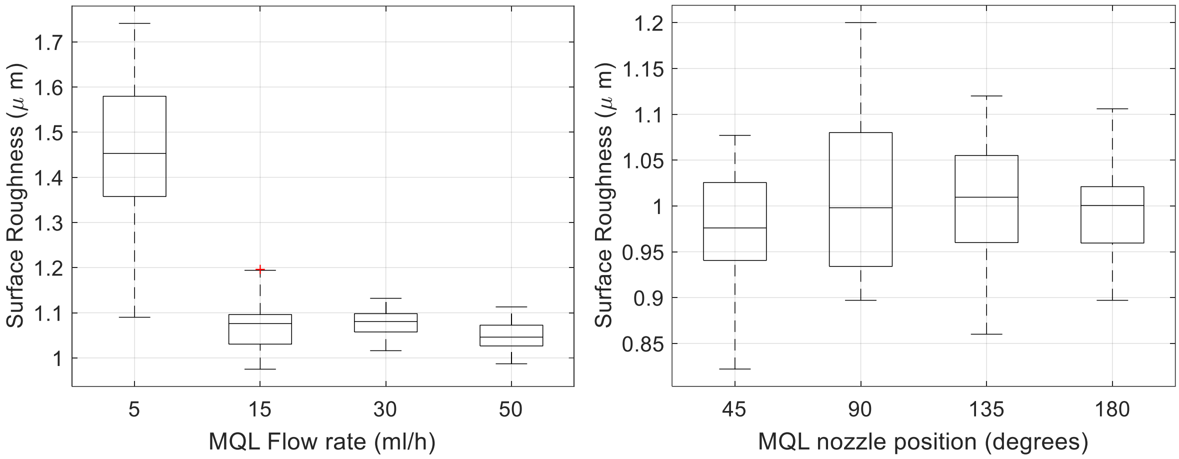

Figure 6. Effect of nozzle position and flow rate on surface roughness. Cutting conditions: V_c= 125 m/min, f_z = 0.1 mm /tooth.

Finally, the interaction between cutting speed and flow rate is analyzed. It is known that high cutting speeds minimize the BUE phenomenon improving the surface roughness. Furthermore, an increase in cutting speed may prevent the penetration of the biodegradable oil in suspension into the cutting area, reducing the MQL effect on surface roughness and tool wear. Therefore, a DoE is required to analyze whether the MQL effect on surface roughness is only limited to low cutting speeds. The DoE is a factorial DoE with two factors and two levels each, V_c = (100, 200) m/min and Q = (0, 50) ml/h, and two replicates, as presented in Table 1. The influence of both factors at low and high values and their interaction is shown in Figure 7. Note that a value of Q = 0 ml/h means that MQL is not applied. It can be seen that both factors and their interaction are significant, although the most important factor on surface roughness is the cutting speed. The interaction plot shows that when applying MQL, the improvement in surface roughness is higher at high cutting speeds than that obtained at dry conditions, which reveals a positive interaction between cutting speed and flow rate. Thus, not only the use of MQL improves the surface roughness values but also increases the positive effect of using high cutting speeds to reduce the BUE phenomenon at least up to 200 m/min.

Exp	**Lubrication**	**V_c (m/min)**	**f_z (mm/tooth)**	**Q (ml/h)**	**Ra Average (µm)**
1	MQL	100	0.1	0	1.85
2	MQL	200	0.1	0	1.05
3	MQL	200	0.1	50	0.95
4	MQL	100	0.1	50	1.50
5	MQL	100	0.1	50	1.55
6	MQL	100	0.1	0	1.79
7	MQL	200	0.1	50	1.03
8	MQL	200	0.1	0	0.99

Table 1 DoE for analyzing the interaction between V_c and Q.

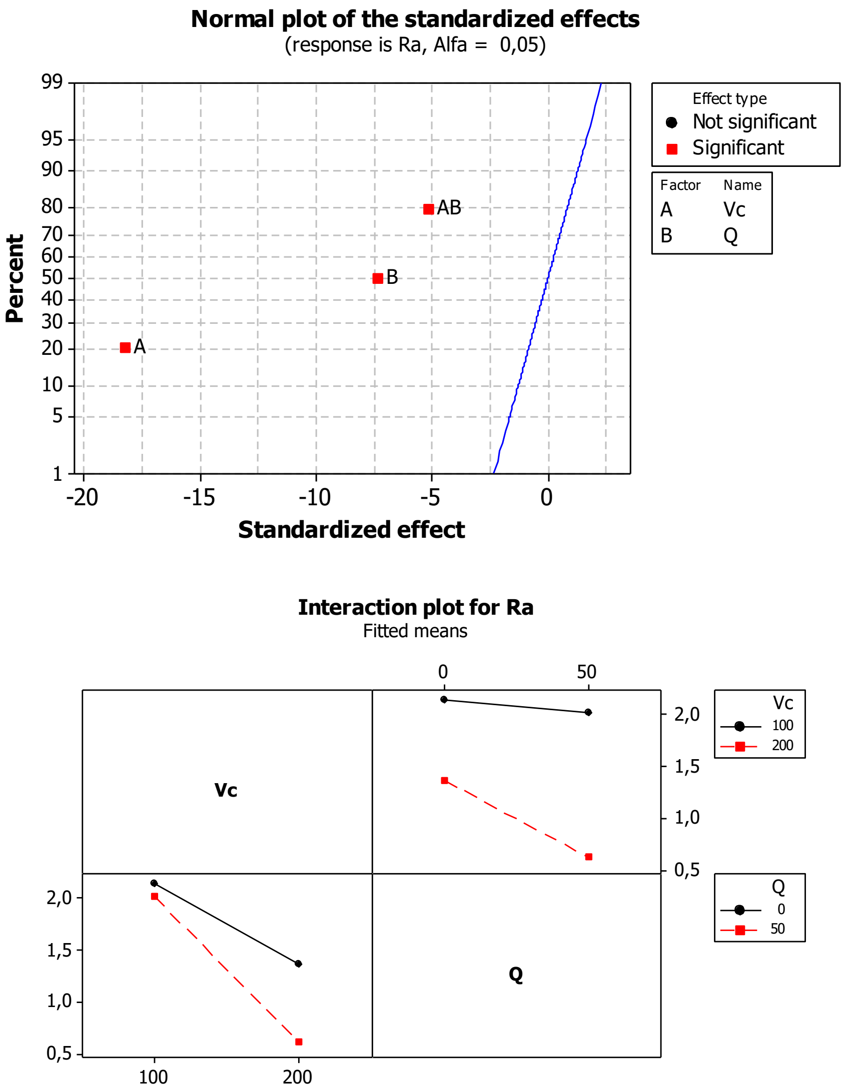

Figure 7. a) Normal probability plot of effects, b) interaction plot between factors.

4.2. Process Modeling

4.2.1 Surface roughness and power consumption model

Surface roughness, power consumption, and tool life are key variables that are related to the cutting parameters and should be modeled to understand, analyze, and optimize the machining process. Surface roughness and power consumption are modeled using the same DoE and new cutting tools. As the radial (a_r) and axial (a_a) depth of cut are predefined (according to the mold manufacturer, a_r is 75% of the diameter and a_a is the depth of 1 mm), only three factors are used in the experimentation: V_c = [100–200] m/min, f_z = [0.05–0.6] mm/tooth, and Q = [15–50] ml/h. Given that the expected results for surface roughness and power consumption are based on linear, quadratic, or second order interaction terms, a Box–Behnken DoE commonly applied for surface response models can fit well for this application. Note that the use of a Box–Behnken DoE for three factors is preferred to other DoE methods, such as central composite designs, because it requires fewer experiments (NIST/SEMATECH, 2012). The DoE conducted is presented in Table 2 and Table 3, and the resulting fitted models are shown in Eqs (1) and (2), with a R^2_{adj} of 80.0% and 99.4%, respectively.

$$Ra' = 5{,}3832 - 0{,}0226 \cdot Vc - 17{,}6527 \cdot fz - 0{,}053 \cdot Q + 27{,}1690 \cdot fz^2 + 0{,}0740 \cdot Vc \cdot fz \pm \varepsilon_{Ra}\ , \tag{1}$$

$$P' = 6127{,}87 - 0{,}4214 \cdot Vc - 3616{,}36 \cdot fz + 83{,}13 \cdot Vc \cdot fz \pm \varepsilon_P\ , \tag{2}$$

where $\varepsilon_{Ra} = \pm\ 0{,}34\ \mu m$ and $\varepsilon_P = \pm 95$ W

Exp	**Lubrication**	**V_c (m/min)**	**f_z (mm/tooth)**	**Q (ml/h)**	**Ra Average (μm)**
1	MQL	150	0.050	50	1.344
2	MQL	100	0.188	50	1.749
3	MQL	150	0.188	32.5	1.405
4	MQL	150	0.188	32.5	1.264
5	MQL	200	0.325	32.5	2.332
6	MQL	150	0.050	15	1.422
7	MQL	100	0.188	15	2.010
8	MQL	150	0.325	50	2.507
9	MQL	150	0.325	15	2.779
10	MQL	200	0.050	32.5	0.572
11	MQL	200	0.188	15	1.559
12	MQL	150	0.188	32.5	1.475
13	MQL	100	0.325	32.5	2.664
14	MQL	100	0.050	32.5	2.941
15	MQL	200	0.188	50	1.433

Table 2 Experimental results for surface roughness modeling based on a Box–Behnken DoE.

Exp	**Lubrication**	**V_c (m/min)**	**f_z (mm/tooth)**	**Q (ml/h)**	**Power consumption (W)**
1	MQL	100	0.600	32.5	8892
2	MQL	100	0.325	50	7506
3	MQL	150	0.325	32.5	8604
4	MQL	200	0.050	32.5	6624
5	MQL	150	0.325	32.5	9045
6	MQL	200	0.325	15	10152
7	MQL	150	0.050	15	6696
8	MQL	200	0.600	32.5	13752
9	MQL	150	0.600	15	11556
10	MQL	150	0.050	50	6462
11	MQL	100	0.325	15	7578
12	MQL	150	0.600	50	11394
13	MQL	100	0.050	32.5	6336
14	MQL	150	0.325	32.5	9108
15	MQL	200	0.325	50	10422

Table 3 Experimental results for power consumption modeling based on a Box–Behnken DoE.

The effect of tool wear in both surface roughness and power consumption is assumed to be a linear factor. Although some studies have experimentally proved that small tool wear values may improve the surface roughness (Barber et al., 2001), the most conservative approach is to assume that the surface roughness increases linearly with tool wear. To evaluate the increase in power and surface roughness due to tool wear, a short DoE with two replicates is conducted for two factors, V_c and f_z, with two levels and a constant flow rate of 15 ml/h. The levels are the minimum and maximum V_c, 100 and 200 m/min, and f_z, 0.05 and 0.325 mm/tooth. This experimentation is conducted twice, once with a new cutting tool and a second time with a worn-out cutting tool. Then, the increases in percentage with respect to power and surface roughness values from the new to worn out states are evaluated. The results are listed in Table 4 and confirm that from the new to worn inserts the increase in surface roughness is critical for ensuring part quality. For the four experimental conditions, the surface roughness always increases when using worn out tools and an increase of up to 50% of surface roughness is reported. However, the increase in power consumption seems to be almost negligible in comparison with the whole machine-tool power consumption.

Exp	V_c (m/min)	f_z (mm/tooth)	Ra (new)	Ra (worn)	ΔRa (%)	Power (new)	Power (worn)	ΔPow (%)
1	200	0.325	2.42	2.76	14%	9712	9784	0.7%
2	100	0.325	2.67	2.94	10%	7937	8137	2.5%
3	200	0.05	0.62	0.90	47%	7284	7128	-2%
4	100	0.05	2.15	2.86	33%	6560	6617	0.9%
5	200	0.188	1.28	1.90	52%	8634	8980	4%
6	100	0.188	2.10	3.10	56%	7242	7341	1.4%

Table 4 Experimental results to evaluate the increase of surface roughness and power consumption when using worn out inserts.

An additional factor for surface roughness modeling is the runout effect. The runout in milling processes is defined as the deviation of the cutting inserts when assembled in the cutter body, which produces different heights of the inserts along the cutting pass. This fact may increase the surface roughness and should be considered in the surface roughness model. To quantify the runout effect, a short experimentation with different inserts should be conducted. In this case, two different cutting conditions are analyzed, each one with five runs. For each run, the five cutting inserts in the mill are replaced by new ones or the same insert is used but with a different cutting edge. Before each run, a coordinate measurement machine (CMM) was used to measure the runout. The conditions tested where V_c = 200 m/min; f_z = 0.1 mm/tooth and V_c = 200 m/min; and f_z = 0.2 mm/tooth. The cutting speed was maintained at 200 m/min, the maximum value recommended by the vendor, because the BUE is minimized at high cutting speeds and the goal of this experimentation is to quantify the runout effect alone. After machining, the average variation in the surface roughness at each run was below ±0.3 µm and the average runout measured by the CMM before each run was below ±30 µm. Thus, the surface roughness deviation due to the assembly of different inserts may modify the expected surface roughness from previous models in ±0.3 µm.

Taking into account all the previous factors, the final model for surface roughness is defined as

$$Ra = Ra' + Ra_{wear} \pm Ra_{runout} , \tag{3}$$

The term Ra_{wear} refers to the increase in surface roughness due to tool wear.

According to the previous experimentation, it is assumed a maximum increase of 50% from the initial surface value when the cutting tool is new, and the increase is assumed to be proportional to its usage time. Then, the variable T_{perc} is defined to indicate the percentage of usage of the cutting tool, for instance, T_{perc} = 0% refers to a new cutting tool and T_{perc} = 100% refers to a cutting tool totally worn out. The proportional contribution of the tool wear on the surface roughness is defined as

$$Ra_{wear} = 0.5 \cdot Ra \cdot \frac{T_{perc}}{100} \ \mu\text{m} \tag{4}$$

The term Ra_{runout} refers to the increase in surface roughness due to runout effects. According to the previous experimentation, a factor of ±0.3 µm is added by Eq. (5)

$$Ra_{runout} = \ \pm 0.3 \ \mu\text{m} \ . \tag{5}$$

The final model for power consumption is defined as

$$P_{mach} = P' + P_{wear} \ , \tag{6}$$

However, according to the experimental results, it is assumed that the increase in power consumption due to tool wear is negligible, and thus, $P_{wear} = 0$.

4.2.1 Tool life model

A tool life model is required for optimizing the machining process because the cutting tool cost and tool changes may be an important factor in the total machining cost. In the literature, the most common tool life model used in machining is the well-known Taylor equation and its extended version (Stephenson and Agapiou, 2016), although other authors have proposed a different extended version to include into the model near-dry machining characteristics such as the mist spray delivery parameters (Marksberry and Jawahir, 2008). In this work, as axial and radial depth of cut are constant parameters, the extended Taylor equation is defined by Eq. (7)

$$T_{life} = \frac{C}{V_c^{n_1} . f_z^{n_2}} \ , \tag{7}$$

where C, n_1, and n_2 are coefficients that depend on a particular tool–workpiece combination. These parameters are obtained by experimentation, wearing out the cutting inserts at a specific cutting parameter combination. Different curves of wearing out were obtained, as shown in Figure 8, measuring the tool flank wear with the microscope every 9 to 25 cutting passes until the flank wear reaches a maximum value of 0.3 mm. The first plot shows three wearing-out curves obtained using a constant feed rate of f_z = 0.1 mm/tooth and three levels of cutting speed, V_c = 240, 200, and 160 m/min. The second plot shows similar curves but using a constant cutting speed of 200 m/min and three levels of feed rates, f_z = 0.2, 0.15, and 0.1 mm/tooth. The final plot shows a comparison between tool life using MQL and air for a given cutting condition. The experimental data from the first two plots was used to experimentally adjust the extended Taylor equation and obtain the coefficients C, n_1, and n_2. The resulting Taylor equation is expressed by Eq. (8)

$$T_{life} = \left(\frac{1036}{Vc}\right)^{\frac{1}{0,285}} \tag{8}$$

and the feed rate was reported to be negligible with respect to tool's life. It should be noted that the proposed methodology is oriented to industrial applications and the experimentation cost is an important limitation. The experimentation could be minimized by setting the factor n_1 to 0.3 according to the recommended values found in the literature for TiC or TiN coated carbides (Stephenson and Agapiou, 2016) and assuming a negligible feed rate. Under these assumptions, only two wearing-out curves are required to estimate the C parameter.

The results from Figure 8 also confirm that the use of MQL increases the cutting tool life by a factor of two. All experiments are conducted with an MQL flow rate of 15 ml/h because, as presented in different research works (López De Lacalle et al., 2006; Wu et al., 2009), no important differences in tool life are obtained by increasing the MQL flow rate as long as a minimum of lubricant reaches the cutting zone correctly.

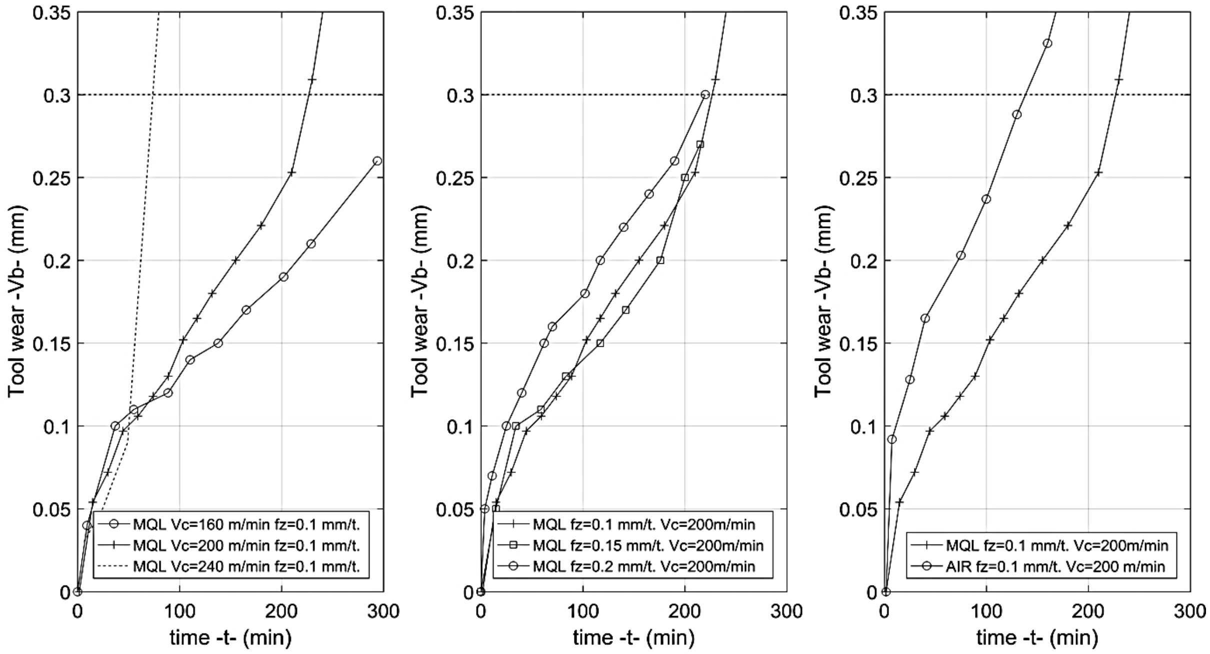

Figure 8. Tool wear evolution for different cutting conditions and cooling techniques. All MQL experiments have been conducted with a flow rate of 15 ml/h.

It should be noted that the experimentation is conducted using one insert instead of five to minimize time and material use. Thus, the tool life test and the results may be not directly the same when the experimental scenario is scaled to the mill with all inserts mounted. As shown by Richetti et al. (2004), the tool life can only be effectively determined under the same real conditions because a change in the number of inserts in the cutter may alter the wear conditions. However, the results using a lesser number of inserts can be used to conduct valid comparisons between two or more machining conditions.

4.3. Optimization results and sustainability impact

4.3.1 Terms of cost

The terms of cost for machining the punch part are defined as a function of the cutting parameters and the MQL parameters for optimization purposes. The milling cost is defined as

$$C_{milling} = C_{machine} + C_{pc} + C_{tool} + C_{lubricant}, \tag{9}$$

and the same equation holds for the cost of grinding, $C_{grinding}$. Each term of cost is defined as follows:

- Cost of the used machine tool ($C_{machine}$)

$$C_{machine} = \frac{(C_{usage}+C_{labor})\cdot t_{op}}{60}, \tag{10}$$

where C_{usage} is the machine tool usage cost rate, and C_{labor} is the operator cost rate, which can be defined as 12 €/h and 18 €/h, respectively (Pusavec et al., 2010b). t_{op} is the operation time, which is defined as

$$t_{op} = t_{mach} + t_{change} + t_{non-mach}. \tag{11}$$

The machining time (t_{mach}) and the cutting tool change time (t_{change}) are defined as

$$t_{mach} = N_p \cdot \frac{V}{MRR}, \tag{12}$$

where V is the machining volume to be removed per part, N_p is the number of parts to be machined, and MRR is the material removal rate (Stephenson and Agapiou, 2016), defined as

$$MRR = a_r \cdot a_a \cdot V_f . \tag{13}$$

In Eq. (13), V_f is the feed rate, evaluated as $N \cdot f_z \cdot z$, where N the spindle speed and z is the number of inserts. The cutting tool change time is defined as

$$t_{change} = t_c \cdot N_{change} \tag{14}$$

where t_c is the time for changing the cutting tool, and the number of cutting tool changes for tool replacement or tool resetting is

$$N_{change} = N_p \cdot \frac{t_{mach}}{T_{life}} \tag{15}$$

where T_{life} is the cutting tool life. The non-machining time ($t_{non-mach}$) depends on the machining operation (air cutting movements, positioning movements, etc.) and should be estimated accordingly.

- Cost of power consumption (C_{pc})

$$C_{pc} = N_p \cdot \left(P_{idle} \cdot (t_{op} - t_{mach}) + P_{mach} \cdot t_{mach}\right) \cdot C_{energy}, \tag{16}$$

where P_{idle} refers to machine-tool power consumption at its idle state, without machining, P_{mach} is the power consumption during machining, which is modeled by Eq. (6) for milling operations, and C_{energy} is the cost of energy in €/kwh. For the grinding machine, the power consumption is assumed as

$$P_{mach} = E_s \cdot V + P_{idle}, \tag{17}$$

where E_s is the specific energy for grinding, assumed as 40 J/mm^3 (Hitchiner et al., 2016), and V is the machining volume per part.

- Cost of cutting tools (C_{tool})

$$C_{tool} = N_{tools} \cdot C_u, \tag{18}$$

where N_{tools} is the number of tools required and C_u is the unitary cost per tool. The number of tools is obtained as

$$N_{tools} = \left(\frac{N_{change}}{N_{edges}}\right), \tag{19}$$

and N_{edges} is the number of cutting edges that can be used per insert. For the grinding machine, N_{edges} is considered to be one as the tool life of the grinding wheel already considers the reuse of the tool.

- Cost of lubricants ($C_{lubricant}$)

In current practice, the mold manufacturer uses air pressure for cooling the milling process and MWFs for the subsequent grinding operations. The costs of lubricant in both processes are estimated as follows. In milling:

$$C_{lubricant} = V_{air} \cdot C_{air} , \tag{20}$$

where C_{air} is the cost of compressed air, which is commonly considered 0.016 €/Nm^3, and V_{air} is the volume consumption of air, which is evaluated as

$$V_{air} = N_p \cdot t_{mach} \cdot Q_{air} . \tag{21}$$

The flow rate of the compressed air is Q_{air}, which is obtained from the specifications of the air-cooling device.

In grinding, the lubricant cost is estimated as

$$C_{lubricant} = C_{MWF} + C_{disposal} + C_{cleaning} , \tag{22}$$

where C_{MWF} is the cost of the MWF, and the costs of disposal and cleaning the filters of the system are $C_{disposal}$ and $C_{cleaning}$, respectively. The disposal and cleaning costs depend on the company practices and equipment, but a good estimation for disposal cost is 0.2 €/l (Pusavec et al., 2010b) and the cleaning cost is directly obtained knowing the frequency of system cleaning and the labor cost.

For the proposed alternatives, the use of MQL is included in the milling operation, and thus, the lubricant cost here is defined as

$$C_{lubricant} = V_{MQL} \cdot C_{MQL} , \tag{23}$$

$$V_{MQL} = N_p \cdot t_{mach} \cdot Q_{MQL} , \tag{24}$$

where Q_{MQL} is the flow rate of the MQL system and C_{MQL} is the cost of the MQL lubricant.

For the manufacturer of the mold under study, the terms of cost are summarized in Table 5.

Workpiece	
Total parts per year (N_p)	500 units
Part dimensions	700 mm x 700 mm x 30 mm
Milling operation	
Cutting edges per insert (N_{edges})	8
Cutting tool replacement time (t_{change})	2 min / tool change
Non-machining time per part ($t_{non\text{-}mach}$)	0.5 min / part
Machine tool consumption at idle state (P_{idle})	6240 W
Milling tool cost (C_u)	50 € (10 €/Insert)
Labor cost (C_{labor})	18 €/h
Usage cost (C_{usage})	12 €/h
Energy cost (C_{energy})	0.13 €/kwh
Compressed air cost (C_{air})	0.016 €/Nm^3
Air flow (Q_{air})	25.5 m^3/h
MQL lubricant cost (C_{MQL})	0.05 €/ml
Grinding operation	
Grinding time per part (t_{mach})	20 min
Non-machining time ($t_{non\text{-}mach}$)	2 min
Cutting tool replacement time (t_{change})	15 min
Cost of grinding wheel (C_u)	1500 €
Tool life (T_{life})	20,000 min
Machine tool consumption at idle state (P_{idle})	3 kw
Specific energy in grinding (E_s)	40 J/mm^3
MWF disposal cost ($C_{disposal}$)	0.2 €/l
MWF cleaning cost ($C_{cleaning}$)	2,500 € (178.5 €/machine-tool*)
MWF cost (C_{MQL})	10 €/l (2,143 €/machine-tool*)

Table 5 Terms of cost for the mold manufacturer under study. *The cleaning cost is considered 1/14 of the total cost since there are 14 machine-tools in the shop-floor.

4.3.2 Optimization and sustainability analysis

The optimization problem is defined as

$$\min_{\{V_c, f_z, T_{perc}\}} Cost = Cost_{milling} + Cost_{grinding} \quad st \quad Ra < Ra_{specifications}, \tag{25}$$

where the range of the cutting parameters for optimization purposes is V_c = [100, 200] m/min, f_z = [0.05, 0.5] mm/tooth, and T_{perc} = [0,100]%. For the optimization step, two optimal solutions are studied. The first solution seeks to minimize the manufacturing cost without replacing the grinding operation and using the MQL system. This solution is called “maximal production,” given that the minimal cost is obtained by maximizing the material removal rate during milling and ensuring a large tool life owing to the use of MQL. After milling, the part is grinded according to the current manufacturer’s practice.

The second solution seeks to replace the grinding operation and uses the milling operation with MQL to ensure that the surface roughness is lower than the surface roughness specification, 1.5 μm. This solution is named “optimal production” as it ensures the part quality and removes the grinding operation, which produces a clear benefit in costs and environmental impact. For this solution, the grinding cost is removed from the total cost as only the milling operation is conducted, but the cutting parameters are optimized to ensure the surface roughness specification after milling. The resulting costs and environmental impact for both solutions are presented in Table 6. For estimating the kg of CO_2 equivalent, 0.000128 kg CO_2-eq per kJ of power consumption is assumed, according to the Ecoinvent Centre database (Ecoinvent-Centre, 2010).

The current practice is conducted under the cutting conditions V_c = 160 m/min and f_z = 0.4 mm/tooth at the milling stage, with an annual cost of machining of 11,401 €. The maximal production is conducted under the optimized cutting conditions V_c = 200 m/min, f_z = 0.5 mm/tooth, and flow rate Q = 15 ml/h, replacing the air-cooling system with the MQL system. Although the cutting speed is increased, the number of cutting tools used is lower than that in the current practice owing to the influence of the MQL in tool life. This approach seeks a maximum production rate, and it decreases the machining cost in 5% and reduces the kg of CO_2 equivalent in 17%. However, the highest benefit of using the MQL system is obtained when the optimal production approach is adopted. For this approach, the optimized cutting conditions are V_c = 200 m/min, f_z = 0.15 mm/tooth, flow rate Q = 50 ml/h, and cutting tool use (T_{perc}) of approximately 40%. Under these conditions, the machining cost and kg of CO_2 equivalent are reduced by 56% and 40%, respectively, mainly because the elimination of the grinding stage. Note that to ensure part quality, the cutting tool should be changed earlier, at 40% of tool's life, which means that the cutting tool is changed when the flank wear is approximately 0.15 mm. Thus, the number of cutting tools at the milling stage increases from 5 to 23 cutting inserts.

	Economic Cost (€)	**Environmental Impact**					
		Nº cutting tools		CO_2 (kg)	Water Use (l)	Lubricant Consumption	
		Nº cutting inserts	Nº grinding wheels			Mineral Oil (l)	Biodegradable Oil (l)
Current Practice (milling with air cooling + grinding)	11,401	5	1	762.4	3357	214.3	0.00
Maximal production (milling with MQL+grinding)	10,714	5	1	630.6	3357	214.3	0.51
Optimal production (milling with MQL)	4,211	23	0	458.5	0.0	0.0	6.11

Table 6 Resulting costs and environmental impact for current practice and the two production alternatives analyzed: maximal production and optimal production.

A further sustainability analysis can be conducted if the environmental impact of the used tools and lubricants are also considered. The energy required for producing coated carbide cutting inserts is assumed to be 1.5 MJ/insert (Rajemi et al., 2010). The energy required for producing the aluminum oxide of the grinding wheels is approximately 50 MJ/kg of material according to Winter (2016). As for lubricants, an emission of 3.56 kg of CO_2 equivalent per kg of mineral oil is commonly applied for sustainability analyses (Pusavec et al., 2010a). Vegetable oils present slightly lower values according to Dumelin (2009), where the maximum value of the different vegetable oils analyzed is 2.5 kg of CO_2 equivalent per kg and it refers to sunflower-based oil. For a conservative approach, this maximum value is used in the analysis.

The results of the three approaches, current practice, maximal production, and optimal production, in terms of economic cost, water use, and total kg of CO_2 equivalent generated for the annual production in the company is shown in Figure 9. The maximal production approach reduces the economic cost and total kg of CO_2 equivalent by 5% and 9%, respectively. This improvement is mainly explained by the increase in the material removal rate, which is commonly the main factor to reduce the total cost (Yoon et al., 2014), and the reduction in the number of used cutting tools owing to the application of MQL. However, the maximal production approach still requires the grinding operation, which increases the final cost and produces a negative impact on the environmental indicators. By adopting the optimal production approach, the milling operation is controlled to ensure a surface roughness within the specifications by reducing the feed rate, increasing the cutting speed, and changing the cutting tool when it reaches a specific cutting tool wear. MQL improves the surface roughness because of its influence on reducing the BUE formation and decreasing the friction coefficient. This approach increases the milling cost as the material removal rate is low in comparison with the other two alternatives and the number of used cutting tools is higher. However, given that the surface roughness is ensured to be within specifications, the grinding operation is excluded and the total cost and total kg of CO_2 equivalent are highly reduced, by 60% and 67%, respectively. Furthermore, 3357 liters of water are annually saved only for the part and operation analyzed under this approach. Besides the economic benefits, the elimination of the grinding operation and its associated MWFs improves the operator working conditions, avoiding common problems such as irritation of the skin and eyes or other more severe conditions.

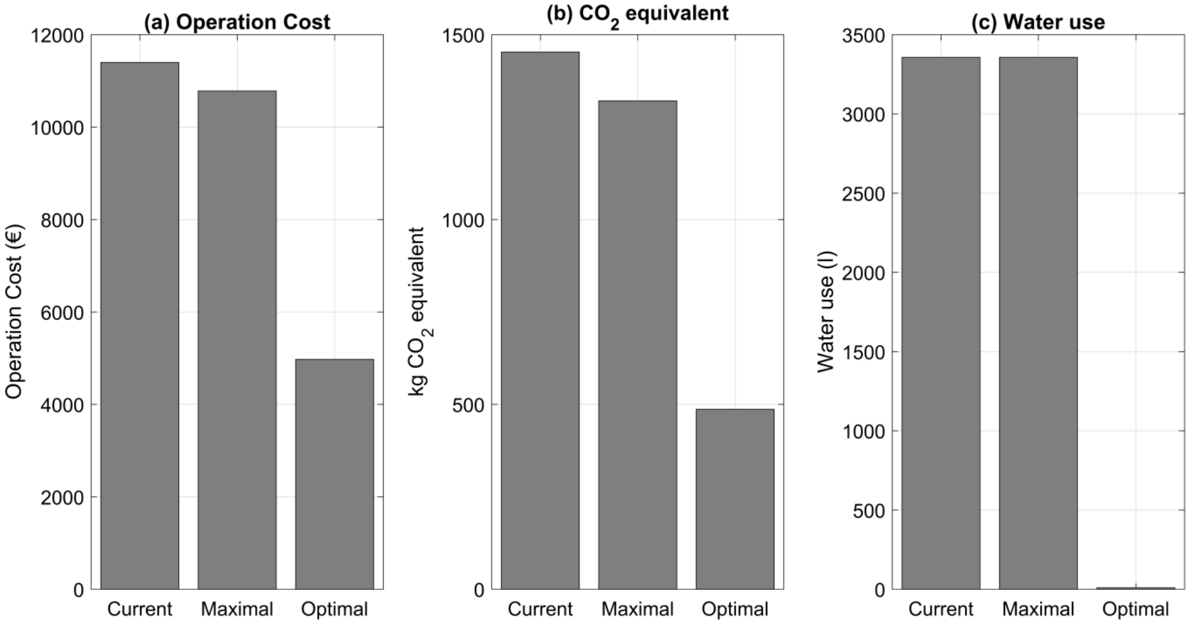

Figure 9. Comparison of the two alternatives (maximal and optimal production) with respect to the current practice in terms of cost, kg of Co_2 equivalent, and water use.

5. Conclusions

A methodology to evaluate the viability of using MQL to improve the sustainability of machining processes has been proposed. With the methodology, the MQL parameters (nozzle position, flow rate) are correctly defined and a Box–Behnken DoE to model surface roughness, power consumption, and tool life is presented. The optimization of the process is conducted afterwards, improving the cutting conditions for minimum cost and environmental impact.

The application of the methodology has been tested in a component of a mold used in the tile industry. Several machining scenarios have been studied and their economic cost and environmental impact in terms of water use and kg of CO2 equivalent were compared. The results showed that, for this case study, the use of MQL considering its influence on surface roughness and tool wear is a better option in both economic and environmental aspects (reduction of 5% in cost and 9% in kg of CO2 equivalent) compared to the current practice with air cooling. Furthermore, the use of MQL with optimal cutting parameters and an early tool change strategy allows excluding the subsequent grinding operation, which results in an important improvement with respect to safe working conditions, environmental impact (reduction of 67% in kg of CO2 equivalent, 3,357 l of water saved), and cost (reduction of 60% in cost).

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