MEKATRONIKA
JOURNAL OF MECHATRONICS AND INTELLIGENT MANUFACTURING
E-ISSN: 2637-0883
VOLUME 6, ISSUE 2, JULY, 2024, 112 – 121
DOI: https://doi.org/10.15282/mekatronika.v6i2.11398

RESEARCH ARTICLE

Evaluating the Impact of Coolants on Tool Wear and Surface Quality in Ball End Milling: A Sustainability Performance Assessment

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ABSTRACT - The role of cutting fluids in machining operations is crucial, impacting productivity, tool lifespan, and work quality. An experimental investigation was conducted on ball end milling of AISI 1040 steel using uncoated HSS tools under various coolant conditions and milling modes. This research encompassed four coolant conditions: dry, mist, 4% coolant concentration, and 8% coolant concentration, with constant cutting parameters. Machining performance was assessed based on tool wear and surface roughness. Results indicate a significant influence of coolant conditions on machining performance and surface quality. Mist coolant in down milling mode exhibited superior performance in terms of tool wear and average surface roughness (0.09mm and 0.462µm, respectively), followed closely by mist coolant in up milling mode, 8% coolant concentration, and lastly, 4% coolant concentration under up milling mode. This research not only evaluated the impact of different cooling conditions but also focused on integrating sustainability into the machining process. It is expected that the regression analysis will develop a model predicting how sustainability and machining attributes interact. This model will demonstrate the benefits of incorporating sustainability parameters into machining conditions, providing valuable insights for optimising processes with environmental and societal considerations. By creating a comprehensive interaction model, the research is anticipated to address practical aspects of coolant performance and support informed decision-making, ultimately enhancing both machining performance and sustainable manufacturing practices.

ARTICLE HISTORY
Received : 9th Oct 2024
Revised : 20th Nov 2024
Accepted : 25th Dec 2024
Published : 30th Dec 2024

KEYWORDS
Cutting Fluids
Ball End Milling
Coolant Conditions
Tool Wear
Sustainability Integration

1.0 INTRODUCTION

Milling is a machining operation where a workpiece is fed past a rotating cylindrical tool, called a milling cutter, which has multiple cutting edges, or teeth, perpendicular to the feed direction. Plain-carbon steel, an alloy primarily of iron and carbon with elements such as manganese, silicon, and copper, demonstrates different properties based on its carbon content, with increased carbon enhancing hardness and strength but reducing weldability and temperature resistance [1, 2]. In sustainable manufacturing, cutting fluids play a crucial role in cooling and lubricating the cutting tool to optimise performance and longevity. These fluids, which include oils, oil-water emulsions, pastes, gels, and mists, are increasingly derived from environmentally friendly sources such as plant oils [3, 4]. High Speed Steel (HSS) cutting tools, composed of around 7% carbon and 4% chromium along with tungsten, vanadium, molybdenum, and cobalt, maintain their hardness up to 600°C and are effective for cutting mild steel at speeds of 0.8 to 1.8 m/s. This study examines the effects of various sustainable cooling conditions and milling modes on tool wear and surface finish during the ball milling of AISI 1040 steel using HSS ball mills, highlighting the importance of environmentally conscious practices in achieving optimal machining outcomes [5, 6].

Recent studies relevant to this research have explored novel cutting fluid formulations aimed at enhancing machining performance and environmental sustainability [7]. Research on advanced machining techniques, such as high-speed machining or cryogenic machining, and their interactions with cutting fluids, is also pertinent [8]. Additionally, investigations into the influence of cutting parameters, such as cutting speed, feed rate, and depth of cut, on the effectiveness of different coolant conditions provide valuable insights for optimising machining processes. Furthermore, studies examining alternative coolant delivery methods, such as minimum quantity lubrication (MQL) or near-dry machining, and their effects on tool wear and surface quality, contribute significant findings to the field of sustainable manufacturing [8, 9].

Another significant aspect of this research lies in its potential to contribute to the development of more sustainable machining practices. By assessing the impact of various coolant conditions on machining performance and surface quality, the study offers insights into optimising coolant selection and usage to minimise environmental impact while maintaining

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productivity [10, 11]. This research can inform the machining industry about the importance of considering environmental factors in coolant selection, encouraging the adoption of more eco-friendly machining practices. Furthermore, identifying coolant conditions that offer superior performance in terms of tool wear and surface roughness can reduce material waste and energy consumption associated with machining processes, thereby promoting sustainability in manufacturing operations [12, 13]. In addition, investigating the interactions between advanced machining techniques, such as high-speed machining or cryogenic machining, and cutting fluids can uncover opportunities for further reducing the environmental footprint while enhancing machining efficiency. Studies exploring alternative coolant delivery methods, such as minimum quantity lubrication (MQL) or near-dry machining, can also provide valuable findings that contribute to the overall goal of sustainable manufacturing. By integrating these approaches, the machining industry can achieve significant advancements in both environmental sustainability and operational performance [12, 14, 15].

The study by [16] aimed to evaluate the effects of dry and cryogenic CO_2 cooling conditions on tool wear and chip morphology during high-speed milling of hardened Inconel 718. The methodology involved conducting milling operations under both cooling conditions and measuring the resulting tool wear and chip characteristics. The research highlighted the potential benefits of using cryogenic CO_2 cooling to reduce tool wear and improve chip morphology, thereby suggesting an environmentally friendly alternative to traditional cooling methods. However, the study noted shortcomings in terms of the scalability and practical implementation of cryogenic cooling in industrial settings, indicating a need for further research to address these challenges and optimise the cooling method for broader application.

The study by [17] aimed to evaluate the effects of CO_2-based cryogenic cooling on cutting forces and tool wear during the milling of Inconel 718. The methodology involved performing milling operations under CO_2 cryogenic cooling conditions and measuring the resulting cutting forces and tool wear. The findings demonstrated that CO_2 cryogenic cooling significantly reduced cutting forces and tool wear compared to traditional cooling methods, presenting a sustainable approach to improving machining quality and extending tool life. However, the study identified shortcomings in terms of sustainable manufacturing, noting that the practical implementation and cost-effectiveness of CO_2 cryogenic cooling in industrial applications remain challenging. The use of CO_2, while beneficial in reducing wear and improving performance, also raises concerns about the environmental impact of its production and supply, suggesting the need for further research to address these sustainability issues and optimise this cooling technique for broader and more eco-friendly use.

The study by [18] aimed to evaluate the effects of MQL on tool wear and surface roughness during the turning of AISI-4340 steel. The methodology involved conducting turning operations under MQL conditions and comparing the results with those obtained under conventional cooling methods. The findings indicated that MQL significantly reduced tool wear and improved surface roughness, highlighting its potential as a more environmentally friendly alternative to traditional cooling methods. However, the study noted shortcomings in terms of sustainable manufacturing, such as the need for precise control over the MQL application to achieve consistent results and potential challenges related to the disposal of used lubricants. Further research is needed to optimise MQL techniques and fully realise their sustainability benefits in industrial applications.

The study by [19] aimed to evaluate the geometrical features of tool wear and other critical machining characteristics in the sustainable turning of aluminium alloys. The methodology involved conducting turning operations under various sustainable practices and measuring the resulting tool wear and machining characteristics. The findings underscored the significance of sustainable practices in reducing tool wear and enhancing machining quality, demonstrating that sustainable methods can effectively improve machining performance. However, the study highlighted shortcomings in sustainable manufacturing, including the need for further optimisation of sustainable practices to achieve consistent and reliable results, as well as addressing the challenges associated with the integration of these practices into existing industrial processes. Further research is required to fully understand and mitigate these challenges to enhance the sustainability of machining operations.

The review by [20] aimed to provide insights into the use of vegetable oil-based nanofluids for MQL in turning operations, exploring their potential as sustainable coolants in machining. The methodology involved a comprehensive analysis of existing studies on the formulation, application, and performance of vegetable oil-based nanofluids in MQL systems. The findings highlighted that these nanofluids can significantly improve tool life, reduce cutting forces, and enhance surface finish, thereby presenting an environmentally friendly alternative to conventional coolants. However, the study identified shortcomings in sustainable manufacturing, such as the high cost of nanoparticle production, potential health risks associated with nanoparticle exposure, and the need for precise control over nanofluid formulation and application to achieve optimal performance. Further research is required to address these challenges and fully harness the benefits of vegetable oil-based nanofluids in sustainable machining practices.

Previous research in the field of machining often falls short in addressing the comprehensive integration of sustainability with machining parameters. While studies have examined the impact of cooling conditions on machining performance, such as tool wear and surface finish, they frequently neglect to incorporate broader sustainability metrics. Many existing analyses focus predominantly on technical aspects like efficiency and productivity without sufficiently considering environmental and societal impacts [21–24]. This gap becomes apparent in the lack of detailed exploration into how sustainability parameters such as energy consumption, waste management, and resource utilisation interact with machining conditions [25, 26]. As a result, the contributions of these studies towards developing sustainable machining practices remain limited, failing to provide a holistic view of the environmental and societal benefits of integrating sustainability into machining processes.

Furthermore, there is often a lack of comprehensive models that integrate sustainability attributes with machining conditions. Previous research tends to use isolated models that assess technical performance separately from sustainability considerations. This approach overlooks the potential synergies between improved machining processes and sustainable practices. For instance, while certain studies may highlight the benefits of specific coolant conditions on tool life and surface quality, they typically do not evaluate how these conditions impact overall sustainability, including factors like reduced environmental footprint or enhanced operator health. By not addressing these interconnected aspects, previous research does not fully support informed decision-making that aligns technical performance with sustainable manufacturing goals. The proposed study aims to bridge this gap by developing a comprehensive interaction model that integrates sustainability parameters with machining conditions, thereby offering valuable insights into optimising both performance and sustainability in machining practices.

This research aims to evaluate the impact of different cooling conditions on the machining performance of an uncoated HSS tool during ball milling of AISI 1040 steel. The project focuses on utilising AISI 1040 steel as the workpiece, employing an 8 mm diameter 2-flute HSS uncoated ball end mill as the cutting tool, and conducting experiments on a HASS VF 1D CNC machine. Various coolant conditions will be examined, including dry cutting, mist coolant, and coolant concentrations of 4% and 8%, while maintaining constant cutting speed, feed, and depth of cut throughout the experiments. This investigation addresses concerns about excessive coolant usage and its impact on operator health and the environment. Additionally, this research seeks to explore the effects of different cooling conditions and milling modes on tool wear, with surface roughness serving as an additional criterion for evaluating coolant performance.

In addition to evaluating the impact of various cooling conditions on the machining performance of an uncoated HSS tool during ball milling of AISI 1040 steel, this research will also focus on integrating sustainability into the machining process. The regression analysis is expected to reveal the characterised model and predict the engagement value for integrating sustainability and machining attributes. This model is also expected to highlight the strength of incorporating sustainability parameters into machining conditions, offering valuable insights for optimising processes with environmental and societal considerations in mind. By developing a comprehensive interaction model, this research is expected to address the practical aspects of coolant performance and support informed decision-making aimed at enhancing sustainability in machining. This dual approach is hoped to ensure that the research contributes to both the technical performance of machining operations and the broader goal of sustainable manufacturing practices.

2.0 METHODOLOGY

2.1 Cutting Tools

For this research, a Somta Ball End Mill, code 335, made from uncoated High-Speed Steel (HSS) of M42 grade was utilised. The composition and mechanical properties of this tool are detailed in Table 1 and Table 2, respectively.

Table 1. Composition of HSS ball end mill

Carbon, C	1.1 %
Chromium, Cr	4 %
Tungsten, W	1.5 %
Molybdenum, Mo	9.5 %
Vanadium, V	1%
Cobalt, Co	8 %

Table 2. Mechanical properties of HSS ball end mill

Diameter, d	8 mm
Diameter, d_1	10 mm
No of flute	2
Milling mode	Up and Down milling
Overall length, l_1	88 mm
Cutting length, l_2	19 mm
Hardness	66-68.5 HRC
Product code	3350800

2.2 Workpiece Materials

The workpiece is composed of medium carbon steel (AISI 1040) with dimensions of 160 mm x 50 mm x 10 mm. The chemical composition and mechanical properties of the workpiece are provided in Table 3 and Table 4, respectively.

Table 3. Nominal chemical composition (%) of AISI 1040 steel

Carbon, (C)	Mangan, (Mn)	Sulfur, (S)	Phosphorus, (P)

0.37-0.44	0.60-0.90	0.05 (max)	0.04 (max)

Table 4. Physical and mechanical properties of work material AISI 1040

Properties		Conditions	
		T (°C)	Treatment
Density (×1000 kg/m^3)	7.845	25	
Poisson's Ratio	0.27-0.30		
Elastic Modulus (GPa)	190-210	25	
Tensile Strength (Mpa)	518.8		
Yield Strength (Mpa)	353.4	25	annealed at 790°C
Elongation (%)	30.2		
Reduction in Area (%)	57.2		
Hardness (HB)	149	25	annealed at 790°C
Impact Strength (J) (*Izod*)	44.3	25	annealed at 790°C

2.3 Measurement and Observation

The surface roughness of the machined workpiece was measured using the Mahr Perthometer M2, with calibration performed using a calibration block before each measurement. The device specifications include a model number M2, a cut-off length of 2.5 mm, and a sample length of 25 mm. Coolant concentration was measured using an ATAGO Master-T hand refractometer. Tool wear images were captured using a Zeiss Video Microscope (Carl Zeiss Stemi 2000-C) with 50X magnification, operating at 240V. The flood coolant used in the experiments was Castrol Syntilo 9954.

2.4 Mist Coolant Apparatus

In this research, Castrol Syntilo 9954 was utilised as lubrication for the Minimum Quantity Lubrication (MQL) condition. The flow rate of the MQL system is as follows:

i. 1 Drop Meter Output (cc/stroke)

ii. High Range: 0.002 cc – 0.033 cc

iii. 24 pulses per minute

iv. Therefore, the flow rate (Q) is calculated as $Q=24\times0.033=0.792Q=24\times0.033=0.792$ ml/min.

2.5 Machining Conditions

In this research, a Somta End Mill Ball Nose 2 Flute, made of uncoated HSS, was used under four different coolant conditions while maintaining a constant cutting speed, feed rate, and axial depth of cut. The up milling mode was employed, performing 32 mm x 32 mm profile cutting using a Haas CNC machine. A total of five cutting profiles were machined for each condition, resulting in a cutting length of 5424 mm. Detailed cutting conditions for the experiment are provided in Table 5.

Table 5. The cutting conditions

Cutting Parameters	HSS Uncoated Carbide Tool
Cutting Speed, V_c (mm/min)	52
Spindle Speed, N (rpm)	856
Axial Depth of Cut, a_p (mm)	0.8
Step over, (mm)	1
Coolant Condition	Mist, Dry, CC 4%, CC 8%

2.6 Sustainability Assessment

Selecting the most sustainable machining condition requires a deep understanding of the capabilities of various manufacturing processes while prioritising environmental and resource efficiency. This involves initial rough estimations of key sustainable machining attributes such as tool wear and surface quality, reflected in sustainability indices. For tool wear, the attribute should consider not only energy consumption and waste management but also the impact of tool wear on the frequency of tool replacement and maintenance, which affects overall operational costs. Additionally, the efficiency of resource utilisation, including the longevity of tools and their impact on production waste, is crucial. Equipment and facility costs, material and consumables costs, labour, and overhead costs all play a role in managing tool wear sustainably. For surface quality, the attribute can be evaluated through indices such as cycle time, setup and changeover time, throughput time, and lead time, with an emphasis on processes that reduce time and energy consumption while maintaining high surface quality. The quality attribute is assessed through metrics like surface roughness and tolerances, as well as financial measures such as cost of quality and yield. It is also important to consider the environmental impact of achieving these quality standards, including the use of eco-friendly materials and processes that can sustainably enhance surface quality.

As highlighted by [27], energy efficiency can serve as a sustainability index, aligning with the triple bottom line aspects by impacting economic, environmental, and social pillars. However, [28] pointed out that current concepts of energy efficiency might be inaccurate. Energy efficiency can be linked to technologies and operations that reduce energy consumption. Various energy-related metrics are available, focusing on energy consumption [29] (e.g., energy usage per product, total energy consumption), environmental impact (e.g., carbon footprint, greenhouse emissions), and economic factors (e.g., energy cost). These metrics can be analysed at different levels, such as the manufacturing process, machine tool, or plant level, with the chosen level influencing data granularity and resolution [30]. The social sustainability aspect can be evaluated based on worker health and safety, overtime requirements, and human toxicity potential, often estimated using life cycle analysis techniques [31].

The goal of this analysis is to identify the optimal alternative process plans for sustainable machining, which necessitates obtaining values for all selected parameters. A total of eight criteria were identified from the literature review (n = 8), reflecting the significant aspects of the three pillars of sustainability, as detailed in Table 6.

Table 6. Identified criteria

Energy efficiency
Raw material efficiency
Waste management
CO_2 emissions
Health and safety of workers
Work quality
Cost efficiency
Ecosystem quality

2.6 Characterisation

In this research, the characterised model (regression model) is used to predict sustainability value. This phase also introduces the criteria definition, categorising sustainability attributes and integrating machining attributes weightage to enhance the understanding of sustainability (see Table 7). Expert elicitation is considered to gather subjective, probabilistic judgements on key variables, providing valuable insights for complex, interdisciplinary issues.

Table 7. Sustainability and machining attributes concept

Sustainability attributes	Machining attributes	
	Tool Wear	**Surface Quality**
Energy efficiency	W_{1E}	R_{1E}
Raw material efficiency	W_{2E}	R_{2E}
Waste management	W_{3E}	R_{3E}
CO_2 emissions	W_{4E}	R_{4E}
Health and safety of workers	W_{5S}	R_{5S}
Work quality	W_{6S}	R_{6S}
Cost efficiency	W_{7C}	R_{7C}
Ecosystem quality	W_{8S}	R_{8S}

3.0 RESULTS

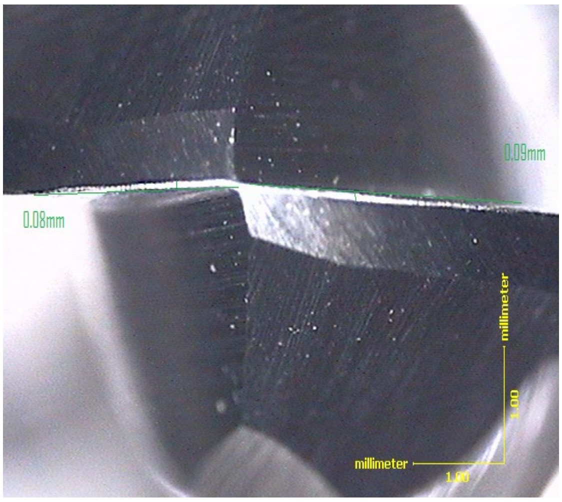
3.1 Tool Wear

The effectiveness of different coolant conditions was evaluated by examining tool wear progression. The flank wear (Vb) of the cutting edge was measured using an optical microscope at the conclusion of the experiment for each condition. The flank wear data for all coolant conditions are presented in Table 8.

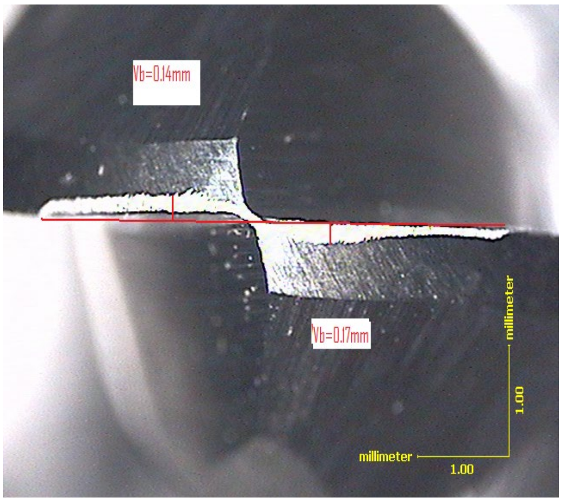
Table 8. Flank wear at cutting length 5424 mm or 106 minutes of cutting time-up milling

Condition	Flank Wear (mm)					
	Cutting edge 1		Cutting edge 2		Average Wear	
	Vb ave 1	Vb max 1	Vb ave 2	Vb max 2	Vb ave	Vb max
Mist	0.08	0.08	0.09	0.09	0.085	0.085
8 % cc	0.1	0.14	0.11	0.17	0.105	0.155
4 % cc	0.11	0.19	0.15	0.2	0.13	0.195
Dry	0.31	0.56	0.21	0.37	0.26	0.465

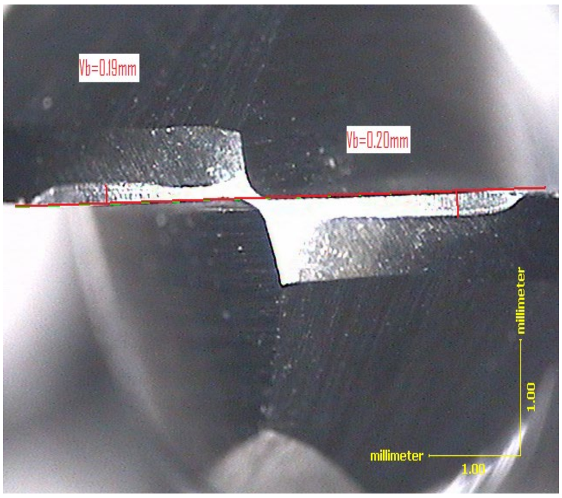
Images of the tool wear at the cutting edge under various coolant conditions are shown in Figure 1.



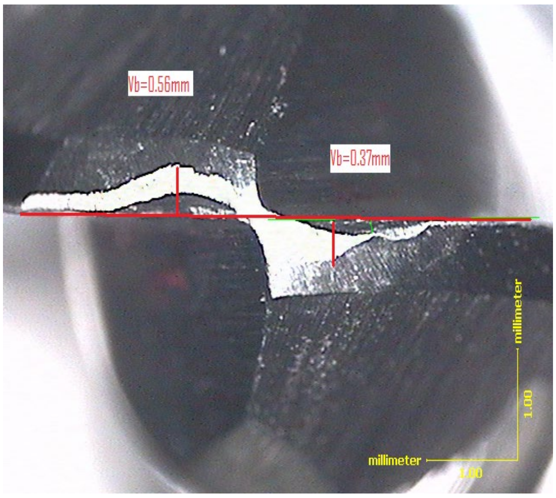
(a) Mist coolant condition – up milling
(Average flank wear = 0.085mm)



(b) 8% coolant concentration – up milling
(Average flank wear = 0.155mm)



(c) 4% coolant concentration – up milling
(Average flank wear = 0.195mm)



(d) Dry coolant concentration – up milling
(Average flank wear = 0.465mm)

Figure 1. Image of flank wear of the cutting edge after ball milling 5424mm under various coolant conditions

Results showed that under all coolant conditions except for dry cutting, the flank wear obtained was well below the normal tool life criteria with Vb ave < 0.3 mm and Vb_max < 0.5 mm. This level of wear is typical and does not significantly affect tool usability until it becomes severe enough to cause cutting edge failure. The tool under dry cutting failed after machining 5424 mm for 106 minutes. Mist coolant recorded the lowest tool wear among the conditions tested. As reported by [32], mist coolant effectively penetrates the cutting zone. [33] observed a similar trend during their investigation on high-speed milling of A356 aluminium alloy. Mist coolant provides benefits by offering lubrication and reducing cutting temperature, which improves chip-tool interaction and maintains the sharpness of the cutting edge. Therefore, it is suggested that mist coolant be adopted when surface roughness and tool wear are primary concerns during ball milling of AISI 1040 steel using uncoated HSS tools. In addition to improving machining performance in terms of tool life and surface finish, mist coolant positively impacts the environment, health, and economy in the machining industry.

3.2 Surface Roughness

The surface roughness (Ra) values for each coolant condition were measured and recorded after cutting at each specified length of time. Figure 2 graphically presents the surface roughness profile for various coolant conditions against the cutting length during the up milling operation. It was observed that all coolant conditions exhibited a similar trend in the surface roughness profile, with a slight increase in surface roughness values at the end of cutting compared to the initial cutting values.

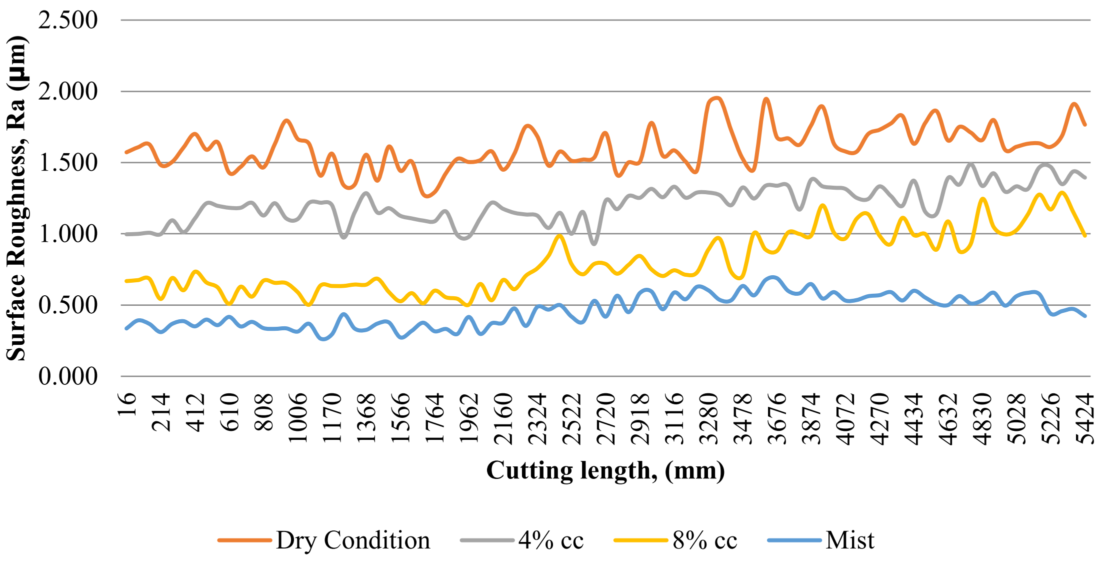


Figure 2. Surface roughness curve against of cutting length for various coolant conditions in up milling mode

The overall results in Table 9 show that the mist coolant condition produced the lowest surface roughness values, with a minimum of 0.265 µm, an average of 0.462 µm, and a maximum of 0.689 µm. The second-best performance was from the 8% coolant concentration, with a minimum surface roughness of 0.502 µm. This was followed by the 4% coolant concentration with a minimum of 0.928 µm. Dry cutting recorded the worst performance, with a minimum surface roughness of 1.279 µm. Mist coolant outperformed other conditions, consistent with findings from researchers such as [34, 35]who reported that mist coolant provides a lubrication effect, reducing friction and improving surface quality. Conversely, dry cutting resulted in the highest surface roughness due to increased heat generation and tool wear, which can negatively impact tool life and machined surface quality [36]. The high temperatures during dry cutting can also affect part accuracy by causing workpiece expansion. Higher coolant concentration (8%) resulted in lower surface roughness compared to 4% concentration and dry cutting, as sufficient cutting fluid supply helps to maintain efficient cutting temperatures, thereby reducing friction and tool wear.

Table 9. Surface roughness value at cutting length 5424mm under various coolant condition with up milling mode

Surface Roughness, Ra(µm)	Dry Cutting	4% cc	8% cc	Mist
Average value	1.607	1.213	0.804	0.462
Maximum value	1.947	1.490	1.289	0.689
Minimum value	1.279	0.928	0.502	0.265

3.3 Sustainability Assessment

The rough assessment of machining attributes determines their ranking, but this initial ranking is qualitative. For a more detailed and quantitative assessment, multi-criteria decision-making techniques like the TOPSIS method should be considered [37–38]. The ranking of machining attributes varies based on utilisation scenarios. For both low and high utilisation scenarios, the best-performing attribute is clear. However, for medium utilisation, the performance differences are minimal, necessitating a more quantitative assessment. The next step is to perform TOPSIS specifically for the medium utilisation scenario, following the framework used by [38–40]. This involves formulating a decision matrix and calculating or assuming variable values based on methods such as energy audits, life cycle analysis, or literature review. Table 10 presents the decision matrix, and Table 11 shows the normalisation of the variable values.

Table 10. Decision matrix for medium utilisation

Sustainability attributes	Machining attributes			
	Dry Cutting	4% cc	8% cc	Mist
Energy consumption per batch	562.5	615	597.5	580
Raw material used per batch	205	195	197.5	202.5
Waste management per batch	82.5	89	85	86.5
CO_2 emissions	950	750	825	875
Health and safety of workers	3	3.8	3.25	3.5
Work quality	1	0.89	0.95	0.93
Cost efficiency	69	74.3	72	71.3
Impact on ecosystem quality	13.5	10	11.5	12

Table 11. Normalised matrix

Sustainability attributes	Machining attributes			
	Dry Cutting	4% cc	8% cc	Mist
Energy consumption per batch	0.477	0.522	0.507	0.492
Raw material used per batch	0.513	0.487	0.494	0.506
Waste management per batch	0.481	0.519	0.495	0.504
CO_2 emissions	0.553	0.436	0.480	0.509
Health and safety of workers	0.441	0.552	0.478	0.515
Work quality	0.532	0.466	0.506	0.492
Cost efficiency	0.481	0.518	0.502	0.497
Impact on ecosystem quality	0.568	0.421	0.484	0.505

The conceptual sustainability attributes, along with the identified criteria, are now integrated with the machining conditions to form the functional characterisation of the sustainability and machining attributes concept. This functional element is introduced to embed the sustainability aspect directly into the context of the sustainability-machining relationship.

The next action is to finalise the performance assessment model, which integrates sustainability concepts with machining attributes and conditions. This model will be supported by regression analysis, showing high engagement values between sustainability parameters (environment, society, cost) and machining conditions (dry cutting, 4% cc, 8% cc, mist). The equations for each condition will be demonstrating how sustainability parameters influence performance. The regression analysis will be confirming a strong correlation, with engagement values exceeding 85% for all parameters, reflecting the model's robustness in predicting sustainability performance in machining processes.

4.0 CONCLUSION

In conclusion, this research successfully met its objective of assessing the impact of coolant conditions on machining performance, specifically examining surface roughness and tool wear during ball milling of AISI 1040 steel with uncoated HSS tools. This research highlighted several important findings: coolant conditions have a significant effect on both surface roughness and tool wear, with mist coolant demonstrating the best performance in up milling, followed by 8% coolant concentration, 4% coolant concentration, and dry conditions. Mist coolant consistently delivered superior results in terms of surface finish and tool wear, with down milling under mist coolant achieving the lowest surface roughness of 0.246 μm.

The regression analysis will be demonstrating that the characterised model will be effectively predicting the engagement value for integrating sustainability and machining attributes. The engagement value, as reflected in the competency model, will be highlighting the strength of the integration between sustainability parameters and machining conditions. This successful demonstration of engagement strength will be marking a significant achievement of this research, completing the development of a comprehensive interaction model for machining in the context of sustainability performance. This model will be offering valuable insights for optimising machining processes while considering sustainability factors, thus contributing to more informed and effective decision-making in the field.

It is expected that the development and application of an interaction model integrating sustainability with machining attributes will provide significant benefits across environmental, societal, and cost dimensions. Environmentally, the model will help identify optimal machining conditions that reduce resource consumption and waste. Societally, it will enhance tool performance and working conditions, improving workplace safety. From a cost perspective, it will lower operational expenses by optimising coolant use and tool wear. Overall, the model is expected to foster a more sustainable and economically viable machining industry, aligning with sustainable development goals.

5.0 AUTHORS CONTRIBUTION

The authors, Ahmad Saifuddin Azraie and Faiz Mohd Turan, carried out the conceptualisation, drafting of the research work, and editing of the final article. Both authors approved the submitted version.

6.0 ACKNOWLEDGEMENTS

This research was funded by a grant from Universiti Malaysia Pahang Al-Sultan Abdullah (RDU233016).

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