



Comparative analysis of electrical energy consumption in sustainable turning of suspension spring equalizer components using a line boring machine

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Abstract

This study aims to analyze the effect of coolant usage on the efficiency of electrical energy consumption in the sustainable turning process of the *suspension spring equalizer* component using a *line boring* machine. Energy efficiency is a key factor in modern machining processes that emphasize sustainability and resource conservation. The experiment was conducted under two conditions, specifically with and without coolant, to analyze the difference in electrical energy consumption during the machining process. The machining parameters consisted of a spindle speed of 234.6 rpm, a cutting depth of 0.5 mm, and a feed rate of 0.86 mm/rev. The electric current was measured using a clamp meter at ten-minute intervals, while the electrical energy consumption was calculated using a three-phase power model to obtain the average consumption value during the machining process. The results showed that the use of coolant reduced the average power consumption from 3655.09 watts to 3308.23 watts, resulting in an energy efficiency improvement of 9,49%. These findings indicate that the application of coolant in machining processes can improve the consistency of the machining operation and provide a positive impact on energy savings within the machining system.

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Keywords

Energy efficiency, Electrical power consumption, Sustainable turning, Line boring

Introduction

Energy efficiency has become a crucial element in achieving sustainable development that balances human needs with environmental preservation. The concept of sustainability has now been widely adopted as a fundamental principle across various sectors, including engineering, manufacturing industries, and product design. Manufacturers are increasingly paying attention to the environmental impacts of

production activities and considering them as key factors in decision-making processes. Sustainability issues have therefore become a major concern in the manufacturing sector. The existing literature generally agrees that sustainable development must encompass three main dimensions, namely economic, social, and environmental aspects.

Industries are required to produce goods that support sustainability principles. One concrete measure that can be implemented is reducing energy consumption during product utilization. Sustainable production practices can serve as an effective solution to lower electrical energy consumption, which directly contributes to high production costs. This issue is also highly relevant in the field of machining engineering, where energy efficiency during manufacturing processes plays a critical role.

Reducing energy consumption is one of the key aspects in achieving sustainability, enabling a balance between human activities and long-term well-being. Sustainability has become an increasingly critical requirement across various human activities; therefore, the concept of sustainable development emphasizes that social, economic, and environmental issues must be addressed in an integrated and holistic manner throughout the development process. These sustainability principles have been implemented in multiple sectors, including engineering, manufacturing, and design. Accordingly, manufacturers are demonstrating growing and serious concern toward sustainability-related issues.

Machining process is a vital stage in the manufacturing process; therefore, reducing energy consumption at this stage can have a significant impact on the overall energy usage in production. Optimizing energy utilization in the manufacturing sector is essential for lowering product energy intensity and mitigating the effects of energy price fluctuations. This approach can also reduce production costs and improve energy efficiency in production machinery, which typically requires substantial electrical power supply. Several studies have been conducted to optimize cutting parameters in order to reduce costs and enhance energy efficiency. In a later study, Rusdi developed a method to determine optimal cutting parameters based on minimum cost criteria in the turning process [1].

Depending on the type of material being machined, the concept of high-speed machining is inherently material-specific. However, compared with conventional cutting methods, high-speed machining offers the potential to reduce machining time and costs while producing components with higher efficiency, improved accuracy, and superior quality [2]. In other words, the magnitude of the cutting speed is also influenced by the type of material being machined. In steel alloys, cutting speeds of ≥ 200 m/min are classified as high-speed cutting in turning processes [3]. Based on the results reported by Prayogo, process parameter optimization using the Taguchi–Grey Relational Analysis (Taguchi-GRA) method revealed that the significant variable combination for maximizing the material removal rate (MRR) while minimizing surface roughness consists of a voltage of 48 V, an electrolyte concentration of 150 g/L, and a gap width of

2 mm. Contribution analysis further indicated that voltage was the most dominant factor, accounting for 65.18% of the total variation, followed by gap width at 23.55% and electrolyte concentration at 11.22% [4].

In a subsequent study, it was reported that the minimum tool wear occurred at a process parameter combination of 180 rpm spindle speed, 1.5 mm depth of cut, and 0.8 mm/min feed rate. Variation analysis showed that feed rate was the most influential factor on tool wear, contributing 35%, followed by depth of cut at 10%, while cutting speed had no significant effect on the variation of tool wear [5], [6]. In his study, Joko reported that cutting speed and depth of cut significantly affect the roundness of internal turning results in terms of geometric assessment. Based on optimization results, the optimum process parameters were determined as a cutting speed of 200 m/min, a feed rate of 0,05 mm/rev, and a depth of cut of 0.25 mm [7]. In his study, Prabowo optimized CNC turning parameters for surface roughness and roundness of ST 42 workpieces using the Response Surface Methodology (RSM), with process variables including cutting speed, feed rate, and depth of cut. ANOVA analysis showed that cutting speed and depth of cut significantly affected surface roughness, while all three process parameters had a significant impact on roundness. The optimal conditions for achieving minimum surface roughness were determined as a cutting speed of 264.56 m/min, a feed rate of 0.254 mm/rev, and a depth of cut of 0.1 mm, with a predicted roughness value of 0.158 Ra. Meanwhile, the optimal conditions for roundness were a cutting speed of 105.48 m/min, a feed rate of 0.279 mm/rev, and a depth of cut of 0.337 mm, with a predicted roundness value of 14.15 μm [8].

Furthermore, in Khanna's study, machining of Inconel 718 demonstrated that cryogenic turning can significantly improve machinability, as evidenced by an increase in tool life of up to 133% compared to dry turning, while performing comparably to wet turning. In addition, cryogenic turning was found to reduce energy consumption by 8–17% and decrease surface roughness (Ra) by 20–37% across various material removal rates (MRR), indicating its potential to replace less sustainable conventional machining practices [9]. Soori's study demonstrated that a virtual machining system based on the finite element method can accurately predict the effects of coolant on cutting temperature, tool wear, and surface quality during turning of Ti6Al4V titanium alloy, showing good agreement with experimental data. Similarly, research on Inconel 718 machining showed that cryogenic turning can significantly enhance machinability, as evidenced by a 133% increase in tool life, along with reductions in energy consumption and surface roughness compared to conventional methods [10].

Kannan investigated the turning of 6063 aluminium alloy to minimize cutting forces using the Taguchi method under low feed rates and shallow depths of cut for finishing conditions. A total of 27 experiments were conducted under dry conditions to align with sustainable machining practices. The optimal parameter combination (v_3 - f_1 - d_1) achieved a cutting force of 21 N, feed force of 21.22 N, and surface roughness of 0.9546 μm . Depth of cut had the greatest influence on cutting and feed forces, while feed rate primarily

affected surface roughness. Multi-response optimization confirmed the same parameters, with experimental and predicted results in good agreement, demonstrating improved quality characteristics [11]. Rathod conducted a study applying the Taguchi method to optimize turning parameters for SS304 material, aiming to enhance tool life and reduce production time. The machining parameters considered were feed rate, cutting speed, and depth of cut, with Analysis of Variance (ANOVA) used to evaluate their effects. Signal-to-noise (S/N) ratios from the experiments were employed to identify optimal conditions. Results showed that feed rate significantly influenced tool life, while cutting speed had a major effect on production time. The optimal parameters for maximizing tool life were a feed rate of 0,14 mm/rev, depth of cut 0,40 mm, and cutting speed of 350 m/min, whereas the optimal conditions for minimizing production time were a cutting speed of 550 m/min, feed rate of 0.14 mm/rev, and depth of cut 0.40 mm [12].

In a subsequent study, the effect of vegetable oil-based cutting fluids on the surface roughness of AISI 1045 steel during CNC turning was investigated. Two types of oils, coconut and palm, were tested using a Taguchi experimental design. The results showed that coconut oil produced the lowest surface roughness of 1.554 μm , compared to 1.614 μm for palm oil, achieved at a cutting speed of 1273 rpm, depth of cut of 0.50 mm, and feed rate of 0.16 mm/rev, indicating its effectiveness as an eco-friendly and efficient coolant [13]. Hasan investigated the effect of HSS tool angles (60° , 75° , and 80°) on the surface roughness and hardness of AISI 1045 steel using Dromus coolant. Turning was performed at a 1 mm depth of cut and 460 rpm spindle speed. Results showed that a 60° tool angle produced the highest surface roughness (3.745 μm), while 75° and 80° angles yielded smoother surfaces (3.115 μm and 3.129 μm). The 80° angle achieved the highest hardness (37.50 HRC) due to uniform pressure distribution and increased temperature, whereas 60° remained close to the initial material hardness (34.70 HRC). The study highlights the importance of optimizing tool angles in turning for desired surface characteristics, with further research suggested on spindle speed, coolant type, and depth of cut [14].

Munoz et al, developed process-based modeling approaches to evaluate the environmental performance of machining operations, with particular emphasis on energy utilization. They subsequently introduced a methodology that integrates analytical process models into machining system resources to quantify energy consumption and material flow. In this framework, electrical energy demand is estimated as a function of machining time and material removal rate, thereby enabling a systematic assessment of process efficiency and energy performance [15]. Herrera et al. reported that in the dry turning of Ti6Al4V, cutting parameters significantly influence cutting temperature, cutting forces, and energy performance, with depth of cut identified as the most dominant factor affecting temperature, forces, and power consumption, while feed rate primarily governs overall energy consumption. Using RSM, ANOVA, and GRA-based optimization, their study demonstrated that appropriate

parameter selection can improve machining efficiency, reduce energy usage and tool wear, and enhance process sustainability [16], [17]. Adel T. Abbas applied a Taguchi L27 experimental design combined with a machine learning approach to optimize the dry turning parameters of AISI 1045 steel based on multiple performance responses. The optimized setting (V_c 160 m/min, a_p 1 mm, f 0.135 mm/rev) improved overall machining performance by balancing surface roughness, cutting forces, temperature, and material removal rate [18].

Based on the above overview, this study focuses on the line boring process of suspension spring equalizer components, both with and without coolant. The aim of the research is to optimize machining parameters within the framework of sustainable turning to enhance electrical energy efficiency [19]. An experimental approach was employed, conducting tests on the repair process of suspension spring equalizer components during line boring, followed by quantitative analysis of the results to assess the machining parameters and the associated electrical power consumption.

Method

The method employed in this study is an experimental approach, focusing on the repair process of suspension spring equalizer components during line boring. The machining process was carried out using a line boring machine equipped with a hydraulic power pack motor with a capacity of 3 kW, a boring bar diameter of 50 mm, and a bar length of 1500 mm. The independent variables include machining conditions with and without the use of coolant, aimed at identifying the effects of coolant on electrical power consumption and the geometric quality of the machined components. In addition, the depth of cut was fixed at 0.5 mm and the spindle speed was set at 234.6 rpm to maintain consistent machining conditions. Data were collected at 10-minute intervals to capture the characteristics of changes in power consumption and geometric quality throughout the machining process for the production of suspension spring equalizers.

The research procedure for operating the line boring machine is as follows and is illustrated in Figure 1.

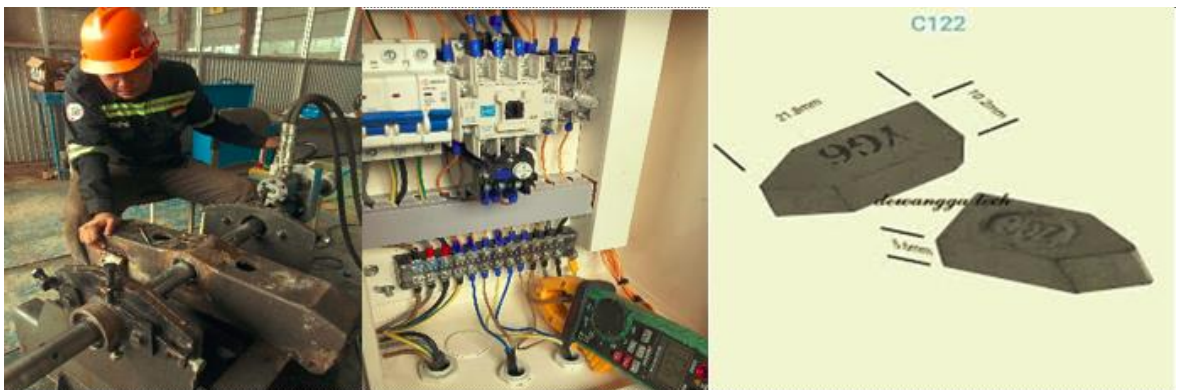


Figure 1. Experimental setup for the line boring process

1. Prepare the equipment and materials to be used.
2. Place the workpiece on the table of the line boring machine.

3. Position the shaft at the center of the hole to be line bored using a caliper.
4. Use a caliper to set the depth of cut at 0,5 mm and check the machining conditions with and without coolant.
5. Use a clamp meter to record the electrical current (Amperes) at 10-minute intervals throughout the process.

Based on the study by Gutowski et al., [20], the electrical power requirement of the machine (P) can be calculated using the following equation.

$$P = P_o + P_t \dots\dots\dots(1)$$

Where P is the power [W] consumed during the machining process, Po is the power [W] consumed by all machine modules during no-load operation, k is the specific energy requirement [Ws/mm³] for the cutting process, and v is the material removal rate (MRR) [mm³/s].

$$P = V.I.\sqrt{3}\cos\phi \dots\dots\dots(2)$$

Where V is the voltage and I is the current [A], with a power factor (cosφ) ranging from 0.8 to 0.95.

Results and discussion

Tables 1, 2, and 3 present the analysis of electrical power consumption during the line boring process under machining conditions using coolant.

Table 1. Results of the calculations for equalizer 1 under coolant condition

No.	Time (minute)	Condition	Speed (rpm)	Temp (°c)	Current (A)		Po (Watt)	Pt (Watt)	PC (Watt)
					I _o	I _t			
1	10	With Coolant	234.6	29.3	2.6	2.96	1454.58	1655.98	3110.56
2	20			29.0	2.6	2.92	1454.58	1633.60	3088.18
3	30			31.0	2.6	3.18	1454.58	1779.06	3233.63
4	40			37.0	2.6	2.89	1454.58	1616.82	3071.39
5	50			44.7	2.6	3.11	1454.58	1739.90	3194.47
6	60			55.8	2.6	3.37	1454.58	1885.35	3339.93

Table 2. Results of the calculations for equalizer 2 under coolant condition

No.	Time (minute)	Condition	Speed (rpm)	Temp (°c)	Current (A)		Po (Watt)	Pt (Watt)	PC (Watt)
					I _o	I _t			
1	10	With Coolant	234.6	38.6	2.6	3.49	1454.58	1952.49	3407.07
2	20			48.6	2.6	3.45	1454.58	1930.11	3384.69
3	30			52.3	2.6	4.07	1454.58	2276.97	3731.55
4	40			49.2	2.6	3.77	1454.58	2109.14	3563.71
5	50			41.4	2.6	2.76	1454.58	1544.09	2998.66
6	60			32.0	2.6	2.82	1454.58	1577.66	3032,23

The electrical power consumption in this study was determined based on the current flowing during the line boring process at a machine operating voltage of 380 V. The power calculation considered the characteristics of the three-phase motor, ensuring that the measured values represent the actual energy requirement during machining.

Next, the analysis results of electrical power consumption during the line boring process under machining conditions without coolant are presented in Tables 4, 5, and 6. The data in these tables illustrate the characteristics of power consumption throughout the machining process at each data collection interval.

Table 3. Results of the calculations for equalizer 3 under coolant condition

No.	Time (minute)	Condition	Speed (rpm)	Temp (°c)	Current (A)		Po (Watt)	Pt (Watt)	PC (Watt)
					I _o	I _t			
1	10	With Coolant	234.6	31.5	2.6	3.06	1454.58	1711.92	3166.50
2	20			33.5	2.6	2.92	1454.58	1633.60	3088.18
3	30			38.2	2.6	3.51	1454.58	1963.68	3418.25
4	40			46.1	2.6	3.82	1454.58	2137.11	3591.68
5	50			51.9	2.6	3.65	1454.58	2042.00	3496.58
6	60			54.0	2.6	3.89	1454.58	2176.27	3630.85

Table 4. Results of the calculations for equalizer 1 under no-coolant condition

No.	Time (minute)	Condition	Speed (rpm)	Temp (°c)	Current (A)		Po (Watt)	Pt (Watt)	PC (Watt)
					I _o	I _t			
1	10	Without	234.6	39.1	2.6	4.04	1454.58	2260.19	3714.76
2	20	Coolant		58.7	2.6	4.05	1454.58	2265.78	3720.36
3	30			59.6	2.6	3.41	1454.58	1907.73	3362.31
4	40			56.9	2.6	4.65	1454.58	2601.45	4056.03
5	50			75.4	2.6	3.94	1454.58	2204.24	3658.82
6	60			65.7	2.6	4.40	1454.58	2461.59	3916.17

Table 5. Results of the calculations for equalizer 2 under no-coolant condition

No.	Time (minute)	Condition	Speed (rpm)	Temp (°c)	Current (A)		Po (Watt)	Pt (Watt)	PC (Watt)
					I _o	I _t			
1	10	Without	234.6	41.8	2.6	3.84	1454.58	2148.30	3602.87
2	20	Coolant		68.1	2.6	4.14	1454.58	2316.13	3770.71
3	30			56.2	2.6	3.53	1454.58	1974.87	3429.44
4	40			47.4	2.6	2.95	1454.58	1650.38	3104.96

Table 6. Results of the calculations for equalizer 3 under no-coolant condition

No.	Time (minute)	Condition	Speed (rpm)	Temp (°c)	Current (A)		Po (Watt)	Pt (Watt)	PC (Watt)
					I _o	I _t			
1	10	Without	234.6	56.5	2.6	3.90	1454.58	2181.86	3636.44
2	20	Coolant		71.4	2.6	4.27	1454.58	2388.86	3843.44
3	30			44.2	2.6	3.25	1454.58	1818.22	3272.80
4	40			39.2	2.6	3.68	1454.58	2058.78	3513.36
5	50			50.8	2.6	4.68	1454.58	2618.24	4072.81
6	60			54.2	2.6	3.87	1454.58	2165.08	3619.66
7	70			77.2	2.6	4.38	1454.58	2450.40	3904.98
8	80			68.2	2.6	4.74	1454.58	2651.80	4106.38

The analysis of electrical power consumption during the line boring process, based on the calculations presented in Tables 1-6, is illustrated in graphical form. The following figures and discussion describe the power consumption for each workpiece specimen throughout the line boring process.

The electrical power consumption recorded during the line boring process under the three coolant conditions exhibits a consistent fluctuation pattern throughout the machining time, as shown in Figure 2.

1. Coolant 1 recorded a peak consumption of 3339.93 W at minute 60, with a cutting power (Pt) of 1855.35 W, while the lowest value occurred at minute 10 at 3088.18 W (Pt = 1523.60 W).
2. Coolant 2 showed a maximum consumption of 3731.55 W at minute 30, with Pt = 2276.97 W, whereas the minimum consumption was observed at minute 50 with 2998.66 W (Pt = 1544.98 W).
3. Coolant 3 reached its highest power consumption of 3591.68 W at minute 40, with Pt = 2137.11 W, and its lowest value was found at minute 20 at 3088.18 W (Pt = 1633.60 W).

The electrical power consumption measured during the line boring process under the three coolant conditions shows a consistent pattern of fluctuation throughout the machining duration, as shown in Figure 3:

1. Equalizer 1 recorded the highest power consumption at minute 40, reaching 4056.03 W with a cutting power (Pt) of 2601.45 W, while the lowest value occurred at minute 30 at 3362.31 W (Pt = 1907.73 W).
2. Equalizer 2 showed a peak consumption at minute 15 of 3770.71 W (Pt = 2316.13 W), and the lowest value at minute 40 with 3104.96 W (Pt = 1650.38 W).
3. Equalizer 3 reached the highest consumption at minute 50, measured at 4072.81 W (Pt = 2618.24 W), while the minimum occurred at minute 30 with 3272.80 W (Pt = 1818.22 W).

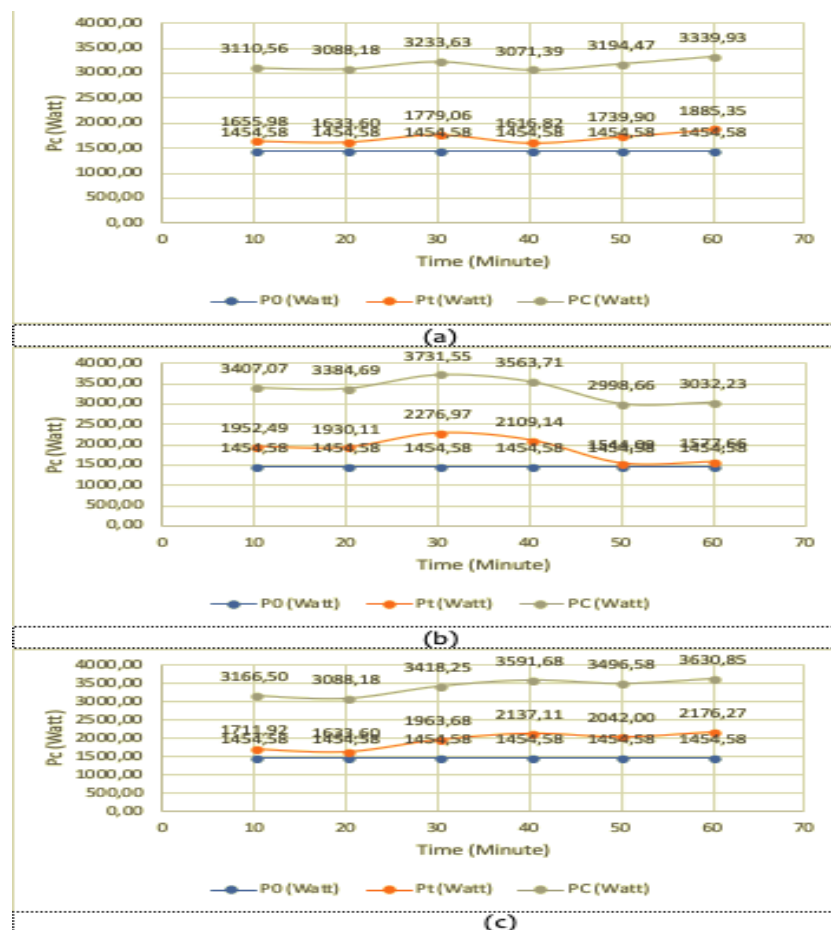


Figure 2. Electrical power consumption during line boring with coolant for equalizer 1,2,3 (a.b.c)

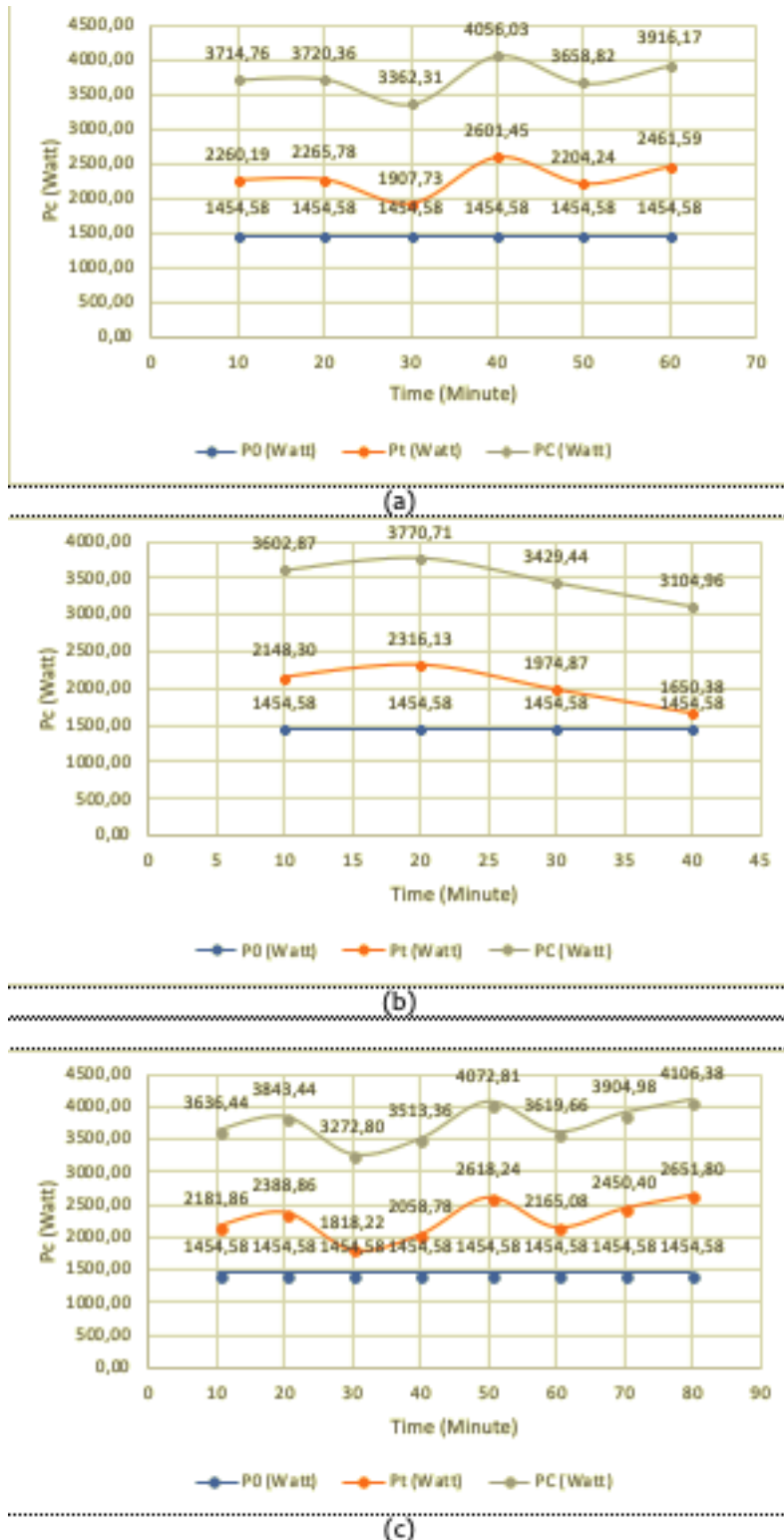


Figure 3. Electrical power consumption during line boring without coolant for equalizer 1,2,3 (a.b.c)

Average results of the calculations using coolant show in Table 7 and 8. Based on the measured power during machining with load (Pt) shown in Figure 4, the highest power was recorded during the process without coolant, reaching 2200.51 watts, while the lowest power occurred with coolant, at 1853.65 watts. Furthermore, for the total power consumption (Pc), the highest value was observed in the machining process without

coolant at 3655.09 watts, whereas the lowest consumption was recorded when using coolant at 3308.23 watts.

Table 7. Average results of the calculations using coolant

No.	Equalizer	Condition	Speed (rpm)	Temp (°c)	Current (A)		Po (Watt)	Pt (Watt)	PC (Watt)
					Io	Ii			
1	1	With Coolant	234.6	41.8	2.6	3.07	1454.58	1717.52	3172.10
2	2			68.1	2.6	3.39	1454.58	1896.54	3351.12
3	3			56.2	2.6	3.48	1454.58	1946.89	3401.47
Average					2.6	3.31	1454.58	1853.65	3308.23

Table 6. Average results of the calculations without coolant

No.	Equalizer	Condition	Speed (rpm)	Temp (°c)	Current (A)		Po (Watt)	Pt (Watt)	PC (Watt)
					Io	Ii			
1	1	Without	234.6	39.1	2.6	4.08	1454.58	2282.57	3737.14
2	2	Coolant		58.7	2.6	3.62	1454.58	2025.22	3479.79
3	3			59.6	2.6	4.10	1454.58	2293.75	3748.33
Average					2.6	3.93	1454.58	2200.51	3655.09

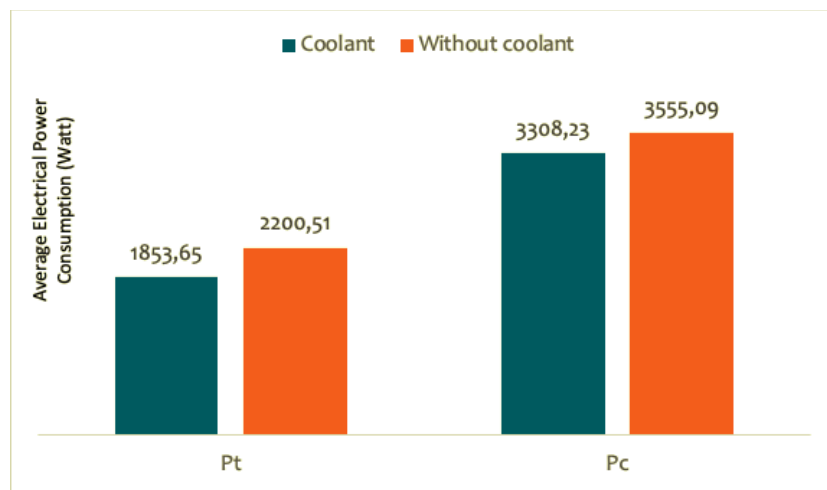


Figure 4. Comparison of average electrical power consumption under load (Pt) and overall average electrical power consumption (Pc)

The reduction in electrical power consumption observed when using coolant can be explained from a thermomechanical perspective of the cutting process. The presence of coolant improves heat dissipation in the cutting zone, thereby reducing cutting temperature and stabilizing the tool–workpiece interaction. Lower cutting temperatures contribute to reduced friction at the tool–chip interface, which subsequently decreases cutting force and the mechanical load acting on the spindle motor. As reported by Khanna et al. [9], the application of sustainable cooling strategies can reduce energy consumption by 8–17% during turning operations, which is consistent with the 9.49% reduction obtained in the present study.

Furthermore, Soori and Arezoo [10] demonstrated that coolant application significantly decreases cutting temperature and tool wear, leading to improved machining stability. From an energy modelling perspective, Munoz and Sheng [15] explained that electrical energy demand in machining is directly influenced by process time and material removal rate, both of which are affected by cutting resistance and thermal conditions. When

machining is performed without coolant, higher temperatures increase friction and cutting resistance, resulting in greater cutting power (P_t) and consequently higher total power consumption (P_c). This phenomenon is also aligned with recent reviews on energy efficiency in machining processes, which highlight that thermal control and lubrication play a critical role in reducing specific energy consumption [5].

Therefore, the present findings confirm that coolant application not only enhances machining stability but also contributes to measurable electrical energy savings in line boring operations, supporting sustainable manufacturing objectives.

Conclusion

Influence of machining parameters on electrical power consumption, this study shows that the selection of appropriate machining parameters, particularly a spindle speed of 234.6 rpm and a depth of cut of 0.5 mm, significantly affects electrical power consumption. The use of coolant during the line boring process resulted in an average power consumption of approximately 3308.23 W, whereas the line boring process without coolant consumed an average power of about 3655.09 W. These results indicate that the application of coolant in the line boring process is effective in reducing electrical power consumption by 346.86 W, equivalent to reduction of 9.49%.

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