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RESEARCH ARTICLE

Developing a Sustainability Assessment Model for Coolant Impacts on Surface Quality in Ball End Milling

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ABSTRACT - Cutting fluids play a critical role in machining operations, yet excessive or inefficient use poses environmental challenges and affects workers' health, highlighting the need for optimised and sustainable practices. This study addresses the challenge of balancing machining performance and sustainability by experimentally investigating ball end milling of AISI 1040 steel using uncoated HSS tools under dry, mist, 4% coolant, and 8% coolant conditions with constant cutting parameters. Machining performance was evaluated based on surface roughness, with mist coolant in down milling achieving the best results (average roughness of 0.462 μm), followed by mist coolant in up milling, 8% coolant, and 4% coolant in up milling. The research highlights the significant impact of coolant conditions on machining performance and surface quality while integrating sustainability principles. A regression-based model was developed to predict interactions between sustainability parameters and machining attributes, offering insights to optimise processes with environmental and societal considerations, thereby supporting sustainable manufacturing practices.

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1.0 INTRODUCTION

Milling is a widely used machining process in which a rotating cylindrical tool, known as a milling cutter, removes material from a workpiece as it moves past the cutter. The milling cutter features multiple cutting edges, or teeth, positioned perpendicular to the direction of feed, enabling efficient material removal and high-precision shaping. The properties of the workpiece material significantly influence machining performance. Plain-carbon steel, an iron-carbon alloy containing elements such as manganese, silicon, and copper, exhibits varying mechanical characteristics depending on its carbon content. Higher carbon levels enhance hardness and strength but simultaneously reduce weldability and resistance to high temperatures [1, 2]. In sustainable manufacturing, cutting fluids are essential for improving machining efficiency by cooling and lubricating the cutting tool, thereby reducing friction, tool wear, and thermal damage. These fluids traditionally include oils, oil-water emulsions, pastes, gels, and mists. However, there is a growing shift towards more sustainable alternatives, such as plant-based oils, to minimise environmental impact while maintaining performance [3, 4]. High-Speed Steel (HSS) remains a popular choice for cutting tools due to its superior hardness, wear resistance, and ability to retain strength at elevated temperatures. HSS tools typically contain around 7% carbon and 4% chromium, along with alloying elements like tungsten, vanadium, molybdenum, and cobalt, which enhance their performance in high-stress machining applications. With the ability to maintain hardness up to 600°C, HSS cutters are well-suited for milling mild and medium-carbon steels at cutting speeds ranging from 0.8 to 1.8 m/s. This study investigates the impact of various sustainable cooling conditions and milling strategies on tool wear and surface quality during the ball milling of AISI 1040 steel using uncoated HSS ball end mills. By analysing the influence of different coolant application methods—including mist cooling and varying coolant concentrations—this research aims to optimise coolant selection for enhanced machining performance while promoting environmentally responsible practices. The findings will contribute to advancing sustainable machining techniques, balancing productivity with reduced ecological footprint [5, 6].

Recent studies in sustainable machining have explored innovative cutting fluid formulations designed to enhance both machining performance and environmental sustainability [7]. These formulations aim to reduce the ecological impact of traditional coolants while maintaining or even improving their lubrication and cooling efficiency. Research has also examined advanced machining techniques, such as high-speed machining and cryogenic machining, to understand their interactions with cutting fluids and their influence on tool life, surface integrity, and overall process efficiency [8]. Understanding these interactions is critical for optimising machining strategies that balance performance with environmental responsibility. Furthermore, investigations into the effects of key cutting parameters such as cutting speed, feed rate, and depth of cut on the performance of different coolant conditions have provided valuable insights for

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optimising machining processes. These parameters play a crucial role in determining heat generation, tool wear, and surface roughness, which are all directly affected by coolant application methods. In addition, studies exploring alternative coolant delivery techniques, such as minimum quantity lubrication (MQL) and near-dry machining, have contributed significant findings to the field of sustainable manufacturing by demonstrating reductions in fluid consumption, environmental emissions, and energy use [8, 9]. A key contribution of this research is its potential to advance sustainable machining practices by systematically evaluating the impact of different coolant conditions on machining performance. By assessing tool wear, surface roughness, and overall process efficiency, this study provides critical insights into optimising coolant selection and usage to minimise environmental impact while maintaining high productivity levels [10, 11]. These findings can inform machining industries about the importance of integrating sustainability considerations into coolant selection, encouraging a shift towards more environmentally friendly machining practices. Additionally, identifying optimal coolant conditions that enhance tool performance can lead to reduced material waste and lower energy consumption in machining operations, further promoting sustainability in manufacturing [12, 13]. Exploring the interactions between advanced machining techniques, such as high-speed and cryogenic machining, and cutting fluids may uncover new opportunities for reducing the environmental footprint while enhancing machining efficiency. Moreover, research into alternative coolant delivery methods, including MQL and near-dry machining, continues to provide valuable knowledge for improving both environmental sustainability and operational performance. By integrating these strategies, the machining industry can make significant progress towards achieving sustainable and resource-efficient manufacturing [12, 14, 15].

Studies on sustainable cooling techniques in machining have demonstrated notable advancements in tool wear reduction, machining efficiency, and environmental sustainability while also revealing critical challenges that hinder their widespread industrial adoption. Research by [16] and [17] investigated the use of cryogenic CO_2 cooling in the milling of Inconel 718, demonstrating its ability to significantly reduce tool wear and cutting forces while improving chip morphology. These findings suggest that cryogenic CO_2 cooling can serve as a viable alternative to conventional cooling methods, potentially extending tool life and enhancing machining efficiency. However, concerns remain regarding the scalability of this approach in industrial settings, as well as the cost-effectiveness and practicality of integrating cryogenic systems into existing manufacturing processes. Additionally, the environmental impact of CO_2 production and supply raises sustainability concerns that must be addressed before this technique can be widely implemented. Similarly, studies by [18] and [19] examined the impact of minimum quantity lubrication (MQL) in machining operations, particularly in the turning of AISI-4340 steel and aluminium alloys. Their findings indicate that MQL effectively minimises tool wear and enhances surface roughness, offering a more environmentally friendly alternative to flood cooling. Despite these benefits, several challenges hinder MQL's broader adoption, including the need for precise control over lubricant application to ensure consistency and efficiency. Additionally, issues related to the disposal of used lubricants and potential health risks associated with airborne oil mist require further investigation to develop safer and more sustainable lubrication strategies.

Furthermore, the review by [20] explored the application of vegetable oil-based nanofluids in MQL systems, highlighting their potential to improve tool life, reduce cutting forces, and enhance surface finish. While these nanofluids present an eco-friendly alternative to synthetic lubricants, their high production costs, potential health risks from nanoparticle exposure, and the need for precise control over formulation and application pose significant challenges. Addressing these limitations is essential for making vegetable oil-based nanofluids a feasible and sustainable option in machining operations. Collectively, these studies underscore the promising role of sustainable cooling and lubrication techniques in modern machining while also emphasising the necessity for further optimisation. The integration of cryogenic CO_2 cooling, MQL, and nanofluid-based lubricants into industrial applications requires a balanced approach that considers technical performance, cost efficiency, and environmental impact. Future research should focus on refining these methods to overcome existing limitations, ensuring their practicality in large-scale manufacturing while aligning with sustainability goals.

Previous research in the field of machining has primarily focused on optimising technical parameters, often overlooking the comprehensive integration of sustainability principles into machining processes. While numerous studies have investigated the effects of cooling conditions on machining performance particularly in terms of tool wear, surface finish, and machining efficiency, many have not fully incorporated broader sustainability metrics. The emphasis in existing research tends to be on improving productivity, reducing manufacturing costs, and enhancing tool life, with limited attention given to the environmental and societal implications of machining operations [21–24]. A critical gap in current studies lies in the insufficient exploration of how key sustainability parameters, such as energy consumption, waste management, and resource utilisation, interact with machining conditions. While some research has acknowledged the potential environmental impact of coolant selection and cutting fluid consumption, these studies often lack a structured approach to quantify and integrate sustainability considerations into decision-making frameworks [25, 26]. As a result, the contributions of these studies remain fragmented, failing to provide a holistic view of how machining practices can be optimised to achieve both high performance and environmental responsibility. Addressing this research gap is essential for developing machining strategies that align with global sustainability goals. A more comprehensive approach, one that evaluates not only the technical performance of machining processes but also their ecological footprint and social implications is necessary to drive the adoption of sustainable manufacturing practices. This includes assessing how different coolant conditions influence energy efficiency, minimising hazardous waste generation, and optimising resource utilisation to balance economic viability with environmental stewardship. By bridging these gaps, future research can provide actionable insights for industries seeking to transition towards greener and more responsible machining operations.

Additionally, there is a significant gap in the development of comprehensive models that effectively integrate sustainability attributes with machining conditions. Much of the existing research relies on fragmented or isolated models that assess technical performance such as tool wear, surface quality, and machining efficiency, separately from sustainability considerations. This segmented approach fails to capture the potential synergies between optimised machining processes and sustainable manufacturing practices. For instance, while certain studies may demonstrate the advantages of specific coolant conditions in extending tool life and improving surface finish, they often do not examine the broader sustainability implications of these conditions. Key aspects such as the reduction of hazardous waste, energy consumption, or the long-term environmental impact of coolant disposal remain underexplored. Moreover, worker health and safety, critical factors in sustainable manufacturing are frequently overlooked in favour of purely technical evaluations. Without addressing these interconnected elements, previous research does not provide a holistic framework for making informed decisions that balance machining efficiency with sustainability objectives. To address this gap, the proposed study seeks to develop a comprehensive interaction model that integrates key sustainability parameters such as energy efficiency, resource utilisation, waste management, and occupational health with machining conditions. By doing so, this research will offer a structured approach to evaluating machining performance in alignment with sustainability principles. The findings will provide actionable insights for manufacturers, enabling them to optimise machining operations while minimising environmental impact and enhancing workplace safety. Ultimately, this study aims to support the transition toward more sustainable manufacturing practices by bridging the divide between technical optimisation and ecological responsibility.

This research aims to comprehensively evaluate the influence of various cooling conditions on the machining performance of an uncoated high-speed steel (HSS) tool during the ball milling of AISI 1040 steel. The study specifically focuses on analysing tool wear and surface roughness as key performance indicators, providing insights into how different cooling strategies affect machining efficiency and sustainability. The experimental setup consists of AISI 1040 steel as the workpiece material and an 8 mm diameter, 2-flute, uncoated HSS ball end mill as the cutting tool. Machining trials will be conducted on a HASS VF 1D CNC machine to ensure precision and consistency. To systematically assess coolant performance, four distinct cooling conditions will be examined: dry cutting, mist coolant, and coolant concentrations of 4% and 8%. Throughout the experiments, critical machining parameters, including cutting speed, feed rate, and depth of cut will be maintained at constant values to isolate the effects of coolant conditions on machining performance. This investigation addresses the growing concerns surrounding excessive coolant usage, particularly its environmental impact and potential health risks for machine operators. By exploring alternative coolant delivery methods and their effects on tool wear and surface roughness, this study aims to identify optimal cooling conditions that strike a balance between machining efficiency and sustainability. The findings are expected to contribute valuable knowledge for manufacturers seeking to reduce coolant consumption while maintaining high-quality machining outcomes, ultimately supporting the advancement of sustainable manufacturing practices.

Beyond evaluating the effects of different cooling conditions on the machining performance of an uncoated high-speed steel (HSS) tool during the ball milling of AISI 1040 steel, this research also aims to integrate sustainability considerations into the machining process. A key component of this study is the development of a regression-based model that characterises the interactions between machining attributes and sustainability parameters. This model will predict the engagement value of various coolant conditions, providing a structured framework for balancing machining efficiency with environmental and societal factors. By incorporating sustainability metrics such as energy consumption, coolant usage, waste generation, and operator health impacts, this study seeks to highlight the significance of sustainable machining practices. The regression analysis is expected to quantify the benefits of different cooling strategies, demonstrating the practical advantages of optimising coolant performance with sustainability in mind. The resulting model will serve as a decision-support tool, offering manufacturers data-driven insights for selecting coolant conditions that enhance both technical performance and environmental responsibility. This research takes a dual approach, bridging the gap between machining efficiency and sustainability objectives. By developing a comprehensive interaction model, the study will not only contribute to improving tool wear resistance and surface quality but also promote eco-friendly machining practices. Ultimately, the findings are expected to guide manufacturers and researchers toward more sustainable machining solutions, ensuring that industrial advancements align with broader environmental and societal goals.

2.0 METHODOLOGY

2.1 Machining Conditions

In this research, a Somta Ball End Mill, code 335, made from uncoated High-Speed Steel (HSS) of M42 grade was utilised for machining AISI 1040 medium carbon steel. The cutting tool had a diameter of 8 mm, two flutes, and was capable of both up and down milling. The workpiece dimensions were 160 mm x 50 mm x 10 mm. The machining experiments were conducted on a Haas CNC machine under four different coolant conditions: dry cutting, mist coolant, and flood coolant with concentrations of 4% and 8%. A constant cutting speed, feed rate, and axial depth of cut were maintained throughout the experiments. The milling operation involved profile cutting of 32 mm x 32 mm, with each coolant condition being tested over five cutting profiles, resulting in a total cutting length of 5424 mm. The surface roughness of the machined workpiece was measured using the Mahr Perthometer M2, with calibration performed before each measurement. Tool wear images were captured using a Zeiss Video Microscope (Carl Zeiss Stemi 2000-C) with 50X magnification. The coolant used for mist and flood conditions was Castrol Syntilo 9954, with mist coolant delivered via a Minimum Quantity Lubrication (MQL) system operating at a flow rate of 0.792 ml/min. The detailed cutting conditions are summarised in Table 1.

Table 1. 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%

2.2 Sustainability Assessment

Achieving sustainability in machining requires a comprehensive understanding of manufacturing processes while prioritising environmental and resource efficiency. This involves an initial estimation of key sustainability attributes, particularly tool wear and surface quality, which are incorporated into sustainability indices. Sustainable tool wear management goes beyond energy consumption and waste management. It also accounts for tool replacement frequency, maintenance costs, and overall operational expenses. Maximising resource efficiency, including extending tool life and minimising production waste, is crucial. Additionally, factors such as equipment and facility costs, material and consumable expenses, labour, and overhead costs contribute to sustainable machining practices. Surface quality is evaluated using indices such as cycle time, setup and changeover time, throughput time, and lead time. Sustainable processes prioritise reducing time and energy consumption while maintaining high surface quality. Further assessment includes surface roughness, tolerances, cost of quality, and yield. Moreover, environmental considerations, such as the use of eco-friendly materials and sustainable techniques to enhance surface quality, play a significant role in sustainable machining.

Energy efficiency is a key sustainability metric that aligns with the triple bottom line framework by impacting economic, environmental, and social dimensions [27]. However, [28] highlights that conventional energy efficiency metrics may be imprecise. Energy efficiency is influenced by technologies and operational strategies that reduce energy consumption. Various energy-related metrics exist, including energy usage per product, total energy consumption [29], environmental impacts (e.g., carbon footprint, greenhouse gas emissions), and economic factors (e.g., energy costs). The level at which these metrics are analysed—whether at the manufacturing process, machine tool, or plant level—affects data granularity and resolution [30]. The social dimension of sustainability is evaluated based on worker health and safety, overtime requirements, and human toxicity potential. These factors are often analysed using life cycle assessment techniques [31]. The goal of this analysis is to identify the most sustainable alternative process plans for machining by evaluating a range of parameters. Through a literature review, eight key criteria (n = 8) were identified, each representing critical aspects of economic, environmental, and social sustainability, as detailed in Table 2.

Table 2. Identified criteria

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

2.3 Characterisation

This research employs a characterised regression model to predict sustainability values, facilitating data-driven decision-making in machining processes. The model integrates sustainability and machining attributes, enabling a comprehensive assessment of machining conditions. A key aspect of this phase is the definition and categorisation of sustainability attributes, which are systematically aligned with machining attributes to enhance understanding and evaluation (see Table 3). By incorporating machining attributes' weightage, the model ensures a balanced representation of sustainability factors, allowing for more precise optimisation.

To strengthen the analysis, expert elicitation is incorporated, providing subjective and probabilistic judgments on key variables. This approach is particularly valuable for addressing complex and interdisciplinary challenges, where direct measurements may be limited. Experts contribute insights that refine the model by capturing practical considerations, uncertainties, and domain-specific knowledge. The integration of expert knowledge helps improve the accuracy and reliability of sustainability predictions, ultimately supporting more informed decision-making in sustainable machining practices.

Table 3. Sustainability and machining attributes concept

Sustainability attributes	Machining attributes			
	Mist	8 % cc	4 % cc	Dry
Energy efficiency, E	M_{1E}	E_{1E}	F_{1E}	D_{1E}
Raw material efficiency, E	M_{2E}	E_{2E}	F_{2E}	D_{2E}
Waste management, E	M_{3E}	E_{3E}	F_{3E}	D_{3E}
CO_2 emissions, E	M_{4E}	E_{4E}	F_{4E}	D_{4E}
Health and safety of workers, S	M_{5S}	E_{5S}	F_{5S}	D_{5S}
Work quality, S	M_{6S}	E_{6S}	F_{6S}	D_{6S}
Cost efficiency, C	M_{7C}	E_{7C}	F_{7C}	D_{7C}
Ecosystem quality, E	M_{8S}	E_{8S}	F_{8S}	D_{8S}

3.0 RESULTS

3.1 Surface Roughness

The surface roughness (Ra) values for each coolant condition were systematically measured and recorded at specified cutting intervals to evaluate the impact of different cooling methods on machined surface quality. The comprehensive results, presented in Table 9, reveal that mist coolant demonstrated the most favourable performance, yielding the lowest surface roughness values. Specifically, mist coolant achieved a minimum Ra of 0.265 µm, an average of 0.462 µm, and a maximum of 0.689 µm. This superior performance can be attributed to the enhanced lubrication effect of mist coolant, which significantly reduces friction at the tool-workpiece interface, thereby minimising cutting forces and improving surface finish. These findings align with previous studies [32, 33], which have also reported that mist coolant effectively lowers cutting temperatures and enhances machining efficiency.

Among the flood coolant conditions, the 8% coolant concentration exhibited the second-best surface quality, with a minimum surface roughness of 0.502 µm, followed by the 4% coolant concentration, which recorded a minimum of 0.928 µm. The improved performance of the 8% coolant condition compared to the 4% concentration can be attributed to its ability to maintain effective thermal regulation, reducing thermal expansion of the workpiece and minimising tool wear. In contrast, dry cutting resulted in the highest surface roughness, with a minimum recorded value of 1.279 µm. The absence of coolant in dry cutting led to increased heat generation at the cutting zone, accelerating tool wear and contributing to poorer surface quality. Elevated temperatures during dry machining can also induce workpiece expansion, compromising dimensional accuracy. The results confirm that the appropriate selection of coolant conditions plays a crucial role in achieving optimal surface roughness, with mist coolant emerging as the most effective option for minimising surface irregularities and enhancing machining performance.

Table 4. 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

3.2 Sustainability Assessment

The preliminary evaluation of machining attributes provides an initial ranking based on qualitative assessments. However, this rough ranking lacks the precision needed for a comprehensive sustainability evaluation. To achieve a more detailed and quantitative assessment, multi-criteria decision-making (MCDM) techniques such as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) should be employed [34–36]. This method enables a structured comparison of machining attributes by considering multiple performance criteria, thereby enhancing the objectivity of the ranking process. The ranking of machining attributes varies depending on utilisation scenarios. In both low and high utilisation cases, the best-performing attribute is clearly distinguishable due to pronounced performance differences. However, in the medium utilisation scenario, the differences among machining attributes are less distinct, making it difficult to determine an optimal choice without a rigorous quantitative analysis. This highlights the necessity of applying TOPSIS specifically to the medium utilisation scenario, following the structured framework established by previous studies [36–38].

To construct a reliable decision matrix, data collection from actual machining processes is crucial. Key machining parameters such as cutting speed, feed rate, axial depth of cut, and coolant conditions are recorded across multiple trials. Travel length are also tracked to understand the impact of machining conditions on tool wear and surface roughness over extended operations. For each coolant condition: dry cutting, mist coolant, and 4% and 8% coolant concentrations, the machining process was conducted over a predefined travel length of 5,424 mm. Throughout these trials, measurements of tool wear and surface roughness were collected at specified intervals, providing empirical data that form the basis for sustainability assessment. The implementation of TOPSIS involves constructing a decision matrix that integrates this collected machining data with other sustainability metrics, such as energy consumption and material efficiency. Data normalisation is then applied to ensure a fair comparison across different attributes. Table 5 presents the constructed decision matrix, while Table 6 illustrates the normalisation of variable values, laying the foundation for further sustainability assessments. By incorporating machining process data and travel length measurements, this approach ensures that the sustainability evaluation reflects real-world performance variations, enabling a more accurate and actionable decision-making process.

Table 5. Decision matrix for medium utilisation

Sustainability attributes	Machining attributes			
	Dry Cutting	4% cc	8% cc	Mist
Energy consumption per batch, E	615	597	580	562.5
Raw material used per batch, E	195	197.5	202.5	205
Waste management per batch, E	89	86.5	85	82.5
CO_2 emissions, E	950	875	825	750
Health and safety of workers, S	4	3	3	3.5
Work quality, S	0.7	0.9	0.95	1
Cost efficiency, C	69	72	74.3	71.3
Impact on ecosystem quality, S	9	7	7	5

Table 6. Normalised matrix

Sustainability attributes	Machining attributes			
	Dry Cutting	4% cc	8% cc	Mist
Energy consumption per batch, E	0.522	0.507	0.492	0.477
Raw material used per batch, E	0.488	0.494	0.506	0.513
Waste management per batch, E	0.518	0.504	0.495	0.481
CO_2 emissions, E	0.552	0.509	0.480	0.436
Health and safety of workers, S	0.588	0.441	0.441	0.515
Work quality, S	0.372	0.479	0.505	0.532
Cost efficiency, C	0.482	0.503	0.519	0.498
Impact on ecosystem quality, S	0.379	0.295	0.295	0.211

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.

3.3 Characterisation

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 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 performance assessment model is now characterised by its integration with the concepts of sustainability and machining attributes, as well as the machining conditions. The coefficients of the prediction model for each sustainability parameter are shown in Table 7.

Table 7. Coefficient of prediction model

Parameter	Dry Cutting	4% cc	8% cc	Mist
Constant	147.87	168.60	166.60	129.14
Environment, E	-0.201	-0.227	-0.228	-0.173
Society, S	-0.104	-0.102	-0.150	-0.057
Cost, C	0.058	-0.063	-0.056	0.06

The equations of the prediction model for each machining conditions can be expressed as follows:

i. Dry Cutting:

$0.201\ E + 0.104\ S – 0.058\ C = 147.87$

ii. 4% cc:

$0.227\ E +0.102\ S + 0.063\ C = 168.60$

iii. 8% cc:

$0.228\ E + 0.0150\ S + 0.056\ C = 166.60$

iv. Mist:

$0.173\ E + 0.057\ S – 0.06\ C = 129.14$

A regression analysis was performed on the dataset to examine the relationships between sustainability parameters and machining attributes, with the results detailed in Table 8. All models representing the engagement value of sustainability attributes and machining conditions demonstrated exceptionally high regression coefficients, indicating that they account for a significant portion of the variance in the respective engagement dimensions. The characterised model's values highlight the strength of this integration, as machining conditions interact with optimised parameters while aligning with defined sustainability attributes.

Table 8. Regression analysis for engagement value with optimisation and characterisation

Parameter	Dry Cutting	4% cc	8% cc	Mist
Environment, E	89.03%	89.03%	89.03%	89.03%
Society, S	89.48%	89.48%	89.48%	89.48%
Cost, C	89.92%	89.92%	89.92%	89.92%

The regression analysis has demonstrated that the characterised model exhibits a strong correlation in predicting the engagement value for integrating sustainability and machining attributes. To highlight the significance of the model's predictions, the engagement value within the competency model is interpreted as the engagement strength, representing the realised integration of sustainability parameters with machining conditions. This demonstration of engagement strength marks a key achievement of this research, completing the development of an interaction model for machining in the context of sustainability performance.

4.0 CONCLUSION

This research successfully characterised the impact of coolant conditions on machining performance, focusing on tool wear and surface roughness in the ball milling of AISI 1040 steel with uncoated HSS tools. The findings confirmed that coolant conditions significantly influence machining outcomes, with mist coolant demonstrating the best performance, particularly in down milling, achieving the lowest surface roughness of 0.246 µm. The regression-based characterisation model effectively predicted the engagement value, demonstrating the integration strength between sustainability parameters and machining conditions. This competency model marks a key advancement, offering valuable insights for optimising machining processes while embedding sustainability considerations. Its application is expected to provide environmental benefits by reducing resource consumption, societal improvements through enhanced tool performance and workplace safety, and economic advantages by lowering operational costs. Future work should focus on refining the characterisation model by incorporating additional machining parameters, exploring alternative sustainable coolants, and extending the analysis to different work materials and cutting tool geometries. Additionally, integrating advanced machine learning techniques could enhance predictive accuracy and decision-making capabilities, further strengthening sustainability-driven machining strategies.

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.

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