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Investigation and Evaluation of Cutting Temperature with Various Cooling Conditions and Parameters in Milling Machining Process

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ABSTRACT

In the manufacturing industry, especially those engaged in the machining process, the results of product quality and tool life are always the main focus of the industry. These factors can be influenced by the friction that occurs between the cutting tool or chisel and the workpiece during the machining process which will cause high cutting temperatures so that the cutting temperature problem must be resolved immediately. This study aims to analyze the effect of machining parameters and conditions on the cutting temperature in the milling machining process. Variations in machining conditions and parameters used include dry, flood, and air-cooling techniques; Spindle speed parameters 500, 800, and 1100 rpm; Feed rate parameters 60, 100, and 140 mm/min. The method used is an experimental method. The cutting temperature was measured using an infrared thermometer. The results of the analysis in this study indicate that the combination of variables in the milling machining process that obtains the most optimal response value to reduce the cutting temperature is the use of the flood coolant cooling technique, then a spindle speed of 800 rpm, and a feed rate of 100 mm/min.

Keywords: *Cutting Temperature, Cooling Condition, Machining Parameters*

ABSTRAK

Dalam industri manufaktur khususnya yang bergerak dalam bidang proses pemesinan selalu menjadikan hasil kualitas produk dan masa pemakaian alat sebagai fokus utama industri. Faktor tersebut dapat dipengaruhi dari adanya gesekan yang terjadi antara alat potong atau pahat dan benda kerja pada saat proses pemesinan dijalankan yang akan menimbulkan suhu pemotongan yang tinggi sehingga masalah suhu pemotongan harus segera diatasi. Penelitian ini bertujuan untuk menganalisis pengaruh parameter dan kondisi pemesinan terhadap adanya suhu pemotongan pada proses pemesinan milling. Variasi kondisi dan parameter pemesinan yang digunakan yaitu meliputi Teknik pendinginan dry, flood, dan udara; Parameter spindle speed 500, 800, dan 1100 rpm; Parameter feed rate 60, 100, dan 140 mm/min. Metode yang digunakan yaitu metode eksperimen. Suhu pemotongan diukur menggunakan alat infrared thermometer. Hasil analisa pada penelitian ini menunjukkan bahwa kombinasi variabel pada proses pemesinan milling yang mendapatkan nilai respon paling optimal untuk meredam suhu pemotongan yaitu pada penggunaan teknik pendinginan flood coolant, kemudian spindle speed sebesar 800 rpm, dan feed rate sebesar 100 mm/min.

Kata kunci: Suhu Pemotongan, Kondisi Pendinginan, Parameter Pemesinan

Introduction

The manufacturing industry has made great progress along with the increasing need for products resulting from the machining process. This progress is marked by the increasing technology that is increasingly modern in the metal cutting manufacturing industry (Habiby et al., 2023). Machining operations play an important role in today's manufacturing industry, which is defined as a cutting operation to reduce the desired dimensions, shapes, and surfaces in contact between the cutting tool and the workpiece (Kui et al., 2022). Milling is a versatile machining process that is capable of cutting workpieces with flat, curved, and partially complex geometric surfaces to eat stationary workpieces by means of rotating cutting tools (Rizal et al., 2014). In the machining process, especially milling, friction will occur between the endmill and the workpiece being cut. This friction will cause wear which will result in a short cutting tool life and poor machining results because it causes high cutting temperatures in the machining process so that problems related to this cutting temperature are the main problems that must be immediately addressed or reduced (Deng et al., 2018; M. et al., 2020). During milling operations, the interaction between the rotating cutting tool and the workpiece inevitably generates friction, which leads to a rise in cutting temperature. Excessive heat accelerates tool wear, decreases tool life, and degrades surface quality. Therefore, controlling cutting temperature is essential to ensure machining stability, minimize tool degradation, and maintain the desired surface integrity. Therefore, machining conditions and machining parameters have an important role in the machining process to analyse the generation of heat.

Dry cutting is a machining condition that is often used to reduce machining costs and environmental pollution due to the absence of coolant in the cutting area (Boswell et al., 2017). However, dry cutting is known to generate high heat due to friction and adhesion and cause wear of cutting tools due to the absence of adequate coolant (Zhang et al., 2023). In addition, machining conditions using conventional coolant sprayed with the flood method are also commonly used in the machining process, but flood spraying requires a lot of fluid and increases machining costs and environmental pollution due to waste disposal (Kui et al., 2022; Ekinovic et al., 2015; Ruggiero et al., 2016). In addition, using air as a cooling medium is known to reduce machining costs because it does not require additional coolant, the application of air blow in the machining process will be the right strategy because it has adequate advantages, so this needs to be explored more deeply related to the application of air blow in the machining process because it can help reduce the emergence of hot temperatures due to friction and this heat reduction can reduce surface roughness (Grzesik & Ruszaj, 2021; Prabakaran et al., 2024; Gao et al., 2024).

The cooling conditions in this study will be explored combined with variations in other parameters such as feed rate and spindle speed. Achadiah et al., (2021) studied the effect of feed rate and depth of cut on face milling, the results showed that the higher the feed rate, the roughness will increase. Akiyama et al., (2023) studied the effect of feed rate and spindle speed, the results showed that the higher the feed rate and spindle speed, the surface roughness increased. Zha et al., (2024) experimentally explored the effect of feed rate on cutting temperature and cutting force, the results showed that the higher the feed rate, the higher the temperature and cutting force. Habiby, (2024) studied the effect of cutting direction and spindle speed, the results showed that the higher the spindle speed combined with the effect of cutting direction, the higher the surface roughness. Tefera et al., (2023) conducted a study with a combination of three parameters, namely the effect of cutting speed, feed rate, and depth of cut using the Taguchi method on the turning machining process, showing that the combination of the three parameters that produced the best roughness was a cutting speed of 1200 rpm, a feed rate of 0.05 mm/rev, and a depth of cut of 1.05 mm. Liu et al., (2023) explained that there is a correlation between the cutting temperature that occurs in the machining process and the integrity of the surface of the workpiece, therefore, control of the cutting temperature is very necessary and important to evaluate. Karaguzel & Budak, (2018) explained that there is a strong relationship between tool wear and cutting temperature. The cutting temperature will decrease as the radial cutting depth decreases. Therefore, it can be said that to increase tool life, the cutting temperature can be reduced by reducing heat by adjusting other parameters so that tool wear can be reduced.

However, most previous studies have focused either on machining parameters alone or on cooling techniques independently, without systematically evaluating the combined influence of both factors on cutting temperature in milling operations. In addition, only a limited number of studies directly compare dry, flood, and air-blow cooling conditions under the same experimental framework. Furthermore, research that applies a structured optimization approach—such as the Taguchi method—to analyze the interaction between cooling conditions and machining parameters in reducing cutting temperature is still scarce. These limitations highlight a clear research gap regarding comprehensive guidelines for selecting the optimal combination of cooling methods and machining parameters to minimize thermal effects during milling.

Sometimes in the manufacturing industry there are demands for work speed and good workpiece results. This can be realized by using a low feed rate to have low roughness too, but the machining process will take longer, if the feed rate is too high then the workpiece results will get worse due to high heat. Therefore, the combination of appropriate machining parameters and appropriate cooling conditions must be explored properly, to get the right combination of parameters with many parameters can use the taguchi method. The taguchi method is an optimization method used to improve product and process design in a study, this method can be used for various product and process designs including in the manufacturing process for more optimal results (Freddi & Salmon, 2019).

This study uses the Taguchi method to optimize the cooling conditions and milling machining parameters against the cutting temperature that occurs in the machining process. Variations in machining conditions and parameters used include dry, flood, and air-cooling techniques; Spindle speed parameters 500, 800, and 1100 rpm; Feed rate parameters 60, 100, and 140 mm/min. The purpose of this study is to obtain the right cooling conditions and the most optimal machining parameters to produce low cutting temperatures in the milling machining process, then the results will be correlated with previous research and appropriate theories, and will be displayed with images and graphs to support and facilitate readers to be more easily understood.

Therefore, this study aims to address these research gaps by systematically investigating the combined effects of cooling conditions and machining parameters on cutting temperature in a milling process using the Taguchi optimization method. The specific objectives of this research are: (1) to determine the most effective cooling condition for reducing cutting temperature; (2) to identify the optimal combination of spindle speed and feed rate that minimizes thermal generation; and (3) to compare and validate the experimental findings with previous studies and theoretical principles. Visual analyses in the form of graphs and images are provided to support clarity and improve reader understanding.

Literature Review

Research Gap on Cooling Conditions

Metal machining processes, especially milling machining, are one of the important processes in the modern manufacturing industry (Habiby, 2025). One of the critical parameters in this process is the cutting temperature, which affects tool life, workpiece surface quality, as well as energy efficiency and production costs (Davim, 2008). High cutting temperatures can cause rapid tool wear, thermal distortion of the workpiece, and degradation of surface quality (Mubarok et al., 2023).

Several studies have shown that cooling conditions play a significant role in controlling cutting temperatures. Cooling techniques such as dry cutting, flood cooling, and Minimum Quantity Lubrication (MQL) have yielded varying results in reducing temperatures in the cutting zone (Dhar et al., 2006). Among these methods, flood cooling and MQL often prove to be more effective in reducing temperatures and increasing tool life than dry cutting (A. K. Sharma et al., 2016).

The influence of process parameters such as spindle speed and feed rate on cutting temperature has also been extensively studied. Research by Suresh et al., (2002) showed that increasing spindle speed and feed rate significantly increased the temperature in the cutting zone due to increased mechanical energy and friction velocity. However, there is a need to balance these parameters to maintain process efficiency and tool life.

Several analytical and statistical approaches such as temperature average analysis and Signal-to-Noise (S/N) Ratio in the Taguchi method are used to evaluate the influence of machining parameters on temperature results. Determining the optimal parameter combination with this approach is proven to be able to identify efficient and environmentally friendly cutting conditions.

However, there is still a gap in the literature regarding comprehensive studies comparing cutting temperatures based on variations in cooling and machining parameters simultaneously, especially for specific materials and real-world industrial conditions. Therefore, this study aims to experimentally evaluate the effect of various cooling conditions and machining parameters on cutting temperatures in the milling process, to obtain an optimal combination that can be applied in manufacturing practices based on thermal performance and sustainability.

The Importance of Temperature Control in the Milling Process

Cutting temperature is a critical parameter in the milling process because it directly impacts tool life, surface quality, and energy efficiency. High temperatures can cause rapid tool wear, thermal deformation of the workpiece, and surface degradation. Therefore, temperature control through effective cooling techniques has become a major focus in modern machining research (Lubis et al., 2019).

Conventional and Modern Cooling Techniques

Traditional cooling techniques such as dry cutting and flood cooling have been widely used. However, dry cutting tends to produce higher cutting temperatures due to the absence of a coolant, while flood cooling can pose environmental and occupational health concerns. As an alternative, the Minimum Quantity Lubrication (MQL) technique has been developed to reduce coolant use while increasing cooling efficiency. Research by V. S. Sharma et al., (2009) shows that MQL can reduce cutting temperature and improve surface quality compared to dry cutting.

Use of Nanofluids in MQL

The incorporation of nanoparticles into MQL fluids has shown significant improvements in cooling efficiency. Studies by Abbas et al., (2021) showed that the addition of Al_2O_3 nanoparticles into MQL can reduce cutting temperature and improve surface quality in the milling process of stainless steel 316. Similarly, research conducted by Tuan et al., (2023) found that the use of MoS_2 nanoparticles in MQL can increase tool life and reduce cutting forces.

Cryogenic and Hybrid Cooling

Cryogenic cooling techniques, such as the use of liquid CO_2 or liquid nitrogen, have been shown to be effective in significantly reducing cutting temperatures. Musfirah et al., (2015) reported that cryogenic cooling can reduce cutting temperatures by up to 70% compared to dry cutting in the milling process of Inconel 718. In addition, a hybrid approach combining MQL with cryogenic cooling has shown promising results. Laghari et al., (2023) found that the combination of MQL and liquid CO_2 can improve cutting efficiency and reduce carbon emissions in the milling process of aluminum alloys.

Optimization of Machining Parameters to Control Temperature

In addition to cooling techniques, optimization of machining parameters such as spindle speed and feed rate also plays an important role in temperature control. Studies by J. Liu et al., (2025) used the finite element method to model the temperature distribution in the milling process of thin-walled titanium alloy, showing that optimization of machining parameters can significantly reduce the cutting temperature and improve the quality of the final result.

Environmental and Sustainability Implications

With increasing attention to sustainability, environmentally friendly cooling techniques such as MQL and the use of bio-nanofluids are becoming increasingly important. Sugiantoro et al., (2019) investigated the use of bio-nanofluids in the milling process of hardened steel and found that this technique can reduce cutting temperatures and tool vibrations, and produce good surface quality according to ASTM standards.

Method

Experimental Setup and Materials

In this study, a milling machine was used for the machining process stage, then for spraying flood coolant, a nozzle was used in the machine using conventional dromus coolant. Then for spraying compressed air as a variation of the cooling method using a compressor hose to spray air, the compressed air in the compressor will be sprayed with a pressure of 2 bar. Then for the cutting tool, an HSS endmill with 4 flutes with a diameter of 8 was used.

For cutting temperature measurement in this study using thermogun or infrared thermometer tool. Cutting temperature measurement in this study using infrared thermometer because it has advantages including the level of accuracy in measurement, can measure cutting temperature quickly, without touching the workpiece or cutting tool to measure cutting temperature as was done in the study of J. Sharma & Sidhu, (2014).

Measurement of cutting temperature in this study was carried out once when the cutting tool began cutting the workpiece. The workpiece used in this study was ST-40 steel with dimensions of 50x50x20 (pxlxt). Cutting of the workpiece was carried out with a straight facing which would be carried out by an HSS endmill with a cutting depth of 1mm which would then measure the cutting temperature using an infrared thermometer.

The data obtained in this study are data obtained from the results of the experimental process related to the parameters tested. The results of the experiments carried out were testing the cutting temperature that had been determined using several cooling conditions and milling machining parameters according to the experimental design Table 3.

The results of cutting temperature measurements were carried out using an infrared thermometer when the milling machining process was carried out. Measurements were made in the cutting zone between the cutting tool and the workpiece when experiencing friction. Cutting temperature measurements were carried out 3 times in each variation of the experimental design carried out.

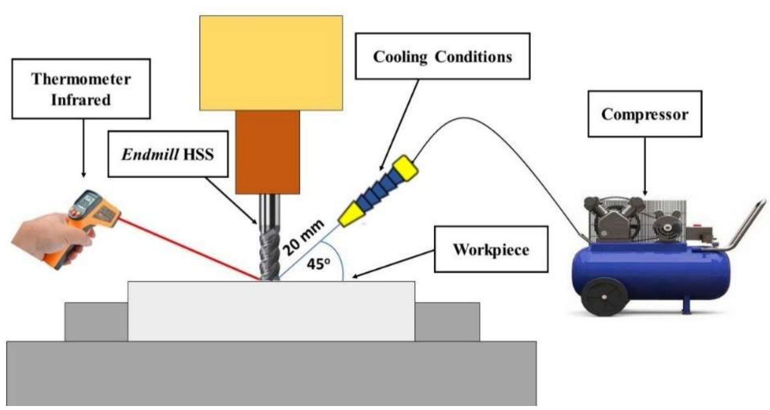

Figure 1. Illustration of the milling machine, coolant delivery system, and infrared thermometer positioning

The data obtained are then processed to obtain the relationship between the influence of each parameter on the resulting cutting temperature and the optimization of each parameter, so that the optimal parameters from the test are the conclusions that can be drawn. The results of the experiments that have been carried out are then analyzed using the Taguchi and ANOVA methods to determine the influencing factors and the optimum factor level, where this method is used to find the relationship between the independent variables and the dependent variables, so that the magnitude of the influence of each parameter can be known.

Experimental Design (Taguchi L9)

This study uses the Taguchi method to optimize milling machining parameters. The initial stage in this study is to select factors and interactions that will be evaluated using a cause-and-effect diagram. At this stage, an analysis of the factors that influence the optimum debinding process is carried out. After knowing the factors that will influence based on the literature study that has been done previously.

The feed rate values were corrected and expressed in standard units of 120 mm/min and 140 mm/min. The spindle speed settings of 800, 950, and 1100 rpm were applied based on the tool diameter utilized in this experiment, representing fixed machine speed parameters rather than values derived from a constant cutting velocity.

This study uses an experimental design based on the orthogonal array approach with three factors and three levels, where the column is a factor that can be changed in the experiment and the row is a combination of levels of factors in the experiment. In accordance with the orthogonal array pattern obtained as in Table 1.

Table 1. Experimental Design

Factor	Level		
	1	2	3
Cooling Conditions	Dry	Flood	Air Blow
Spindle Speed (rpm)	500	800	1100
Feed Rate (mm/min)	60	100	140

The selection of independent variables in this study is based on the literature study that has been studied and has a factor on changes in cutting temperature in the machining process, so that this parameter is selected, then after that determine the orthogonal array where in determining the orthogonal array based on the value of the degree of freedom. The total degree of freedom available in the orthogonal array is equal to the number of trials minus 1. So in determining the orthogonal array must meet the requirements that the degree of freedom of the orthogonal array must be greater than the degree of freedom of the factor and interaction.

Procedure for Cutting Temperature Measurement

Cutting temperature was measured using a calibrated infrared thermometer (Model KM-380 AH, Accuracy ±1.5°C), which is suitable for high-gradient temperature fields in metal cutting. Prior to experimentation, the instrument was calibrated using a reference blackbody source to verify emissivity settings and ensure measurement accuracy. The emissivity was fixed at 0.95, corresponding to the oxidized surface of the workpiece material used in this study.

During each experimental run, the temperature measurement was conducted after the cutting process reached a steady-state thermal condition. Steady state was defined based on pre-trial observations, indicating that transient temperature fluctuations during initial tool–workpiece engagement dissipate after approximately 10–12 seconds of continuous cutting or after the tool traverses a cutting length of approximately 15–20 mm. This definition ensured that the measured temperature reflected stable thermal behavior rather than the initial heat-up phase.

To maintain consistent measurement conditions, the infrared sensor was mounted on a rigid stand positioned at a fixed distance of 100 ± 2 mm from the cutting zone and oriented at a 45° angle relative to the tool–workpiece interface. This configuration minimized parallax error, optimized the sensor's field of view, and ensured that the hottest region (primary shear zone) remained within the measurement spot diameter. The sensor was isolated from machine vibration using a damping fixture to avoid misalignment during cutting.

For each of the nine experimental conditions in the Taguchi L9 matrix, measurements were conducted in three replications. Each replication consisted of a complete cutting pass under the same parameter combination. The cutting temperature recorded for each replication represented the peak steady-state temperature over a sampling interval of 2 seconds. The three values were averaged to obtain the final temperature data used for analysis. Any replication with anomalous readings—defined as deviations exceeding ±5% from the mean—was discarded and repeated to maintain data validity.

Environmental variables such as room temperature, airflow, and machine warm-up conditions were controlled to avoid thermal disturbances. All experiments were performed inside a closed machine enclosure with no external air movement. The machine spindle was allowed to operate for five minutes prior to testing to stabilize bearing temperature. No additional heat sources were present in the vicinity of the measurement setup. This standardized procedure ensured high repeatability and reliability of temperature data, enabling accurate evaluation of the effects of cooling conditions and machining parameters on thermal behavior during the milling process.

Orthogonal Array Selection

Based on the experimental design consisting of 3 factors where each of the 3 factors has 3 levels, the orthogonal array used is L9. The orthogonal array matrix in this study can be seen in Table 2 below:

Table 2. Orthogonal Array Metric Design

Exp. No.	Factor		
	Cooling Conditions	Spindle Speed	Feed Rate
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

The next step is to place the factors/interactions into the specified orthogonal array column and carry out the experiment, namely the process in the milling machining process according to the experimental variations based on the orthogonal array column The experiment was carried out based on the specified orthogonal array with 3 repetitions of the cutting temperature test to produce more valid data which will then be averaged and optimized from the results (see Table 3).

Table 3. Experimental Design

Exp. No.	Cooling Conditions	Spindle Speed (rpm)	Feed Rate (mm/min)
1	Dry	500	60
2	Dry	800	100
3	Dry	1100	140

Exp. No.	Cooling Conditions	Spindle Speed (rpm)	Feed Rate (mm/min)
4	Flood	500	100
5	Flood	800	140
6	Flood	1100	60
7	Air Blow	500	140
8	Air Blow	800	60
9	Air Blow	1100	100

Data Collection and Analysis Techniques

An L9 orthogonal array was used to examine three machining parameters (cooling condition, spindle speed, and feed rate) at three levels. This array was chosen because it provides an efficient experimental structure while maintaining balanced comparison among factors. The signal-to-noise (S/N) ratio with the 'smaller-the-better' formulation was applied to evaluate the variability and performance of each trial. Analysis of means (ANOM) and S/N ratio response tables were then used to identify the optimal parameter settings for minimizing cutting temperature.

Cutting temperature was measured using an infrared thermometer directed at the tool–workpiece interaction zone. The temperature reading was taken after the cutting tool reached full engagement with the workpiece, approximately 3–4 seconds after the tool began cutting, to ensure a stable thermal condition. The measurement was conducted at a constant cutting depth of 1.5 mm. For each experimental trial, the temperature was recorded three times and the average value was used for analysis. This replication approach ensures measurement consistency and reduces random variation during data collection. To ensure reliability, each temperature measurement was repeated three times under identical conditions, and the mean value was used in subsequent Taguchi and statistical analyses. This procedure provides standardized and repeatable temperature data across all cooling conditions and machining parameter.

Results and Discussion

Effect of Cooling Conditions on Cutting Temperature

The cutting temperature showed significant variation among the three cooling techniques. Dry cutting consistently produced the highest temperature due to the absence of lubrication and cooling media, which intensified friction and adhesion at the tool–workpiece interface. Flood cooling generated the lowest temperature because the fluid provided continuous convection and lubrication, effectively removing heat from the shear zone. Air-blow cooling produced intermediate temperatures; although it does not provide lubrication, the high-velocity air stream assisted in chip evacuation and reduced thermal accumulation on the cutting edge. These results align with previous findings, which reported that the combination of friction reduction and convective heat transfer is the main mechanism behind effective temperature control during milling operations.

The results of the machining process with variations in cooling conditions, spindle speed, and feed rate that will affect the cutting temperature results of the milling machining process according to the parameter design described previously, then the cutting temperature measurement will be carried out using an infrared thermometer. The results of the data from the experiments that have been carried out in this study will be shown in Table 4.

Table 4. Cutting Temperature Results in the Machining Process

Exp. No.	Cooling Conditions	Spindle Speed (rpm)	Feed Rate (mm/min)	Cutting Temperature (°C)			
				Test 1	Test 2	Test 2	Average
1	Dry	500	60	60.5	62.8	65.2	62.83
2	Dry	800	100	56.7	55.3	58.6	56.86
3	Dry	1100	140	70.2	71.3	72.5	71.33
4	Flood	500	100	32.4	34.5	36.4	34.43
5	Flood	800	140	29.5	30.5	32.5	30.83
6	Flood	1100	60	35.7	37.8	39.1	37.53
7	Air Blow	500	140	50.4	52.6	55.2	52,733
8	Air Blow	800	60	43.3	45.6	48.3	45.73
9	Air Blow	1100	100	40.2	42.5	45.5	42.73

Accordingly, it is known that the highest cutting temperature value is obtained by using dry machining conditions and a combination of spindle speed machining parameters of 1100 rpm and a feed rate of 140 mm/min, which is 71.33°C, which is marked with the red column. While the lowest cutting temperature value is obtained by using flood cooling conditions with a combination of spindle speed machining parameters of 800 rpm and a feed rate of 140 mm/min, which is 30.83°C, which is marked in the blue column.

Effect of Spindle Speed and Feed Rate on Cutting Temperature

Both spindle speed and feed rate strongly influenced thermal behavior. Increasing spindle speed increased the cutting temperature due to higher shear strain rates and rapid chip formation, which intensified heat generation per unit time. Similarly, higher feed rates resulted in higher temperatures because the cutting edge removed a larger volume of material per second, increasing cutting forces and frictional sliding. However, the magnitude of this increase varied depending on the cooling condition. Under flood cooling, the temperature rise at higher feed rates was less pronounced due to better heat dissipation, whereas under dry cutting the temperature rose sharply. These trends are consistent with prior studies reporting that cutting temperature is a function of mechanical load and tool–material interaction dynamics.

These results are in accordance with existing references that increasing spindle speed and feed rate parameters will cause an increase in cutting temperature, surface roughness, and tool life, demonstrated that optimizing the coolant delivery efficiency significantly lowers thermal accumulation at the tool–workpiece interface.

In the present study, a similar trend is observed; however, the magnitude of temperature reduction is more pronounced, particularly when higher spindle speeds are combined with fine mist lubrication. This difference may be attributed to improved droplet penetration and faster evaporation–cooling effects under the tested MQL configuration (Wang et al., 2016).

Also noted that temperature behavior tends to stabilize when the coolant enhances the tribological contact at higher feed rates. Our results show partial agreement, but unlike Pollák's findings, the temperature rise at high feed rates did not plateau; instead, it increased steadily under dry machining while remaining moderated under MQL. This suggests that the cooling mechanism in the current study has a stronger influence on frictional heat suppression, likely due to better coolant atomization and distribution. Such distinctions indicate that the cooling strategies evaluated here provide a more effective thermal response than those reported in earlier studies (Pollák et al., 2022)(A. Sharma & Dwivedi, 2020).

This can happen because a spindle speed that is too high will increase the number of cutting edges per unit time, but will cause more vibrations which will affect the cutting temperature. While too high a feed rate will increase the material lifting per unit time which will produce more heat, but can slow down the machining process (Kiswanto et al., 2014)(Kiswanto et al., 2019). So it is necessary to use balanced parameters or the right combination of spindle speed and feed rate parameters to reduce the cutting temperature in the machining process so that it will also affect the reduction of cutting tool wear and the quality of the workpiece surface.

These comparisons highlight that although the overall tendencies align with previous research, the present experiments provide new insights into how combined parameter variations (cutting speed, feed rate, depth of cut) interact with different cooling modes to affect temperature generation. This study therefore offers a more comprehensive temperature evaluation across multiple machining regimes compared to earlier single-parameter investigations.

Optimization and Statistical Validation (Taguchi Analysis and ANOVA)

The Taguchi S/N ratio analysis identified cooling condition as the most influential factor, followed by spindle speed and feed rate. Flood cooling at medium spindle speed and high feed rate yielded the optimal combination for minimizing cutting temperature. ANOVA results confirmed that cooling condition accounted for the highest percentage contribution to temperature variation, demonstrating its dominant role in thermal control. The statistical findings agree with the physical interpretation that cooling directly governs heat extraction, whereas machining parameters mainly influence heat generation. The consistency between Taguchi trends, ANOVA significance levels, and physical mechanisms validates the robustness of the optimization results.

Table 5. Response Table for Means

Level	Cooling Conditions	Spindle Speed	Feed Rate
1	63.68	50.00	48.70
2	34.27	44.48	44.68
3	47.07	50.53	51.63
Delta	29.41	6.06	6.96
Rank	1	3	2

Based on table 5, it can be seen that the factors that affect the milling machining process according to the parameter design that has been explained in sequence are cooling conditions, feed rate, and spindle speed. The three sequences of factors will greatly influence the cutting temperature in the milling machining process.

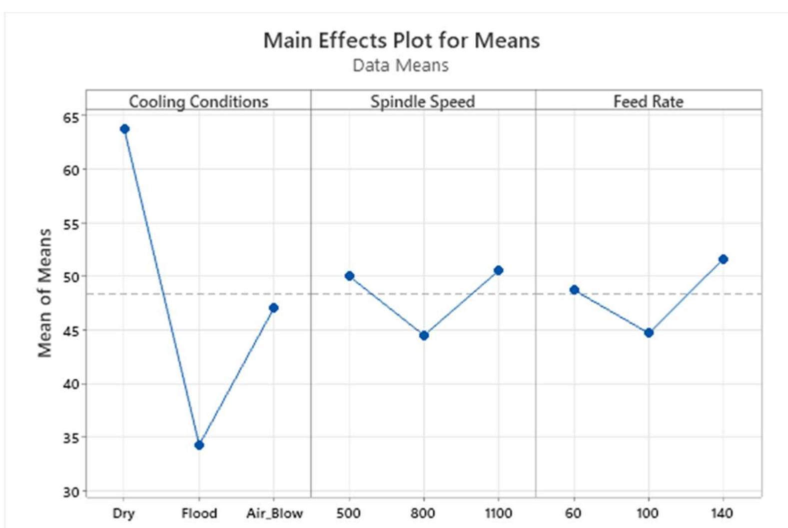

Figure 2. Main effects plot for means

Based on Fig. 2, it explains that from the average results of the cutting temperature tests that have been carried out previously, the minimum parameter obtained has a cutting temperature value. In addition, the best combination of parameters from each experiment that has been carried out can be seen that the use of flood cooling conditions with a spindle speed of 800 rpm and a feed rate of 100 mm/min is the best combination of parameters to reduce the cutting temperature in the milling machining process based on the average value obtained.

The variations in cutting temperature across the tested parameters can be explained by differences in heat generation and the ability of each cooling condition to dissipate thermal energy. Higher spindle speeds produced elevated temperatures because the increase in shear strain rate and chip formation intensity generates more heat at the primary deformation zone. Under dry machining, this heat accumulates rapidly due to the absence of lubrication, leading to high friction at the tool–workpiece interface. In contrast, the application of MQL significantly reduces the temperature because the fine mist forms a thin lubricating film that lowers frictional resistance, while the atomized droplets enhance convective heat removal. Flood cooling shows moderate temperature reduction, but its efficiency decreases at high cutting speeds due to reduced coolant penetration into the cutting zone. These mechanisms explain why MQL consistently results in lower temperatures, especially when combined with moderate feed rates that promote stable chip evacuation.

At higher feed rates, the cutting temperature increased regardless of cooling condition, which is consistent with greater material removal per tooth and higher contact pressure between tool and workpiece. However, the relative increase under MQL was smaller because the lubricant improved boundary lubrication at the tool–chip interface, reducing the frictional component of heat generation. This indicates that cooling effectiveness is strongly influenced by the interaction between lubrication performance and mechanical loading conditions imposed by the cutting parameters.

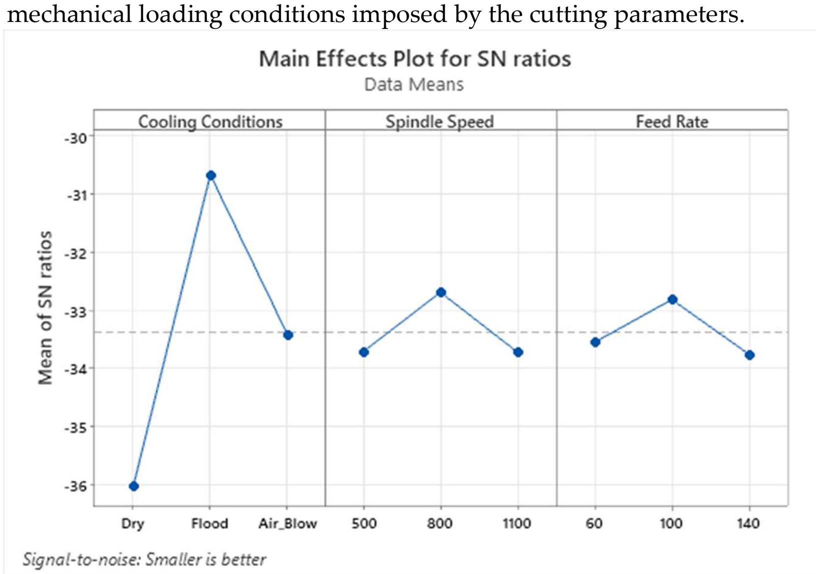

Figure 3. Main effects plot for SN ratios

Based on Fig. 3, it explains that the magnitude of the signal to noise ratio will describe the magnitude of the parameters in influencing the minimum cutting temperature results. To determine the SN ratio, the method is the signal divided by noise, so the greater the SN ratio, the better it is to reduce the cutting temperature, namely by using the flood cooling condition parameter with a spindle speed of 800 rpm and a feed rate of 100 mm/min as the best combination of parameters to reduce the cutting temperature in the milling machining process based on the average value obtained.

Table 6. Results of Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Cooling Conditions	2	3914.35	1957.17	199.00	0,000
Spindle Speed	2	202.35	101.17	10.29	0.001
Feed Rate	2	219.49	109.74	11.16	0.001
Error	20	196.70	9.84		
Total	26	4532.88			

Table 6. shows the results of the analysis of variance (ANOVA) of each parameter in the milling machining process that has been carried out, from the results of the calculation, the F value is obtained for each parameter, namely cooling conditions of 199.00, spindle speed of 10.29, and feed rate of 11.16. Meanwhile, from the f table with a significance level of α = 0.05, it shows that there is a hypothesis that shows a significant effect, meaning that there is an effect or difference in the cutting temperature value when the parameter is used.

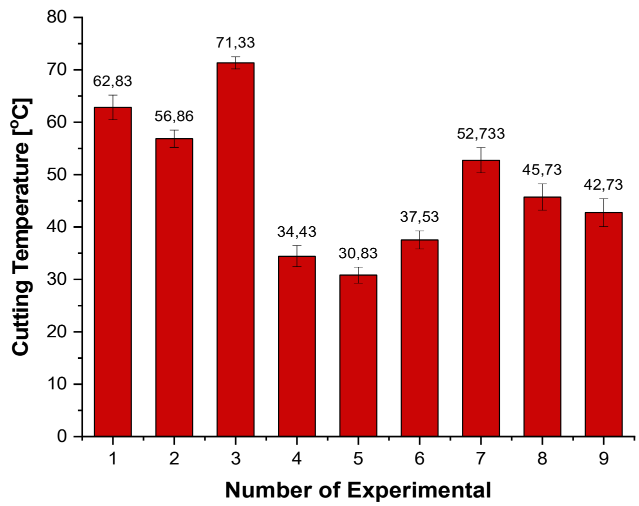

Figure 4. Experimental Results on Cutting Temperature Values

Based on Fig. 4. Explains that the lowest cutting temperature value was obtained in the use of experiment 5, namely flood cooling conditions with a spindle speed of 800 rpm and a feed rate of 140 mm/min. While the highest cutting temperature value was obtained in the use of dry cooling condition parameters, spindle speed 1100 rpm, and feed rate 140 mm/min. in the use of dry machining conditions here always obtains a high cutting temperature value, dry cutting has been used to reduce machining costs and environmental pollution because no cutting fluid is used in machining, but because there is no cooling media in the cutting area, the friction and adhesion processes will be greater which can cause high heat (Boswell et al., 2017)(Pereira Guimarães et al., 2022)(Karaguzel & Budak, 2018)(Ogedengbe et al., 2019). who observed significant temperature escalation under dry machining due to stronger frictional interaction and insufficient heat dissipation.

This condition likely provides a balance between mechanical load and effective heat removal. Flood coolant delivers continuous liquid directly to the cutting zone, enabling efficient convective heat transfer and lubrication at the tool–workpiece interface. When combined with a moderate spindle speed, the heat generated from shear deformation and chip formation remains manageable, allowing coolant to dissipate it effectively. Although the feed rate used in this experiment is relatively high (140 mm/minin), the presence of abundant coolant supports better chip evacuation and reduces adhesion, preventing excessive thermal accumulation.

The findings further indicate that both spindle speed and feed rate significantly influence temperature trends regardless of cooling strategy. Higher spindle speeds increase the velocity of chip formation, while higher feed rates increase the volume of material removed per unit time—both factors intensifying heat generation. However, the degree to which these parameters elevate temperature is strongly moderated by the cooling condition. Flood cooling consistently dampens the thermal effect, whereas dry machining magnifies it. This interaction reveals that parameter optimization cannot be separated from the cooling strategy; they function as an integrated thermal system.

Overall, these results underscore the importance of selecting cooling methods that match the intended productivity parameters. For industries aiming for higher feed rates and spindle speeds, liquid-based cooling remains essential to maintain thermal stability. Meanwhile, dry machining may still be viable for low to moderate cutting conditions, but requires careful parameter selection to avoid excessive heat accumulation.

In addition to identifying the optimal combination of cooling conditions and machining parameters, the findings of this study also provide meaningful implications for industrial milling operations. The lower cutting temperature obtained under flood cooling at 800 rpm and 140 mm/min indicates better thermal stability in the tool–workpiece interface. This condition is strongly associated with extended tool life because reduced thermal load minimizes coating degradation, micro-chipping, and diffusion wear. From a production standpoint, maintaining lower cutting temperatures can improve dimensional accuracy and surface integrity, reducing the number of rejected parts and enhancing process reliability. Furthermore, the use of an efficient cooling strategy can contribute to operational cost reduction through decreased tool replacement frequency and improved process consistency. In terms of sustainability, the identification of optimal cooling–parameter combinations help manufacturers minimize unnecessary coolant consumption and energy use, supporting more environmentally responsible machining practices. Overall, the results offer practical guidance for industries seeking to balance productivity, quality, and sustainability in milling operations.

Conclusion

The results showed that the cutting temperature was greatly influenced by temperature conditions and a combination of machining parameters such as spindle speed and feed rate. Dry cutting conditions consistently produced higher cutting temperatures due to the absence of coolant that can reduce circulation and adhesion during the cutting process. Therefore, selecting a balanced combination of machining parameters and using the right coolant is very important to reduce temperature reduction, reduce tool wear, and improve the surface quality of the machined results.

The findings of this study provide a deeper understanding of heat generation and control in milling operations. The consistent temperature reduction achieved by air-blow cooling demonstrates that effective heat management does not always require liquid-based coolant; instead, enhancing convective heat removal and improving chip evacuation can be equally influential in limiting thermal buildup. Meanwhile, the sensitivity of temperature to spindle speed and feed rate confirms that thermal behavior in milling is primarily governed by shear deformation intensity and the resulting friction at the tool–workpiece interface. These insights show that cutting parameters and cooling strategies must be considered as an integrated system rather than independent factors.

From a machining science perspective, the results reinforce the theoretical link between mechanical loading and thermal generation, while also providing empirical evidence that air-based cooling can moderate temperature even under increasing spindle speeds. Practically, this research contributes to industrial machining by offering a structured guideline for selecting cooling methods and parameter combinations that minimize cutting temperature without sacrificing productivity. The optimization using the Taguchi method provides a systematic basis for real-world decision-making, supporting manufacturers in improving tool life, dimensional accuracy, and process sustainability.

Future studies are recommended to explore a broader range of parameters, including higher cutting speeds, different tool geometries, and additional cooling strategies such as MQL, cryogenic cooling, or nanofluid-based systems. Incorporating multi-point temperature measurement or thermal imaging could provide more comprehensive thermal mapping. Further investigations should also correlate cutting temperature with tool wear progression, surface roughness, and machining stability to develop deeper insights into thermal–mechanical interactions in milling. Such work would enhance understanding of heat control strategies and expand the applicability of the findings to diverse industrial scenarios.

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Declaration of Conflict of Interest

The authors declare that there are no potential conflicts of interest related to this article's research, writing, and/or publication.

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