*metals*

*Article*

# The Effects of MQL and Dry Environments on Tool Wear, Cutting Temperature, and Power Consumption during End Milling of AISI 1040 Steel

**Emin Salur [1], Mustafa Kuntoğlu [2], Abdullah Aslan [3] and Danil Yurievich Pimenov [4,*]**

1 Technology Faculty, Metallurgical and Material Engineering Department, Selcuk University, Konya 42130, Turkey; esalur@selcuk.edu.tr
2 Technology Faculty, Mechanical Engineering Department, Selcuk University, Konya 42130, Turkey; mkuntoglu@selcuk.edu.tr
3 Engineering and Architecture Faculty, Mechanical Engineering Department, Selcuk University, Konya 42130, Turkey; aaslan@selcuk.edu.tr
4 Department of Automated Mechanical Engineering, South Ural State University, Lenin Prosp. 76, 454080 Chelyabinsk, Russia
* Correspondence: danil_u@rambler.ru

**Abstract:** Minimum quantity lubrication (MQL) is a sustainable method that has been efficiently applied to achieve machinability improvements with various materials in recent years, such as hardened steels, superalloys, soft metals, and composites. This study is the first to focus on the performance evaluation of MQL and dry milling environments with AISI 1040 steel. The tool wear, cutting temperature, and power consumption were considered as the quality responses while cutting speed, feed rate and machining environment are taken as input parameters. The effects of the influential factors are analyzed using analysis of variance (ANOVA) and bar charts. Additionally, Taguchi signal-to-noise (S/N) ratios are utilized in order to determine the optimum parameters for the best quality responses. The results show that the MQL system provides better performance compared to dry milling by reducing the tool wear, cutting temperature, and power consumption. According to the ANOVA results, the cutting environment affects the cutting temperature (37%) and power consumption (94%), while cutting speed has importance effects on the tool wear (74%). A lower cutting speed (100 m/min) and feed rate (0.10 mm/rev) should be selected under MQL conditions to ensure minimum tool wear and power consumption; however, a higher feed rate (0.15 mm/rev) needs to be selected along with a low cutting speed and MQL conditions to ensure better temperatures. A comparative evaluation is carried out on the tool wear, cutting temperature, and power consumption under MQL and dry environments. This investigation is expected to contribute to the current literature, highlighting the superiority of sustainable methods in the milling of industrially important materials.

**Keywords:** end milling; minimum quantity lubrication (MQL); dry environment; tool wear; temperature; power consumption

check for updates

**Citation:** Salur, E.; Kuntoğlu, M.; Aslan, A.; Pimenov, D.Y. The Effects of MQL and Dry Environments on Tool Wear, Cutting Temperature, and Power Consumption during End Milling of AISI 1040 Steel. *Metals* **2021**, *11*, 1674. https://doi.org/10.3390/met11111674

Academic Editor: Badis Haddag

Received: 16 September 2021
Accepted: 15 October 2021
Published: 20 October 2021



## 1. Introduction

During any machining operation, the primary aim is to cut the material into small pieces to ensure good workpiece quality, dimensions, and geometry. Such processes require huge amounts of energy owing to the large amount of plastic deformation [1]. This energy is needed for the relative motion of the cutting tool and workpiece, as well as the high rotating and linear motions. Most of the energy is transformed into heat, which causes extremely high temperatures at the cutting zone. The negative effects of the excessive temperature are damaging to the material properties, shortening the tool life and increasing the tool wear progression [2,3]. Depending on these developments, the cutting forces can increase and mechanical vibrations can be triggered, which causes poor surface roughness and leads to high power consumption as a result of losing the cutting ability of the cutting tool [4,5]. For this reason, it is critical to keep the cutting temperatures under control, which are related to the optimum cutting parameters and cutting medium; therefore, the use of cutting fluid in metal cutting operations seems to be an effective method. Cutting fluids are able to create a thin layer on the tool-chip interface, which provide less friction on the faces of the cutting tools [6]; however, conventional flood cooling has hazardous impacts on the environment and human health owing to the petroleum-based structure involved. This method provides good lubrication results, but provides insufficient cooling due to the low thermal properties, despite the fluid being consumed abundantly [7]. In addition, the surplus usage of fluid causes extra costs [8]. On the other hand, dry cutting has an advantage in that it requires no fluid, which also removes the extra equipment needed to supply the fluid and reduces the cleaning and disposal costs. Nevertheless, some disadvantages emerge from dry machining, such as insufficient chip evacuation, rapid tool wear, sudden tool breakage, and reduced surface quality [9,10]. It is necessary to use sustainable and clean methods as alternatives to conventional flooding, thereby reducing the quantity of the fluid used and improving the machining efficiency [11]. This situation has been questioned by many researchers and promising results have been found in the past.

The main objectives of using cutting fluids in machining are to prolong tool life and produce a good surface finish by cooling and lubricating the cutting zone [12]. Considering the challenging aspects of dry and conventional flood cooling, MQL can be used as a problem-solving approach considering environmental factors, productivity enhancements, and employee health issues [13,14]. MQL or semi-dry machining is a cooling and lubricating approach based on sending a minimal quantity of fluid in the form of mist into the target zone using pressurized air. In this way, the coolant can access the hard-to-reach tool-chip interface much more effectively, which increases the machining productivity. The name comes from the minimal amounts of cutting fluid consumed with this approach, which is in the range of approximately 10–100 mL/h [15]. One of the prominent advantages of MQL is the fast heat transfer that is achieved through the evaporation of the oil. This eliminates pollution, disposal, and cleaning cycles and medical issues resulting from the cutting fluid [16]. In addition to these, the usage of small amounts of fluid is beneficial to the machining economy [17].

Many studies have been performed in previous years, focusing on the efficiency of the MQL method in machining operations. Among them, some studies evaluated their findings using several optimization approaches. Two notable methods for parameter optimization were heavily applied, i.e., response surface methodology and Taguchi's S/N ratios; however, the Taguchi method has been the most referred method recently. A wale et al. [18] used the Taguchi method for the multi objective optimization of mist parameters in terms of surface quality, microhardness, and wear conditions during grinding of AISI H13 steel. Mia [19] applied both the response surface method and Taguchi S/N ratios for parametric optimization of cutting parameters and MQL conditions to optimize the specific cutting energy and surface roughness. Viswanathan et al. [20] optimized the machining characteristics in the turning of Mg alloy under dry and MQL conditions. Mia et al. [21] used the Taguchi technique for optimization during milling of hardened steel. Many papers in the literature used Taguchi method for parameter optimization during the turning, milling, and grinding of various materials. The Taguchi method is seemingly reliable, feasible, and efficient for parametric optimization.

With increasing ecological concerns around the world regarding industrial revolution 4.0 enterprises, strict precautions have been taken by governments regarding cleaner production in the heavy metal industry [22]. Carbon emission increases depend on the power consumption level and quantity of cutting fluid during the manufacturing processes [23]. The machining sector has great potential to reduce its energy consumption, more so than other sectors [24], because various types of steels, alloys, composites, and hard-to-cut materials need to be machined for final shaping using machining processes. One of them, AISI 1040, is a medium carbon steel that is utilized in many areas, such as in automotive and railway applications and for the fabrication of couplings, crankshafts, and engine parts; therefore, the optimum conditions must be established for the milling of this important steel. Despite there being several papers in the open literature on the machining of medium carbon steels, few papers have focused on milling under dry and MQL conditions. Padmini et al. [25] focused on the evaluation of the productivity of the different types of oils reinforced by varying number of nanoparticles and reported that compared to dry machining of AISI 1040, the cutting force, tool wear, temperature, and surface roughness were significantly reduced using MQL. Dhar et al. [26] carried out an experimental study with the same material in order to compare the performance of dry and MQL-assisted machining, showing that near-dry machining is a perfect alternative to dry conditions according to obtained results, with better tool wear, surface roughness, dimensional deviation, chip-tool interaction, cutting force, and temperature results being observed. Later, Krishna et al. [27] evaluated the tool flank wear, surface roughness, and cutting temperature results under different cutting speed, feed rate, and cutting medium conditions. They examined the effects of oil from tribological and mechanical perspectives in order to produce better machining indicators. Dhar et al. [28] performed a study based on the measurement of MQL performance measures for turning operations during the machining of AISI 1040 steel. The findings indicated that considerable improvements were obtained by employing MQL as compared to dry machining in terms of chip formation, chip-tool interactions, cutting temperatures, and dimensional accuracy. Srikant and Ramana [29] used a green approach for performance measurement of the machinability of AISI 1040 in terms of the cutting temperatures, cutting forces, and tool wear. They compared vegetable emulsifier with regular cutting fluid, which is based on petroleum, and reported on the optimum oil/emulsifier ratio to ensure the best machining performance. Sharma et al. [30] performed a study based on the characterization of nanoparticle-reinforced MQL during the turning of AISI 1040 steel. The authors compared the mentioned system with conventional and dry machining conditions and showed the superiority of the MQL system by examining the surface roughness, tool wear, cutting force, and chip morphology. Kanth et al. [31] experimentally investigated the usage of nanolubrication with MQL during the turning of AISI 1040 steel. The surface roughness and temperature were included as the performance measures and optimum oil and powder mixtures were obtained for maximal machinability. Gugulothu et al. [32] tried to implement a hybrid nanofluid to improve the machining performance of AISI 1040 steel during turning. They optimized the particle concentrations and reported that the cutting forces, temperature, surface roughness, and flank wear can be reduced simultaneously. As can be seen from the highlighted papers, critical analyses and comparisons of dry and MQL techniques for the turning of AISI 1040 steel exist, but no papers have been published for milling conditions.

As can be seen from the literature, comparisons of dry and MQL conditions in terms of performance measures for medium carbon steels are limited. Furthermore, no papers were found relating to the milling of AISI 1040 steel using different cooling strategies; therefore, the performance of MQL compared to dry cutting in the milling of AISI 1040 steel is the object of this paper. According to the collected information on the above-mentioned topics from the open literature, the purpose of this article is to measure the effects of MQL-assisted and dry machining environments on the tool wear, cutting power, and cutting temperature during the milling of AISI 1040. The cutting speed, feed rate, and cutting medium are selected as the experimental parameters. For the experiments, a full-factorial design principle is used, as all input parameters are included as two levels. The obtained findings are evaluated using bar charts and statistical analysis. Finally, the optimization approach is employed using Taguchi S/N ratios to identify the best milling conditions.

## 2. Methodology

### 2.1. Cutting Tool, Workpiece and Machine Tool Conditions

In this paper, AISI 1040 mild carbon steel, which is used extensively in industrial applications, is selected as the workpiece material. The chemical composition of the material is given in Table 1. Milling tests of the workpieces were performed on a CNC machine (Dahlil, Taichung, Taiwan). The experimental tests were performed three times to ensure the reproducibility. The test samples used in the experiments measured Ø40 mm × 5 mm. 403 BT 40 ER32 × 70 instruments (Mas, Leonberg, Germany) were utilized as tool holders. In the milling experiments, HM90 APKT 1003PDR cutting tool inserts (Iscar, Tefen, Israel) were used. The milling tool had a single head (ST90 AP10 D12 W12 L120 Z01) to manage the cutting operation (tool diameter = 12 mm). In addition, face milling was carried out using one tooth with an end-milling-type milling tool. A zig tool path was utilized along with down-milling during the experiments. In the operational range of the machine tool, two cutting speeds and feed rates were selected, along with two cutting environments, which are presented with their units and levels in Table 2.

**Table 1.** The chemical composition of AISI 1040 mild carbon steel (weight %).

| **Fe** | Mn | C | S | P |
|---|---|---|---|---|
| **bal.** | 0.9 | 0.44 | 0.05 | 0.04 |

**Table 2.** Cutting parameters and conditions.

| **Signature** | **Parameters** | **Unit** | **Level 1** | **Level 2** |
|---|---|---|---|---|
| $v_C$ | Cutting Speed | m/min | 100 | 150 |
| f | Feed Rate | mm/rev | 0.1 | 0.15 |
| e | Environment | - | DRY | MQL |

### 2.2. Experiments and Cutting Environments

Machinability experiments were carried out under dry and MQL-assisted conditions. During the physical tests, an MQL device produced by Kar-tes Company (Istanbul, Turkey) was utilized, providing 50 mL/h lubrication in the unit time. A spraying nozzle was mounted approximately 100 mm away from the cutting area. The MQL system was operated with a pressure of 6 bar and nozzle angle of 30°. The setting conditions were determined via preliminary tests before the actual experiments were performed. The cutting oil in the supplying system, KT 2000 oil, was transferred to the cutting area with a Ø2 mm nozzle. In order to compare the performance of the cutting environments, two different cutting speeds (100–150 m/min) and feed rates (0.1–0.15 mm/rev) were adopted in the experimental plan. The depth of cut was kept constant at 2 mm throughout the experiments. The cutting parameters were selected according to the advice of the manufacturer of the cutting tool. Each cutting tool and workpiece sample was used once for each experiment.

### 2.3. Measurement of Tool Wear, Cutting Temperature, and Consumed Power

Since the cutting power, temperature, and tool wear progression give important information about the suitability of the cutting conditions, their measurement is significant. The thermal camera produced by Testo Company (Beijing, China) works based on the principle of the infrared energy. The temperature of the objects is established from the shapes and colors, which are determined according to the infrared energy. After structural imaging, the temperatures can be monitored according to the areas in the measured scene. The maximum cutting temperature in the cutting zone can be determined with the special device software after each experiment. The device has a resolution of 240 × 180 pixels and can measure temperatures up to 650 °C. A thermal camera was positioned approximately

50 cm from the cutting zone. From the visual results, the peak temperature at the cutting zone was considered. After collecting the measured values, software was utilized to determine the peak temperature. This allowed for the measurement of the temperature levels pixel-by-pixel from the interface. On the other hand, for the power consumption measurements, a power quality analyzer produced by Hioki Company (Nagano, Japan) was used. The device was connected to the main spindle cable of the machine tool for calculation of the current and voltage during cutting operations. The device can be connected to thin cables in confined spaces, meaning it can be setup easily. It gives high-precision measurements with an accuracy level of 0.1%. This device is used by calculating the cycle time during the metal cutting process, after which the maximum required power can be determined from a graphical representation of the power signals. Finally, flank wear progression was measured with a microscope (Leika, Wetzlar, Germany). For the determination of the flank wear value, the maximum depth of wear was considered. The features of the experimental setup are schematically represented as the graphical abstract in Figure 1.

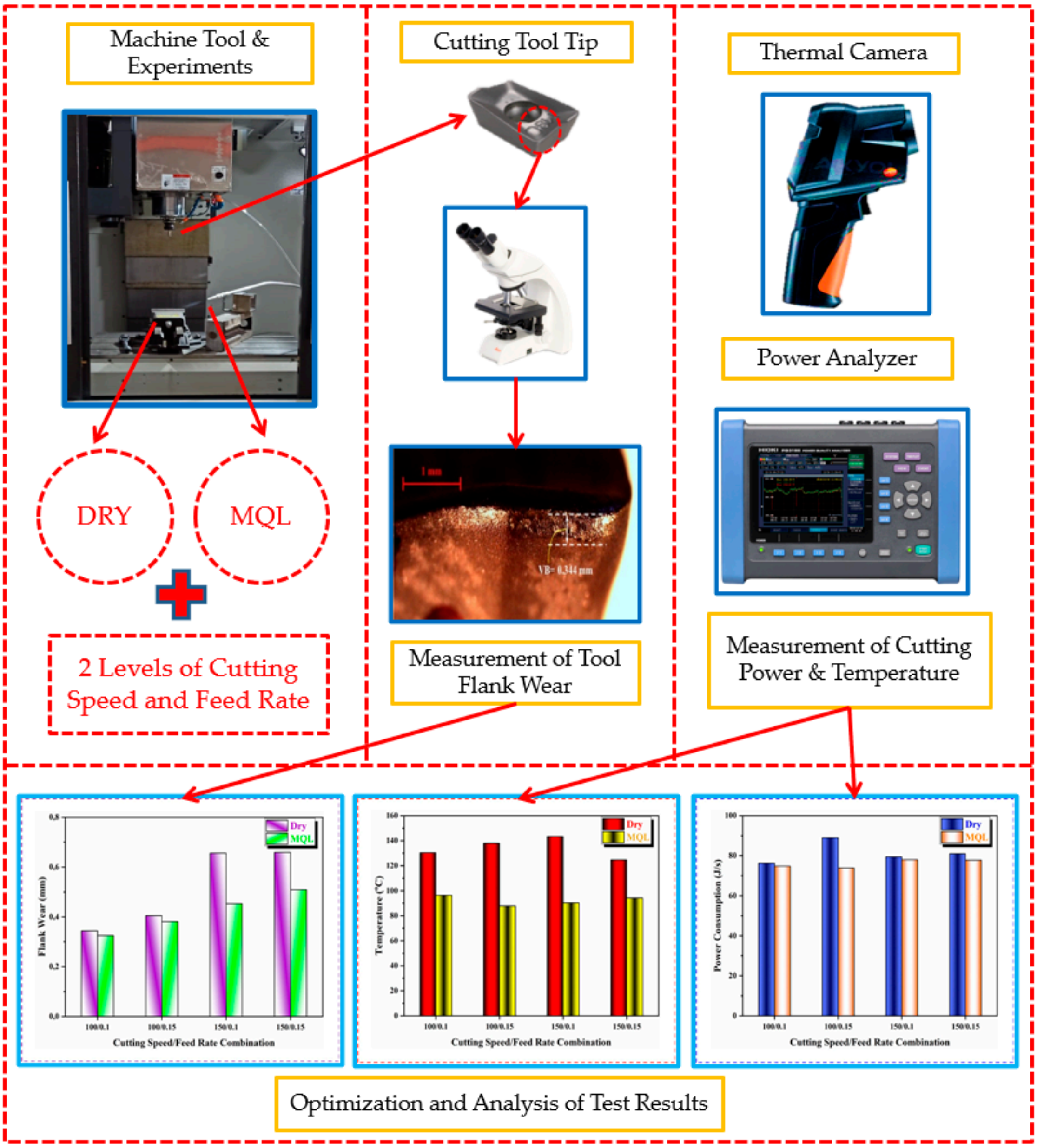


**Figure 1.** Graphical abstract.

### 2.4. Experimental Design, Optimization Approach, and Statistical Analysis

The experiments were carried out according to the Taguchi L8 orthogonal array design, involving two cutting speeds, two feed rates, and two environments. Table 3 outlines the Taguchi L8 orthogonal array plan. This experimental plan is a full-factorial design that allows for the complete analysis of the effects of the parameters. After the experiments, ANOVA-based statistical analysis and Taguchi S/N ratio-based optimization were carried out using Minitab 16 software (Philadelphia, PA, USA). Since the Taguchi-based design and analysis is reliable and preferred for assessing machinability, it was selected in this study for modeling and optimization [33].

As is known, the Taguchi approach uses objective functions in order to optimize the related response parameter. For this, three equations are used, namely maximization, minimization, and normalization equations [34–36]. Since the power, temperature, and wear parameters should ideally be minimal, the second equation is used. In order to minimize the response parameters in this study, a smaller S/N ratio was used. The equation used for the calculation of the S/N ratios of power, temperature, and wear is as follows:

$$\text{S/N ratio}_{\text{ smaller is better}} = -10 \log \left[ \frac{1}{n} \sum_{i=1}^{n} y_i^2 \right] \quad (1)$$

where $y$ shows the responses of the machinability characteristics for trial conditions repeated numerous times.

**Table 3.** The Taguchi $L_8$ full-factorial orthogonal array, including the three main factors, namely the environment, cutting speed, and feed rate.

| Experiment Number | Factor A Environment (mL/h) | Factor B Cutting Speed (m/min) | Factor C Feed Rate (mm/rev) |
|---|---|---|---|
| 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 2 |
| 3 | 1 | 2 | 1 |
| 4 | 1 | 2 | 2 |
| 5 | 2 | 1 | 1 |
| 6 | 2 | 1 | 2 |
| 7 | 2 | 2 | 1 |
| 8 | 2 | 2 | 2 |

## 3. Results and Discussion

In this section, the obtained findings will be examined using graphs and additional methods, such as optimization and analysis. The flank wear, cutting temperature, and power consumption will be evaluated in this manner. The experimental conditions and obtained results for these characteristics and their units are listed in Table 4.

**Table 4.** Experimental conditions and results.

| Experiment Number | Environment | Cutting Speed (m/min) | Feed Rate (mm/rev) | Flank Wear (mm) | Cutting Temperature (°C) | Consumed Power (J/s) |
|---|---|---|---|---|---|---|
| 1 | DRY | 100 | 0.1 | 0.344 | 130.4 | 76.3 |
| 2 | DRY | 100 | 0.15 | 0.405 | 137.9 | 89 |
| 3 | DRY | 150 | 0.1 | 0.656 | 143.4 | 79.5 |
| 4 | DRY | 150 | 0.15 | 0.659 | 124.7 | 81 |
| 5 | MQL | 100 | 0.1 | 0.325 | 96.4 | 74.8 |
| 6 | MQL | 100 | 0.15 | 0.381 | 88 | 73.9 |
| 7 | MQL | 150 | 0.1 | 0.453 | 90.3 | 78.02 |
| 8 | MQL | 150 | 0.15 | 0.509 | 94.3 | 77.8 |

*3.1. Evaluation of Flank Wear under MQL and Dry Cutting Conditions*

Tool wear is one of the most important quality characteristics in machining operations, since it has a critical impact on the cutting geometry, machine surface quality, workpiece dimensions, and cutting mechanism [37]. As tool wear develops on the tool faces, flank wear is accepted as an indicator of the tool life. Flank wear advances on the clearance face of the tool as a result of the high temperature and pressure during cutting operation. Flank wear was the dominant tool wear type in the milling of AISI 1040 steel under dry and MQL conditions in this study. With progressive flank wear, the cutting tool loses its main cutting edge, which leads to greater cutting forces, power consumption, and chatter vibrations; therefore, an in-depth analysis and evaluation of the flank wear is very important. The mechanical load on the cutting tool is the main factor, since it triggers the abrasive wear mechanism between the tool-chip interfaces [38]. Ruptured cutting tool particles result in a harsh cutting zone and have abrasive effects on the tool, resulting in flank wear. During this process, the cutting parameters also have dramatic impacts on the wear conditions. With increased cutting parameters, the cutting tool starts to experience higher cutting loads and cutting forces, resulting in faster wear in theory. In addition, it is important to consider the milling mechanics in order to better understand flank wear with different cutting parameters and cooling conditions.

As can be seen in Figure 2, flank wear occurs on the flank face of the cutting tool. For each experiment, labels were placed on the bottom of the figures and the amount of wear was indicated with markers. To determine the amount of flank wear, the worn zone was detected first, which generally develops along the main cutting edge [39]; however, the spreading form can vary according to the cutting conditions and should be classified as the average and maximum tool wear. The main concern should be to observe whether there is a peak point in the form or whether the worn area continues equally along the cutting edge. In this study, the maximum flank wear land width (VBmax) was considered. According to the observed flank wear values, the minimum flank wear was achieved using MQL-assisted milling with VBmax = 0.325 mm, followed by dry cutting with VBmax = 0.344 mm. The improvement in flank wear was observed to be 5.5% under MQL conditions when compared with dry cutting. An improvement of up to 30.9% was achieved under MQL conditions with a milling speed of 150 m/min and 0.1 mm/rev cutting parameters.

In Figure 3, based on the cooling environment, flank wear developments (mm) are shown according to different cutting speed and feed rate combinations. As can be seen in Figure 3, dry cutting caused worse flank wear under all cutting conditions. As outlined earlier, the tribological conditions have critical impacts on the flank wear development. The MQL approach provides improved cooling from pressurized air and lubrication from oil droplets [40]; therefore, tribological techniques are better than dry milling and produce less tool wear. Regarding the effects of the cutting parameters, it is clear that the cutting speed is the dominant influence on the flank wear progression, irrespective of other factors. When the cutting speed was increased from 100 m/min to 150 m/min, more flank wear was observed. It is worth mentioning that the feed rate showed increasing effects on the flank wear at higher levels (from 0.1 mm/rev to 0.15 mm/rev) as well. This was attributed to the hammering effect of the milling mechanism, which intensified the flank wear progression as the cutting parameters increased.

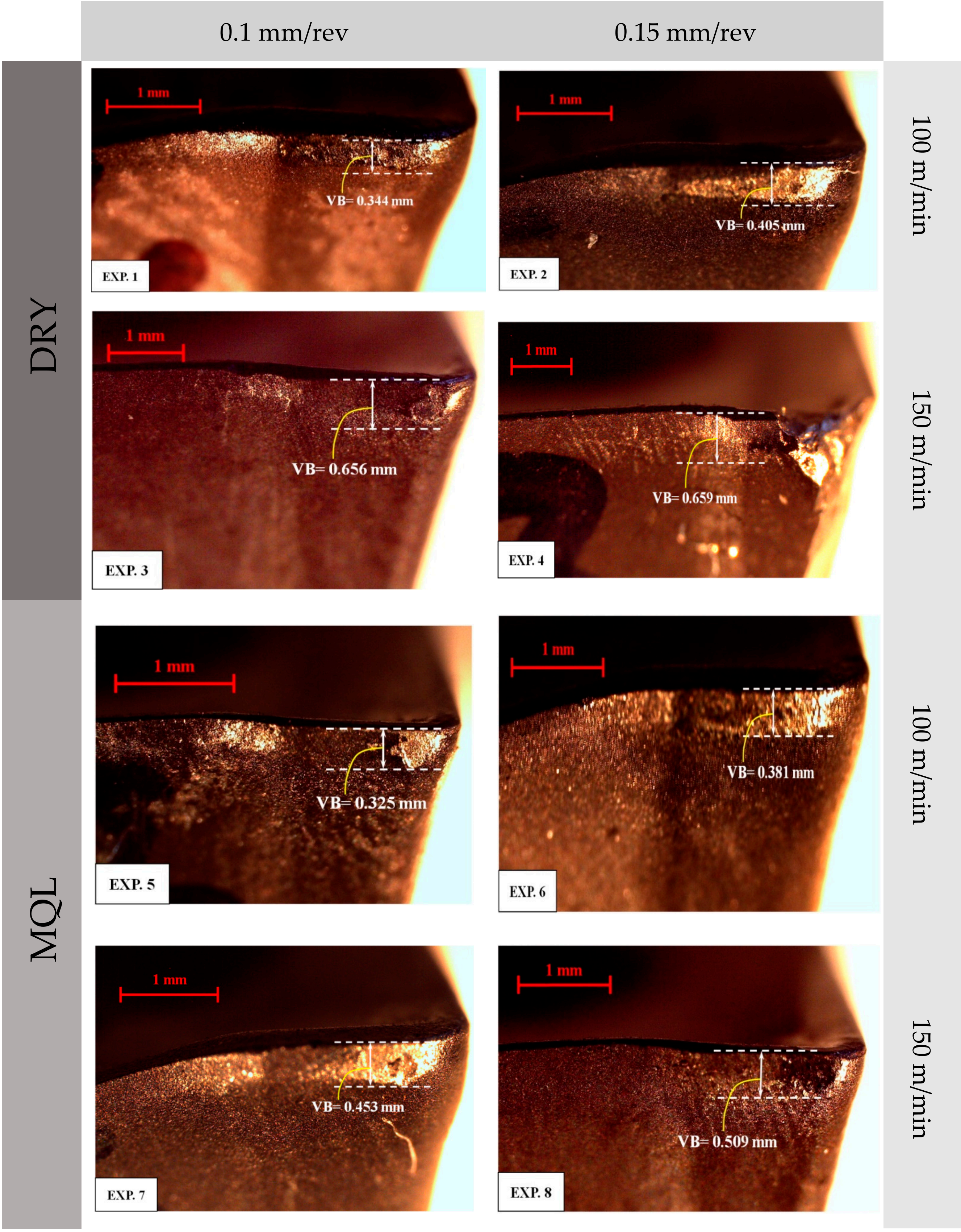


**Figure 2.** Progressive tool wear for each experiment provided as 0.344 mm, 0.405 mm, 0.656 mm, 0.659 mm, 0.325 mm, 0.381 mm, 0.453 mm, 0.509 mm from 1st to 8th experiments.

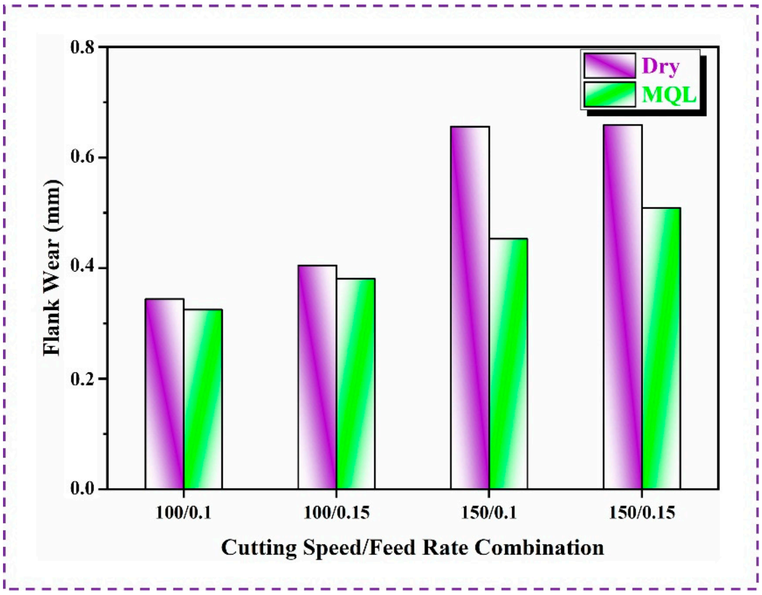


**Figure 3.** Effects of the cutting environment on the flank wear.

### *3.2. Evaluation of Cutting Temperature under MQL and Dry Cutting Conditions*

The temperature in the cutting area is one of the most significant quality factors in metal cutting. In other words, the parameter combinations and cutting geometry directly affect the generated temperature and its dissipation mechanism. A large part of the mechanical energy from the machine tool is converted into heat during the cutting process. Most of the heat generated during cutting should be removed by the chips; however, the dynamic nature of machining makes it hard to achieve the ideal conditions. As a result, the cutting tool and workpiece materials can be affected due to overheating; therefore, cooling is the primary approach used to keep the temperature in the optimal range, which can be achieved with various cutting fluids [41]. The maintenance of the cutting temperature at the desired level plays an important role in the machining efficiency, which can be characterized by the tool life, surface integrity, production costs, and environmental aspects. Dry cutting has traditionally been preferred in machinability studies, although it involves many challenging aspects, such as reduced tool life, excessive cutting temperatures, and a poor surface finish; therefore, the critical point of the temperature is informative in this regard, which is viewed as the peak temperature point in this study. The use of MQL is a good way to overcome these issues, as it provides various positive features, such as being eco-benign and having an effective tool life due to its tribological and thermal properties [42].

As mentioned above, in this study, the critical temperature point is thought to be informative and the peak temperature point is considered from this perspective. Figure 4 shows the experimental results for the peak temperature measured in the cutting zone for dry and MQL conditions when different cutting speed-feed rate combinations were applied. As can be seen in Figure 4, regardless of the cutting parameters, dry cutting produces higher peak temperatures. In MQL machining, the cutting fluid is supplied in the form of oil mist and air, meaning the tool-chip interface can be reached and better lubricating and cooling is provided compared to dry cutting [7,15]. Regarding the minimum peak temperature values, an improvement of 32.5% was obtained with the MQL environment compared to the dry environment. As the cutting speed increased (from 100 m/min to 150 m/min), a general increase in peak temperature was observed, which can be explained by the enhanced friction between the tool and workpiece with the intensifying effects of the cutting speed. No important of meaningful effect was observed for the feed rate on the peak temperature.

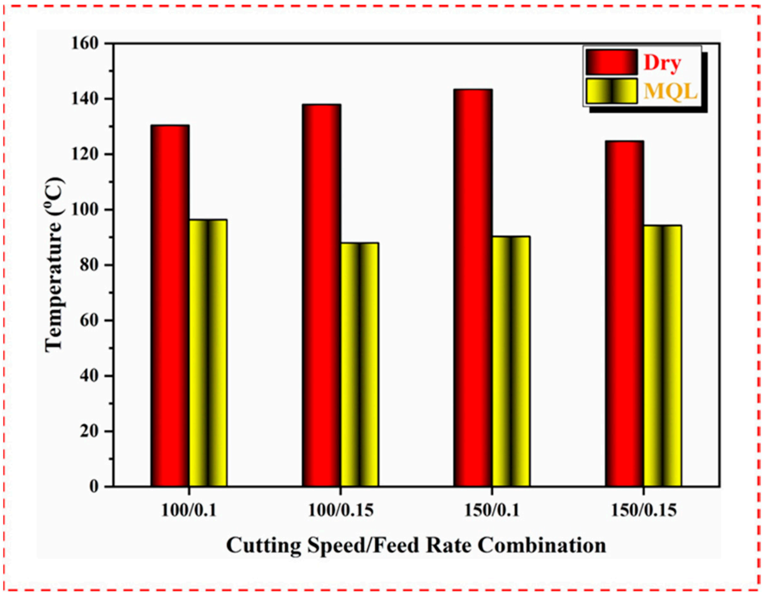


**Figure 4.** Effects of the cutting environment on the cutting temperature.

### *3.3. Evaluation of Power Consumption under MQL and Dry Cutting Conditions*

In industrial companies, the material, time, and energy costs amount to the total cost. A significant portion of the total cost comes from the energy consumption due to the high energy unit prices around the world [8]. Due to increasing environmental concerns, green manufacturing is supported by many governments. Increasing energy consumption not only causes carbon emissions but also the consumption of natural sources, in addition to enhancing the total machining costs [43]. For these reasons, the energy demands of industrial companies should be determined for sustainable manufacturing. Energy consumption is directly related to power consumption, which can be calculated based on the elapsed time. Moreover, almost half of the total costs come from energy consumption [44]. Among other manufacturing methods, machining accounts for a huge amount of the energy consumption due to the long processing periods [45]; therefore, lowering the power consumption is necessary for many reasons and will help avoid machinability issues, resulting in longer tool life and better workpiece-related properties (i.e., surface integrity). In theory, the cutting power depends on the cutting force and cutting speed. In addition, the cutting force is determined by the feed rate, depth of cut, and specific cutting energy; therefore, the basic cutting parameters have significant impacts on the total power consumption. To ensure sustainable and high-quality machining, the effects of the cutting environment on the power consumption need to be evaluated.

As can be seen in Figure 5, different cutting conditions have important effects on the power consumption. When comparing the dry and MQL environments, it is clear that MQL environment always provided minimal power for all parameter combinations. As mentioned before, MQL has tribological and mechanical benefits and allows for the application of optimal cutting parameters. Higher feed rates (0.15 mm/rev) result in increased power consumption under dry conditions; however, the opposite is true under MQL conditions, with lower feed rates (0.1 mm/rev) being observed. This explains why MQL allows for faster machining and lower power consumption. This is attributed to the higher cutting performance of the cutting tool due to the increased tribological properties. Regarding the optimal power values for dry and MQL conditions, an improvement of 16.9% was obtained at 100 m/min and 0.1 mm/rev using MQL compared to dry medium. Regarding the different cutting speed values, a general increase (for MQL but not for dry conditions) in power consumption was observed at the higher cutting speed (150 m/min).

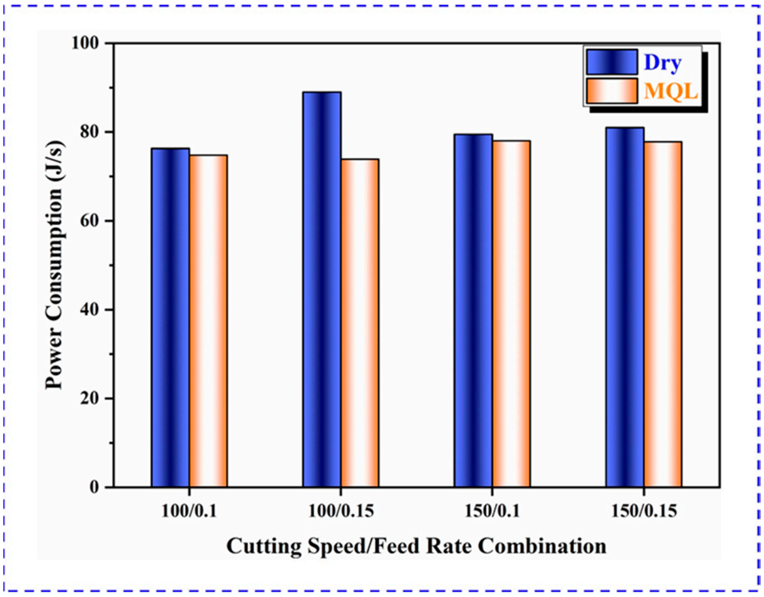


**Figure 5.** Effects of cutting environment on power consumption.

### *3.4. ANOVA Results for the Wear Rate, Weight Loss, and Coefficient of Friction*

ANOVA is a reputable approach that has been extensively applied for engineering applications in many fields. The main purpose of ANOVA is to detect the parameter effects with different statistical approaches. With this comprehensive analysis approach, the most effective parameters based on the responses to numerical indicators can be determined. Three indicators are used to identify the significance of the cutting parameters, namely the F value, *p*-value, and percent contribution (PC). The calculations are made based on the mathematical equations with the sum of the squares of sources, error values, and total values. Table 5 presents the effects of the cutting parameters on the flank wear, cutting temperature, and power consumption. According to Table 5, the cutting environment has the most influence on the power consumption, with a 37% ratio, followed by the cutting temperature, with a 94.5% ratio. On the other hand, the flank wear is most influenced by the cutting speed, with a 74% ratio, which is also verified by the related *p*-value ($0.042 < 0.05$). All of the calculated results show that the F values confirm the obtained findings regarding the effects of the different cutting parameters and environments. All of the ANOVA findings are in good agreement with the previous sections.

**Table 5.** Analysis of variance results for different responses.

| Source | DOF | SS | MS | F Value | *p*-Value | PC (%) |
|---|---|---|---|---|---|---|
| Flank Wear | | | | | | |
| Cutting Speed | 1 | 29.0157 | 29.0157 | 227.62 | 0.042 | 74 |
| Feed Rate | 1 | 1.8536 | 1.8536 | 14.54 | 0.163 | 4.8 |
| Environment | 1 | 5.2546 | 5.2546 | 41.22 | 0.098 | 13.4 |
| Cutting Speed × Feed Rate | 1 | 0.3814 | 0.3814 | 2.99 | 0.334 | 1 |
| Cutting Speed × Environment | 1 | 2.4591 | 2.4591 | 19.29 | 0.143 | 6.3 |
| Feed Rate × Environment | 1 | 0.1094 | 0.1094 | 0.86 | 0.524 | 0.2 |
| Error | 1 | 0.1275 | 0.1275 | - | - | 0.3 |
| Total | 7 | 39.20 | - | - | - | 100 |
| Cutting Temperature | | | | | | |
| Cutting Speed | 1 | 0.000 | 0.00 | 0.00 | 0.997 | 0 |
| Feed Rate | 1 | 0.1634 | 0.1634 | 0.16 | 0.758 | 0.8 |
| Environment | 1 | 21.0275 | 21.0275 | 20.45 | 0.139 | 94.5 |
| Cutting Speed × Feed Rate | 1 | 0.0352 | 0.0352 | 0.03 | 0.883 | 0.1 |
| Cutting Speed × Environment | 1 | 0.0008 | 0.0008 | 0.00 | 0.982 | 0 |
| Feed Rate × Environment | 1 | 0.0122 | 0.0122 | 0.01 | 0.931 | 0.1 |

**Table 5.** *Cont.*

| Source | DOF | SS | MS | F Value | *p*-Value | PC (%) |
|---|---|---|---|---|---|---|
| Error | 1 | 0.1275 | 0.1275 | - | - | 0.3 |
| Total | 7 | 39.20 | - | - | - | 100 |
| Cutting Temperature | | | | | | |
| Cutting Speed | 1 | 0.000 | 0.00 | 0.00 | 0.997 | 0 |
| Feed Rate | 1 | 0.1634 | 0.1634 | 0.16 | 0.758 | 0.8 |
| Environment | 1 | 21.0275 | 21.0275 | 20.45 | 0.139 | 94.5 |
| Cutting Speed × Feed Rate | 1 | 0.0352 | 0.0352 | 0.03 | 0.883 | 0.1 |
| Cutting Speed × Environment | 1 | 0.0008 | 0.0008 | 0.00 | 0.982 | 0 |
| Feed Rate × Environment | 1 | 0.0122 | 0.0122 | 0.01 | 0.931 | 0.1 |
| Error | 1 | 1.0280 | 1.0280 | - | - | 4.5 |
| Total | 7 | 22.2672 | - | - | - | 100 |
| Power Consumption | | | | | | |
| Cutting Speed | 1 | 0.01545 | 0.01545 | 0.08 | 0.826 | 0.8 |
| Feed Rate | 1 | 0.23461 | 0.23461 | 1.19 | 0.472 | 13 |
| Environment | 1 | 0.66165 | 0.66165 | 3.36 | 0.318 | 37 |
| Cutting Speed × Feed Rate | 1 | 0.14970 | 0.14970 | 0.76 | 0.544 | 8.3 |
| Cutting Speed × Environment | 1 | 0.20290 | 0.20290 | 1.03 | 0.495 | 11.3 |
| Feed Rate × Environment | 1 | 0.33184 | 0.33184 | 1.68 | 0.418 | 18.6 |
| Error | 1 | 0.19706 | 0.19706 | - | - | 11 |
| Total | 7 | 1.79320 | - | - | - | 100 |

### *3.5. Optimization of Response Parameters under MQL and Dry Cutting Conditions*

Optimization is one of the most important engineering approaches regarding the requirements of operational plans, such as maximization of the process conditions and minimization of consumption, waste, and costs. From a machining perspective, the optimum parameters provide an ideal cutting geometry and ideal cutting conditions, resulting in minimal cutting forces, tool wear, and cutting temperature and better surface integrity. As mentioned before, minimization of these machining criteria in necessary, namely the wear, temperature, and consumed power. The primary reason that minimal temperatures are crucial is that excessive heat in the cutting zone has harmful impacts on the material properties and reduces the tool life [46]. Moreover, reduced tool life as a result of fast tool wear increases the total manufacturing costs [47]. Additionally, increases in power consumption result in environmental concerns, leading to more carbon emissions and burdening the machining economy [48]. For these reasons, the relevant characteristics need to be optimized; therefore, each response parameter needs to be evaluated under optimal conditions. In this paper, Taguchi-based S/N ratios were in order to obtain the best flank wear, peak temperature, and power consumption parameters. The means of the S/N ratios were calculated for the cutting speed, feed rate, and environment, as shown in Figure 6. A smaller S/N ratio is better when using the Taguchi method, as minimal values are required in order to improve the machinability process. Since the calculations are performed based on the means, higher values are optimal. As can be seen in Figure 6, MQL provides much better tool wear, cutting temperature, and power consumption results compared to dry milling. Unlike dry milling, MQL provides mist oil, which sends homogeneous droplets to the cutting area. In this way, excessive friction can be eliminated by creating a thin film on the contact zones, which is the main reason for high temperatures [49]. Moreover, these droplets can enter the smallest areas around the cutting zone, i.e., tool-chip-workpiece interfaces, reducing the heat through evaporation [47]. Due to these effects of MQL, lower cutting forces are required, which results in lower energy consumption. To ensure minimal tool wear and power consumption, a lower feed rate (0.1 mm/rev) and cutting speed (100 m/min) should be selected, while to ensure the best peak temperature, a high feed rate and cutting speed should be chosen. At this point, it should be noted that due to the increasing material removal rate, higher feed rates increase the tool wear. Due to causing greater deformation, higher cutting speeds increase tool wear [50,51]. It is thought that applying higher feed rate lessens the cutting time, which further affects the power consumption positively. When looking to the cutting temperature plots, the cutting environment is dominant, while other parameter effects can be overlooked.

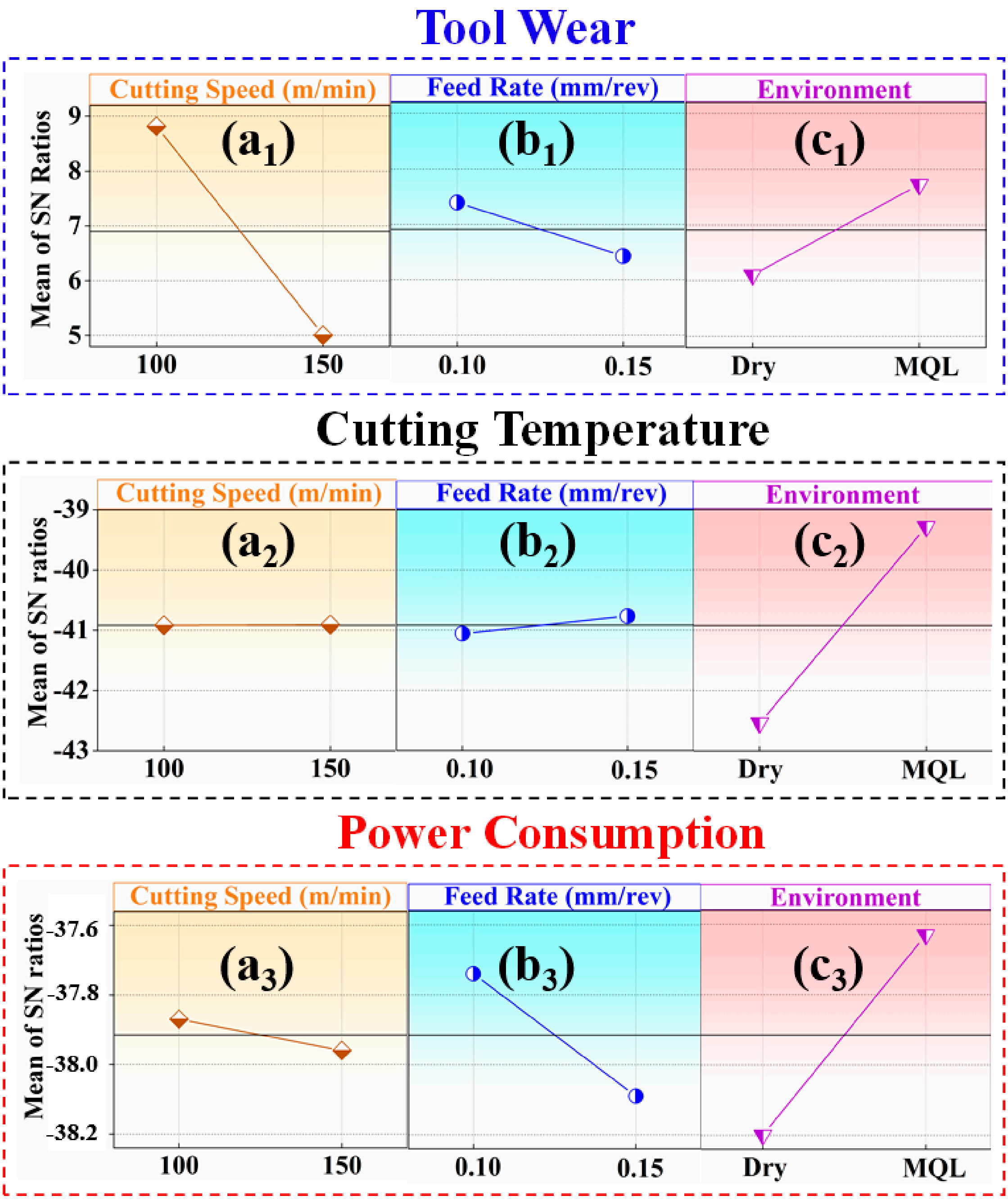


**Figure 6.** Signal-to-noise ratios for the (**a1**–**a3**) tool wear, (**b1**–**b3**) cutting temperature, and (**c1**–**c3**) power consumption related to the tool wear, cutting temperature, and power consumption.

## 4. Conclusions

Some observations can be made based on the results, which are given below:

1. A comparison of MQL and dry environments was carried regarding tool wear, cutting temperatures, and power consumption. MQL results in vital performance improvements in the milling of AISI 1040 steel, due to its ability to remove chips and to cool

and lubricate the cutting area. The tool wear progressions clearly showed that MQL-assisted milling provided better flank wear results than dry cutting under the same cutting conditions. For higher cutting speeds especially (150 m/min), the differences were much greater than for lower cutting speeds (10 m/min);

2. When MQL and dry environments were compared in terms of flank wear, peak temperature, and power consumption, improvements of 30.9%, 32.5%, and 16.9% achieved, respectively;
3. The main benefit of the application of MQL is due to the oil droplets being transmitted to the cutting area during milling operation, reducing the cutting forces by improving the cutting ability of the cutting tool and directly decreasing the power consumption. Better cutting ability brings about resistance to wear, meaning a longer tool life can be achieved. The same mechanism allows for lower cutting temperatures due to the better tribological properties provided by MQL;
4. Thanks to the better cooling and lubrication properties of MQL, the best flank wear, cutting temperature, and power consumption results were obtained under MQL conditions, along with lower cutting speeds (100 m/min). Regarding the minimum cutting temperature, a high feed rate (0.15 mm/rev) and cutting speed (150 m/min) and MQL-assisted milling should be selected;
5. The ANOVA tables outlined the efficacy of the parameters used. Accordingly, the cutting environment is the most effective factor in terms of reducing power consumption (37%) and cutting temperatures (94.5%). On the other hand, flank wear is affected most by cutting speed (74%).

The increasing global industrialization means that cutting operations are becoming more important in the machining world day-by-day. Improved efficiency and the use of environmentally conscious methods are the main demands in today's rapidly increasing market. As such, in this paper a green method was utilized, namely MQL, which improved three significant machining characteristics, including the temperature and tool wear, during the milling of AISI 1040 steel, which is preferred in industry. By applying this method, it is thought that an important contribution can be made not only to the machining economy but also to green technology. The presented method is sustainable and was tested using optimization and analysis methods.

**Author Contributions:** Conceptualization, M.K., E.S. and A.A.; methodology, M.K., E.S. and A.A.; validation, M.K., E.S. and A.A.; formal analysis, M.K., E.S. and A.A.; investigation, M.K., E.S. and A.A.; resources, M.K., E.S., A.A. and D.Y.P.; data curation, M.K., E.S. and A.A.; writing—review and editing, M.K., E.S., A.A. and D.Y.P.; visualization, M.K., E.S., A.A. and D.Y.P.; supervision, D.Y.P.; project administration, M.K., E.S. and A.A.; funding acquisition, M.K., E.S. and A.A. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Yıldırım, Ç.V. Experimental comparison of the performance of nanofluids, cryogenic and hybrid cooling in turning of Inconel 625. *Tribol. Int.* **2019**, *137*, 366–378. [CrossRef]
2. Kuntoğlu, M.; Sağlam, H. Investigation of signal behaviors for sensor fusion with tool condition monitoring system in turning. *Measurement* **2021**, *173*, 108582. [CrossRef]
3. Khanna, N.; Agrawal, C.; Pimenov, D.Y.; Singla, A.K.; Machado, A.R.; da Silva, L.R.R.; Gupta, M.K.; Sarikaya, M.; Krolczyk, G.M. Review on design and development of cryogenic machining setups for heat resistant alloys and composites. *J. Manuf. Process.* **2021**, *68*, 398–422. [CrossRef]

4. Kuntoğlu, M.; Sağlam, H. Investigation of progressive tool wear for determining of optimized machining parameters in turning. *Measurement* **2019**, *140*, 427–436. [CrossRef]
5. Salur, E.; Aslan, A.; Kuntoglu, M.; Gunes, A.; Sahin, O.S. Experimental study and analysis of machinability characteristics of metal matrix composites during drilling. *Compos. Part B Eng.* **2019**, *166*, 401–413. [CrossRef]
6. Şirin, Ş.; Sarıkaya, M.; Yıldırım, Ç.V.; Kıvak, T. Machinability performance of nickel alloy X-750 with SiAlON ceramic cutting tool under dry, MQL and hBN mixed nanofluid-MQL. *Tribol. Int.* **2021**, *153*, 106673. [CrossRef]
7. Yıldırım, Ç.V.; Sarıkaya, M.; Kıvak, T.; Şirin, Ş. The effect of addition of hBN nanoparticles to nanofluid-MQL on tool wear patterns, tool life, roughness and temperature in turning of Ni-based Inconel 625. *Tribol. Int.* **2019**, *134*, 443–456. [CrossRef]
8. Gupta, M.K.; Song, Q.; Liu, Z.; Sarikaya, M.; Jamil, M.; Mia, M.; Singla, A.K.; Khan, A.M.; Khanna, N.; Pimenov, D.Y. Environment and economic burden of sustainable cooling/lubrication methods in machining of Inconel-800. *J. Clean. Prod.* **2021**, *287*, 125074. [CrossRef]
9. Khanna, N.; Shah, P. Comparative analysis of dry, flood, MQL and cryogenic $CO_2$ techniques during the machining of 15-5-PH SS alloy. *Tribol. Int.* **2020**, *146*, 106196. [CrossRef]
10. Sivaiah, P.; Chakradhar, D. Effect of cryogenic coolant on turning performance characteristics during machining of 17-4 PH stainless steel: A comparison with MQL, wet, dry machining. *CIRP J. Manuf. Sci. Technol.* **2018**, *21*, 86–96. [CrossRef]
11. Gupta, M.K.; Song, Q.; Liu, Z.; Sarikaya, M.; Jamil, M.; Mia, M.; Khanna, N.; Krolczyk, G.M. Experimental characterisation of the performance of hybrid cryo-lubrication assisted turning of Ti–6Al–4V alloy. *Tribol. Int.* **2021**, *153*, 106582. [CrossRef]
12. Gupta, M.K.; Pruncu, C.I.; Mia, M.; Singh, G.; Singh, S.; Prakash, C.; Sood, P.; Gill, H.S. Machinability investigations of Inconel-800 super alloy under sustainable cooling conditions. *Materials* **2018**, *11*, 2088. [CrossRef]
13. Kuntoğlu, M. Tool Flank Wear Analysis for MQL Assisted Milling of Strenx 1100 Structural Steel. *Avrupa Bilim Teknol. Derg.* **2021**, 629–635. [CrossRef]
14. Kuntoğlu, M. Surface Roughness Evaluation in Milling of Strenx 1100 Steel under MQL Conditions. *Avrupa Bilim Teknol. Derg.* **2021**, 509–516. [CrossRef]
15. Yıldırım, Ç.V.; Kıvak, T.; Sarıkaya, M.; Erzincanlı, F. Determination of MQL parameters contributing to sustainable machining in the milling of nickel-base superalloy waspaloy. *Arab. J. Sci. Eng.* **2017**, *42*, 4667–4681. [CrossRef]
16. Sharma, V.S.; Singh, G.; Sørby, K. A review on minimum quantity lubrication for machining processes. *Mater. Manuf. Process.* **2015**, *30*, 935–953. [CrossRef]
17. Behera, B.; Ghosh, S.; Rao, P. Application of nanofluids during minimum quantity lubrication: A case study in turning process. *Tribol. Int.* **2016**, *101*, 234–246.
18. Awale, A.S.; Vashista, M.; Yusufzai, M.Z.K. Multi-objective optimization of MQL mist parameters for eco-friendly grinding. *J. Manuf. Process.* **2020**, *56*, 75–86. [CrossRef]
19. Mia, M. Mathematical modeling and optimization of MQL assisted end milling characteristics based on RSM and Taguchi method. *Measurement* **2018**, *121*, 249–260. [CrossRef]
20. Viswanathan, R.; Ramesh, S.; Subburam, V. Measurement and optimization of performance characteristics in turning of Mg alloy under dry and MQL conditions. *Measurement* **2018**, *120*, 107–113. [CrossRef]
21. Mia, M.; Al Bashir, M.; Khan, M.A.; Dhar, N.R. Optimization of MQL flow rate for minimum cutting force and surface roughness in end milling of hardened steel (HRC 40). *Int. J. Adv. Manuf. Technol.* **2017**, *89*, 675–690. [CrossRef]
22. Mia, M.; Gupta, M.K.; Singh, G.; Królczyk, G.; Pimenov, D.Y. An approach to cleaner production for machining hardened steel using different cooling-lubrication conditions. *J. Clean. Prod.* **2018**, *187*, 1069–1081. [CrossRef]
23. Khan, A.; Liang, L.; Mia, M.; Gupta, M.; Wei, Z.; Jamil, M.; Ning, H. Development of process performance simulator (PPS) and parametric optimization for sustainable machining considering carbon emission, cost and energy aspects. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110738. [CrossRef]
24. Krolczyk, G.; Maruda, R.; Krolczyk, J.; Wojciechowski, S.; Mia, M.; Nieslony, P.; Budzik, G. Ecological trends in machining as a key factor in sustainable production–a review. *J. Clean. Prod.* **2019**, *218*, 601–615. [CrossRef]
25. Padmini, R.; Krishna, P.V.; Rao, G.K.M. Effectiveness of vegetable oil based nanofluids as potential cutting fluids in turning AISI 1040 steel. *Tribol. Int.* **2016**, *94*, 490–501. [CrossRef]
26. Dhar, N.; Ahmed, M.; Islam, S. An experimental investigation on effect of minimum quantity lubrication in machining AISI 1040 steel. *Int. J. Mach. Tools Manuf.* **2007**, *47*, 748–753. [CrossRef]
27. Krishna, P.V.; Srikant, R.; Rao, D.N. Experimental investigation on the performance of nanoboric acid suspensions in SAE-40 and coconut oil during turning of AISI 1040 steel. *Int. J. Mach. Tools Manuf.* **2010**, *50*, 911–916. [CrossRef]
28. Dhar, N.; Islam, M.W.; Islam, S.; Mithu, M.A.H. The influence of minimum quantity of lubrication (MQL) on cutting temperature, chip and dimensional accuracy in turning AISI-1040 steel. *J. Mater. Process. Technol.* **2006**, *171*, 93–99. [CrossRef]
29. Srikant, R.; Ramana, V. Performance evaluation of vegetable emulsifier based green cutting fluid in turning of American Iron and Steel Institute (AISI) 1040 steel–an initiative towards sustainable manufacturing. *J. Clean. Prod.* **2015**, *108*, 104–109. [CrossRef]
30. Sharma, A.K.; Singh, R.K.; Dixit, A.R.; Tiwari, A.K. Characterization and experimental investigation of Al2O3 nanoparticle based cutting fluid in turning of AISI 1040 steel under minimum quantity lubrication (MQL). *Mater. Today: Proc.* **2016**, *3*, 1899–1906. [CrossRef]
31. Kanth, V.K.; Sreeramulu, D.; Srikiran, S.; Kumar, M.P.; Jagdeesh, K.; Govindh, B. Experimental investigation of cutting parameters using nano lubrication on turning AISI 1040 steel. *Mater. Today Proc.* **2019**, *18*, 2095–2101. [CrossRef]

32. Gugulothu, S.; Pasam, V.K. Experimental investigation to study the performance of CNT/MoS2 hybrid nanofluid in turning of AISI 1040 stee. *Aust. J. Mech. Eng.* **2020**, 1–11. [CrossRef]
33. Kuntoğlu, M.; Sağlam, H. ANOVA and fuzzy rule based evaluation and estimation of flank wear, temperature and acoustic emission in turning. *CIRP J. Manuf. Sci. Technol.* **2021**, *35*, 589–603. [CrossRef]
34. Kuntoğlu, M.; Acar, O.; Gupta, M.K.; Sağlam, H.; Sarikaya, M.; Giasin, K.; Pimenov, D.Y. Parametric Optimization for Cutting Forces and Material Removal Rate in the Turning of AISI 5140. *Machines* **2021**, *9*, 90. [CrossRef]
35. Şap, E.; Usca, Ü.A.; Gupta, M.K.; Kuntoğlu, M.; Sarıkaya, M.; Pimenov, D.Y.; Mia, M. Parametric optimization for improving the machining process of cu/mo-sicp composites produced by powder metallurgy. *Materials* **2021**, *14*, 1921. [CrossRef] [PubMed]
36. Usca, Ü.A.; Uzun, M.; Kuntoğlu, M.; Şap, S.; Giasin, K.; Pimenov, D.Y. Tribological aspects, optimization and analysis of Cu-B-CrC composites fabricated by powder metallurgy. *Materials* **2021**, *14*, 4217. [CrossRef]
37. Liu, D.; Zhang, Y.; Luo, M.; Zhang, D. Investigation of tool wear and chip morphology in dry trochoidal milling of titanium alloy Ti–6Al–4V. *Materials* **2019**, *12*, 1937. [CrossRef]
38. Gupta, M.K.; Song, Q.; Liu, Z.; Sarikaya, M.; Mia, M.; Jamil, M.; Singla, A.K.; Bansal, A.; Pimenov, D.Y.; Kuntoğlu, M. Tribological performance based machinability investigations in cryogenic cooling assisted turning of α-β titanium alloy. *Tribol. Int.* **2021**, *160*, 107032. [CrossRef]
39. Aslan, A. Optimization and analysis of process parameters for flank wear, cutting forces and vibration in turning of AISI 5140: A comprehensive study. *Measurement* **2020**, *163*, 107959. [CrossRef]
40. Sarikaya, M.; Gupta, M.K.; Tomaz, I.; Danish, M.; Mia, M.; Rubaiee, S.; Jamil, M.; Pimenov, D.Y.; Khanna, N. Cooling techniques to improve the machinability and sustainability of light-weight alloys: A state-of-the-art review. *J. Manuf. Process.* **2021**, *62*, 179–201. [CrossRef]
41. Maruda, R.W.; Krolczyk, G.M.; Wojciechowski, S.; Powalka, B.; Klos, S.; Szczotkarz, N.; Matuszak, M.; Khanna, N. Evaluation of turning with different cooling-lubricating techniques in terms of surface integrity and tribologic properties. *Tribol. Int.* **2020**, *148*, 106334. [CrossRef]
42. Khanna, N.; Agrawal, C.; Gupta, M.K.; Song, Q.; Singla, A.K. Sustainability and machinability improvement of Nimonic-90 using indigenously developed green hybrid machining technology. *J. Clean. Prod.* **2020**, *263*, 121402. [CrossRef]
43. Jamil, M.; Zhao, W.; He, N.; Gupta, M.K.; Sarikaya, M.; Khan, A.M.; Siengchin, S.; Pimenov, D.Y. Sustainable milling of Ti–6Al–4V: A trade-off between energy efficiency, carbon emissions and machining characteristics under MQL and cryogenic environment. *J. Clean. Prod.* **2021**, *281*, 125374. [CrossRef]
44. Gupta, M.K.; Song, Q.; Liu, Z.; Sarikaya, M.; Jamil, M.; Mia, M.; Kushvaha, V.; Singla, A.K.; Li, Z. Ecological, economical and technological perspectives based sustainability assessment in hybrid-cooling assisted machining of Ti-6Al-4 V alloy. *Sustain. Mater. Technol.* **2020**, *26*, e00218. [CrossRef]
45. Zhao, G.; Liu, Z.; He, Y.; Cao, H.; Guo, Y. Energy consumption in machining: Classification, prediction, and reduction strategy. *Energy* **2017**, *133*, 142–157. [CrossRef]
46. Sarıkaya, M.; Güllü, A. Multi-response optimization of minimum quantity lubrication parameters using Taguchi-based grey relational analysis in turning of difficult-to-cut alloy Haynes 25. *J. Clean. Prod.* **2015**, *91*, 347–357. [CrossRef]
47. Danish, M.; Gupta, M.K.; Rubaiee, S.; Ahmed, A.; Korkmaz, M.E. Influence of hybrid Cryo-MQL lubri-cooling strategy on the machining and tribological characteristics of Inconel 718. *Tribol. Int.* **2021**, *163*, 107178. [CrossRef]
48. Danish, M.; Ginta, T.L.; Habib, K.; Abdul Rani, A.M.; Saha, B.B. Effect of cryogenic cooling on the heat transfer during turning of AZ31C magnesium alloy. *Heat Transf. Eng.* **2019**, *40*, 1023–1032. [CrossRef]
49. Yıldırım, Ç.V.; Kıvak, T.; Sarıkaya, M.; Şirin, Ş. Evaluation of tool wear, surface roughness/topography and chip morphology when machining of Ni-based alloy 625 under MQL, cryogenic cooling and CryoMQL. *J. Mater. Res. Technol.* **2020**, *9*, 2079–2092. [CrossRef]
50. Öndin, O.; Kıvak, T.; Sarıkaya, M.; Yıldırım, Ç.V. Investigation of the influence of MWCNTs mixed nanofluid on the machinability characteristics of PH 13-8 Mo stainless steel. *Tribol. Int.* **2020**, *148*, 106323. [CrossRef]
51. Şap, E.; Usca, U.A.; Gupta, M.K.; Kuntoğlu, M. Tool wear and machinability investigations in dry turning of Cu/Mo-SiC p hybrid composites. *Int. J. Adv. Manuf. Technol.* **2021**, *114*, 379–396. [CrossRef]