

Sustainability Analysis of Tool Wear, Energy Efficiency, Surface Quality, and Energy during Dry, MQL, and Wet Turning of Inconel 718

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Abstract

The Inconel 718 alloy has been widely used in the aerospace and industrial sectors owing to its exceptional durability under extreme temperatures and corrosive conditions. This study endeavors to explore the synergistic effects of diverse cooling conditions coupled with various input parameters, such as feed rate, cutting speed, and depth of cut, on machining efficacy during the turning of Inconel 718 using coated carbide cutting tools. The overarching aim is to enhance the sustainability and productivity of manufacturing processes. Key machining parameters, including tool wear rate (R), surface roughness (Ra), specific cutting energy (SCE), and carbon emissions (CE), were evaluated, prioritizing the "smaller-the-better" model for optimization. The Taguchi design of the experiment and Analysis of Variance (ANOVA) were conducted to determine the relative contribution of each parameter. Subsequently, the optimal machining parameters were presented. The findings underscored wet machining as particularly advantageous, manifesting a substantial reduction in tool wear compared with minimum quantity lubrication (MQL) and dry approaches, lower tool wear, and improved surface. Dry machining results in the lowest specific cutting energy and minimum carbon emissions. By adhering to the identified optimum machining conditions, notable enhancements were achieved: 23% reduction in tool wear, 15% decrease in SCE consumption, 8% improvement in Ra, and 12% reduction in CE.

Key words

Inconel 718; Sustainable manufacturing; Energy consumption; Carbon emissions; Tool wear

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Nomenclature

Abbreviation	Full Name		
ANOVA:	Analysis of variance	DC:	Dry cutting
a_p :	Depth of cut	E:	Energy consumption of process
CC:	Cooling conditions	EC_{machine} :	Energy consumption of machine
CE:	Carbon emissions	f:	Feed rate
CEF:	Carbon emission factor	l:	Length of cut (linear)
CE'_{chip} :	CE for chip recycling	ls:	Length of cut (spiral)
CE'_{coolant} :	CE due to coolant disposal	MQL:	Minimum quantity lubrication
CE'_{tool} :	CE due to tool disposal	MRR:	Material removal rate
CE_{coolant} :	CE due to coolant production	P_{actual} :	Actual power
CE_{elec} :	CE due to electricity generation	P_{air} :	Air cut power
CE_{material} :	CE due to material	P_{cut} :	Cutting power
CE_{tool} :	CE due to tools	R:	Tool Wear rate
CE_{Total} :	Total carbon emissions	Ra:	Surface roughness
CE_{waste} :	CE due to waste	SCE:	Specific cutting energy
CEF'_{chip} :	CEF for chip recycling	T:	Coolant usage time
CEF'_{coolant} :	CEF for coolant disposal	tm:	Machining time
CEF'_{tool} :	CEF for tool disposal	T_{tool} :	Cutting tool life cycle
CEF_{coolant} :	CEF for coolant	V_B :	Flank wear
CEF_{Elec} :	CEF for electricity	V_c :	Cutting speed
CEF_{tool} :	CEF of tools	V_{chip} :	Volume of the chips
CNC:	Computerized numerical control	V_{coolant} :	Volume of coolant
D:	Discharge rate of coolant	W_{tool} :	Mass of the tool
		ρ_{chip} :	Chip density

1. Introduction

The recent surge in greenhouse gas emissions has become a significant global concern, leading to adverse effects, such as escalating global temperatures, sea level rise, and glacier retreat (He, Huang, and Wang 2015). This trend is highlighted by the consistent increase in global greenhouse gas emissions, which rose by 62% between 1971 and 2023, peaking at 37.4 billion tonnes (Gt) of CO₂ equivalent in 2023 (IEA 2023). Industrial sector has become an important player, accounting for 38% of global carbon dioxide emissions (IEA 2023). Manufacturing processes and industrial operations growth, usually accompanied by increased energy needs, are expected to contribute to a sharp increase in greenhouse gas emissions and significant pressure on resource conservation (Choi et al. 2015). Due to the increasing awareness of environmental problems, the industry sector has experienced a transformation towards sustainability, actively working to reduce its footprint, which it is now able to do by adopting innovative approaches and using modern technologies (Rosen 2013). Currently, energy efficiency is a priority, with the aim of reducing emissions and mitigating the greenhouse effect (Kanako 2011). There is also growing concern regarding energy security over the depletion of world oil reserves, with peak oil production reported during 2004–2012 (Syed Husain Imran Jaffery et al. 2014). While industries and technologies are developing, the reduction of greenhouse gas emissions remains an essential objective in an attempt to achieve environmental sustainability (Domingo et al. 2013).

Machining processes are essential for various industrial applications, and provide versatility and precision. To enhance productivity while minimizing the environmental impact, optimizing the machining parameters, tool designs, and tool paths is crucial (Trifunović et al. 2021). Among the machining materials, Inconel 718 is of particular importance because of its wide range of applications in industries such as aerospace, nuclear power, and medical devices, where high-performance materials are essential. Inconel 718, a nickel-based superalloy, is highly valued for its exceptional thermal resistance, mechanical strength at elevated temperatures, strong corrosion resistance, and excellent thermal fatigue properties (Ezugwu, Wang, and Machado 1998; Zhu, Zhang, and Ding 2013; Ulutan and Ozel 2011; Dudzinski et al. 2004). **Table 1** summarizes the mechanical properties of Inconel 718 in comparison to those of other aerospace alloys. These attributes make it ideal for components in steam turbines, reciprocating engines, aircraft gas turbines, petrochemical systems, rocket engines, nuclear reactors, and submarines (Pawade et al. 2007; Ramesh, C., Prathap, J. & Pamanabhan 2015; Ulutan and Ozel 2011). In the aerospace industry alone, nickel-based superalloys constitute approximately 50% of an aircraft engine's weight, with Inconel 718 contributing 35% compared to other super alloys because of their superior performance (Thellaputta, Chandra, and Rao 2017). Despite its advantages, Inconel 718 poses significant machining challenges because of its low machinability index, high work-hardening tendency, and poor thermal conductivity. The presence of hard abrasive carbides in the microstructure, coupled with diffusion wear and the formation of a built-up edge (BUE), exacerbates tool wear and reduces machining efficiency (Rahim, Warap, and Mohid 2015). Consequently, machining accounted for 35% of the total manufacturing cost of Inconel 718 components (Thellaputta, Chandra, and Rao 2017). Addressing these challenges requires innovative machining techniques that balance the performance, cost, and environmental sustainability.

Machining methods, such as Dry Cutting (DC), Flooded Machining, and Minimum Quantity Lubrication (MQL), play a critical role in improving productivity and sustainability. Dry cutting is simple and cost-effective, eliminating the use of cutting fluids; however, it often results in higher tool wear and poor surface finish (Kawade and Bokade 2022). However, flooded machining is advantageous with respect to cooling and lubrication, resulting in enhanced tool life and surface integrity; however, it brings health and environmental hazards (Khanna et al. 2020). In cases where removing the cutting fluids is not a viable option, Minimum Quantity Lubrication (MQL) machining presents a possible solution, as it reduces the fluid consumption by a considerable amount and also provides efficient lubrication and cooling (M. M. A. Khan, Mithu, and Dhar 2009; Danish et al. 2021). The most suitable cutting technique for a particular application depends on many parameters such as material properties, machining requirements, environmental influences, and cost. Therefore, it is crucial to understand the cutting techniques that lead to improvements in machining performance and sustainable manufacturing practices. By considering diverse input factors, researchers have optimized various output responses for different workpieces, highlighting the importance of tailored approaches in machining optimization (Frifita et al. 2020; Aslantas, Ekici, and Çiçek 2018; Kosaraju, Vijay Kumar, and Sateesh 2018).

In the manufacturing process, the selection of cooling conditions is an important factor that influences the energy usage, tool wear, and surface quality of the machining process.

As shown in the study by (Xavior et al. 2017), MQL machining has favorable tool performance in comparison to wet and dry conditions, particularly at lower cutting speeds. However, (Khanna et al. 2021) noticed higher and abrupt tool wear issues with MQL operation owing to insufficient heat dissipation. On the energy consumption side, the experts demonstrated lower energy consumption under MQL conditions than under wet conditions, which is attributed to the reduced cutting forces (Pinheiro et al. 2021a; Çakıroğlu 2021). Furthermore, research outcomes have also established that thermal softening effect is a major contributor to the specific cutting energy (SCE) in dry machining (M. A. Khan et al. 2019). The outcomes of roughness studies differ, (Iturbe et al. 2016) favor conventional cooling whereas (Pinheiro et al. 2021b) state that the roughness under MQL conditions is lower, suggesting its applicability in improving the quality of surfaces. Overall, the literature presents a mixed perspective on the efficacy of different cooling conditions for turning the Inconel 718. On the one hand, MQL proved to be beneficial for increasing the tool life, surface roughness, and energy consumption in some cases, although several conflicting findings and arguments in favor of conventional cooling methods also exist. Hence, optimization studies are needed to determine the optimum cooling conditions for the turning of Inconel 718 that take into account the tool wear, surface quality, energy consumption, and carbon emissions (CE). As previous studies (Hegab et al. 2021; M. A. Khan et al. 2019; Younas et al. 2019) have shown, optimization efforts concentrate on both performance measures and practical industrial perspectives to increase machining efficiency and cost-effectiveness. Further research is required to find the best solution for industrial applications, given the numerous performance metrics to consider and the practical limitations.

Table 1. Mechanical properties of Inconel 718 in comparison with other aerospace alloys (Syed H.Imran Jaffery et al. 2016; Salman S. Warsi et al. 2015)

Property	Material						
	Titanium	Ti6Al4V	Ti-6Al6V-2Sn	Ti-10V2Fe-3Al	Inconel 718	Al 7075-T6	Al 6061 T6
Density (g/cm³)	4.5	4.43	4.54	4.65	8.22	2.81	2.7
Hardness (HV)	180–184	285–342	361	303	361–438	~ 175	104
Ultimate tensile strength (MPa)	220	950	1050	970	1350	572	310
Yield strength (MPa)	140	880	980	900	1170	503	275
Modulus of elasticity (GPa)	116	113.8	110	110	200	71.7	69
Ductility (%)	54	14	14	9	16	11	12-14
Fracture toughness (MPa m^{1/2})	70	75	60	-	96.4	20–29	-
Thermal conductivity (W/mK)	17	6.7	6.6	7.8	11.4	130	167
Max. operating temperature (°C)	~150	315	315	315	650	-	-

2. Research Motivation

The primary objective of this study was to investigate the combined effects of different cooling conditions (dry, MQL, and wet) and machining parameters, such as feed rate (f), cutting speed (V_c), and depth of cut (a_p), on the machining performance of Inconel 718, focusing on critical responses, such as tool wear, surface roughness, specific cutting energy (SCE), and carbon emissions (CE). Carbon emissions from machining processes directly impact ecological balance, highlighting the urgent need for close monitoring to achieve sustainable manufacturing practices. While energy analysis for machining processes is a vital research avenue, most existing studies analyze the total machining energy, often making their results machine-tool-specific. In contrast, the energy analysis presented here focuses on the actual energy consumed during metal machining, excluding machine-tool-specific consumption data, offering a unique and focused perspective.

This study explored the relatively under-researched topic of carbon emissions (CE) during the machining of Inconel 718, a material of significant industrial importance. It also integrates the evaluation of specific cutting energy (SCE) and CE, both essential components of sustainable manufacturing, alongside key productivity parameters, such as tool wear and surface roughness, providing a holistic approach to improving machining performance. Building upon Laperrière and Reinhart's concept of productivity as a function of quality, utilization, and efficiency (Laperrière and Reinhart 2014), Although the development of an energy consumption map is beyond the scope of this research, the findings serve as a foundational step towards creating such maps in future work which is the author future endeavor. Energy maps, particularly for SCE, have the potential to act as practical visual tools for selecting the energy-optimum cutting parameters during process planning and shop floor operations. By combining sustainability metrics with machining performance, this study aims to lay the groundwork for future studies while addressing the pressing environmental concerns associated with manufacturing processes.

3. Experimental details

3.1 Workpiece material

A workpiece consisting of the nickel-based alloy Inconel 718, measuring 550 mm in length and 130 mm in diameter, was employed for the study, and its composition is detailed in **Table 2**. The workpiece underwent a standard heat treatment process in accordance with AMS 5383. The heat treatment consisted of homogenization at $1093 \pm 14^\circ\text{C}$ for 1–2 h, followed by air cooling. Next, solution treatment was performed by heating the alloy to $954\text{--}982^\circ\text{C}$ for over 1 h, followed by air cooling. Finally, the workpiece underwent a two-stage aging process: it was held at 718°C for 8 h and then furnace-cooled at 55°C per hour to 621°C , where it was held for another 8 h before air cooling (Dunyong Deng 2018).

Table 2. Composition of Inconel 718.

Element	C	Ti	Co	Si	Cr	Mo	Mn	Nb	B	Fe	Cu	Al	Ni
Weight%	0.08 Max	0.9	1.0 Max	0.35 Max	19.0	3.0	0.35 Max	5.1	0.006 Max	18.0	0.3 Max	0.6	52.5

3.2 Cutting Tool

The selection of a suitable cutting tool is critical for machining Inconel 718 because of its poor machinability, which is attributed to its high strength, low thermal conductivity, and work-hardening behavior. For this study, a coated carbide tool CNMG 12 04 04-SM S205 insert from Sandvik Coromant was used. A schematic of the cutting inserts is shown in **Figure 1** and the detailed specifications of the inserts are presented in **Table 3**. This insert features an 80° included angle, neutral rake angle, 0° clearance angle, and robust chip breaker for controlled chip flow. Its multilayer coating, comprising TiCN, Al₂O₃, and TiN applied via chemical vapor deposition (CVD), enhances wear resistance, thermal stability, and spalling resistance, making it ideal for high-temperature machining (Thakur, Ramamoorthy, and Vijayaraghavan 2012). The Al₂O₃ layer reduces the thermal conductivity at elevated temperatures (Hanasaki et al. 1990), maintaining the mechanical integrity of the tool, whereas the TiN outer layer improves lubricity, chip control, and adhesion resistance (Choudhury and El-Baradie 1998). The coated carbide insert combines the wear resistance of ceramics with the strength of cemented carbides, outperforming uncoated tools by delivering reduced tool wear, improved surface finish, and higher productivity under high-speed, high-feed conditions (Takatsu 1990). These attributes align with the objectives of this study to analyze and optimize tool wear and energy consumption during the machining of Inconel 718.

Table 3. Specifications of cutting insert

Specifications	Description
Tool Holder	PCLNL 2525M 12
Insert	CNMG 12 04 04-SM S205
Company code	SV - Sandvik-Coromant
Insert shape code(SC)	Rhombic 80
Type	Coated with chip breaker
Chip breaker manufacturers designation	SM
Insert mounting style code(IFS)	Cylindrical fixing hole
Fixing hole diameter(D1)	5.156 mm
Inscribed circle diameter (IC)	12.7 mm
Cutting edge effective length (LE)	8.5 mm
Corner radius (RE)	0.397 mm
Hand	Neutral
Substrate	HC
Coating	CVD TiCN+Al ₂ O ₃ +TiN
Insert thickness (S)	4.763 mm
Clearance angle major	0 deg
Weight (WT)	0.01 kg

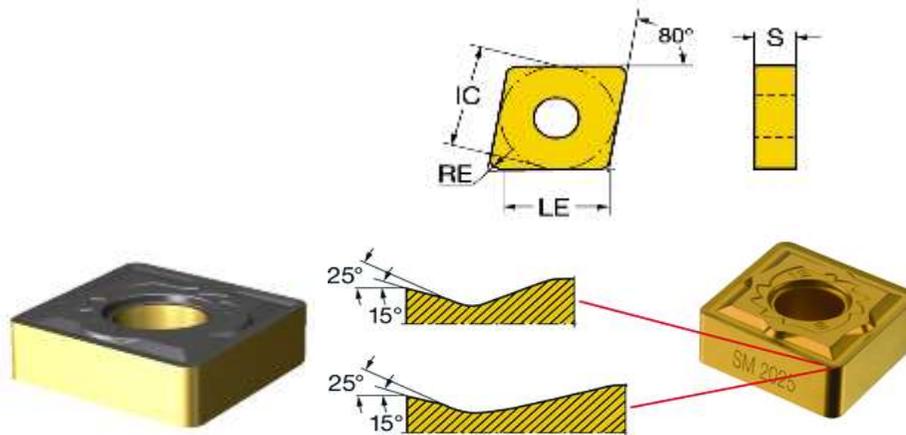


Figure 1. 3D model and schematics of insert

3.3 Experimental setup

Experiments were performed on a Computerized Numerical Control (CNC) turning center, Model ML-300, as shown in **Figure 2**, characterized by a rated power of 26 KW and a spindle speed of 3500 RPM max.

The experiments were conducted under dry, wet, and MQL conditions, respectively. For wet cutting, the embedded cooling system of the CNC turning center was operated using PSO neat metal cutting oil (VG ISO 32), which is the oil grade recommended by the machine tool manufacturer, with a coolant pump rated at 0.8 kW. In the MQL experiments,

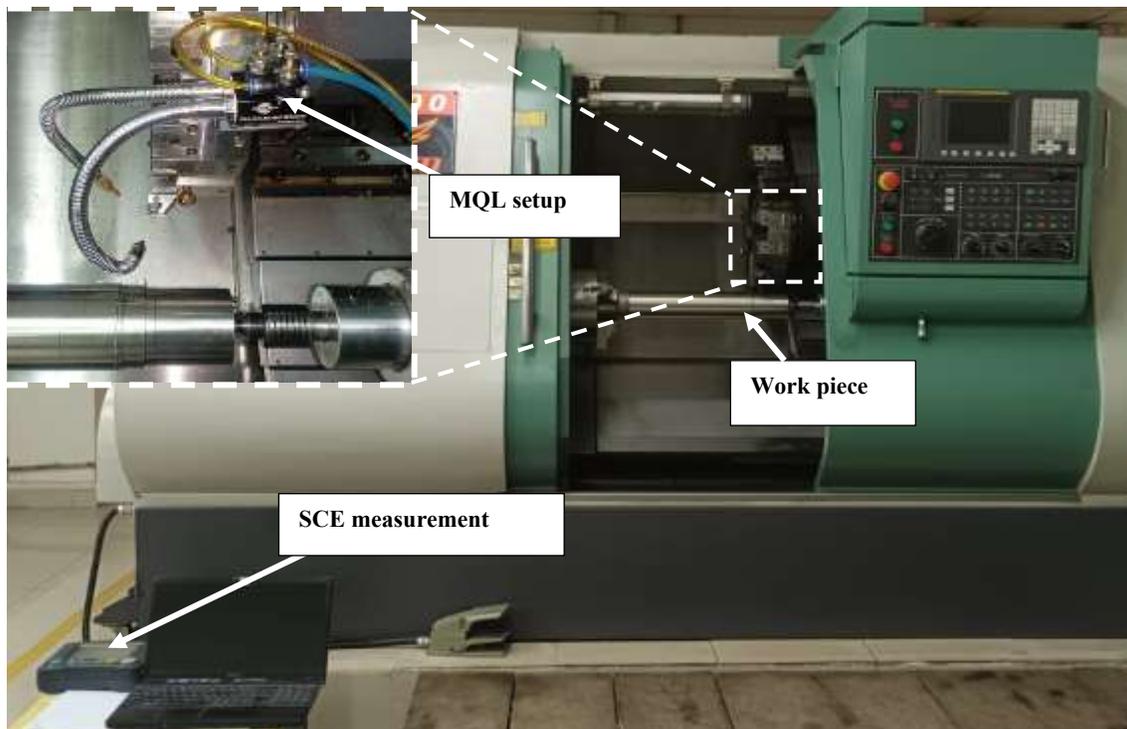


Figure 2. Experimental setup for machining

a COOLRUN mist spray system with two nozzles was used, employing the same PSO neat metal cutting oil (VG ISO 32) as in wet cutting, to assess the effect of cooling strategies. The system comprised a mixing chamber connected to two flexible pipes, each equipped with a spray nozzle at the inlet and outlet. Compressed air was supplied through a flexible inlet pipe linked to the compressor. In addition, the system features two dedicated inlets for the lubricant or coolant, allowing the fluid to be drawn from a container and fed directly to the spray nozzles for effective dispersion. The MQL has independent adjustable knobs for each spray nozzle that control the flow rate. A flow rate of 50 mL/h was maintained with a compressed air pressure of 5 bar for both the nozzles. These nozzles were directed towards the rake and flank faces of the cutting tool, as shown in **Figure 2**.

3.4 Response measurement

This study measured several key responses, including SCE, tool wear rate, surface roughness, and CE. The assessment of tool wear followed the criteria outlined in (“ISO 3685:1993 Tool-Life Testing with Single-Point Turning Tools” 1993), which stipulates that flank wear (V_B) should either average 0.3 mm or reach a maximum of 0.6 mm. Wear measurements were conducted using an Olympus DSX1000 digital high-resolution microscope (**Figure 3**).

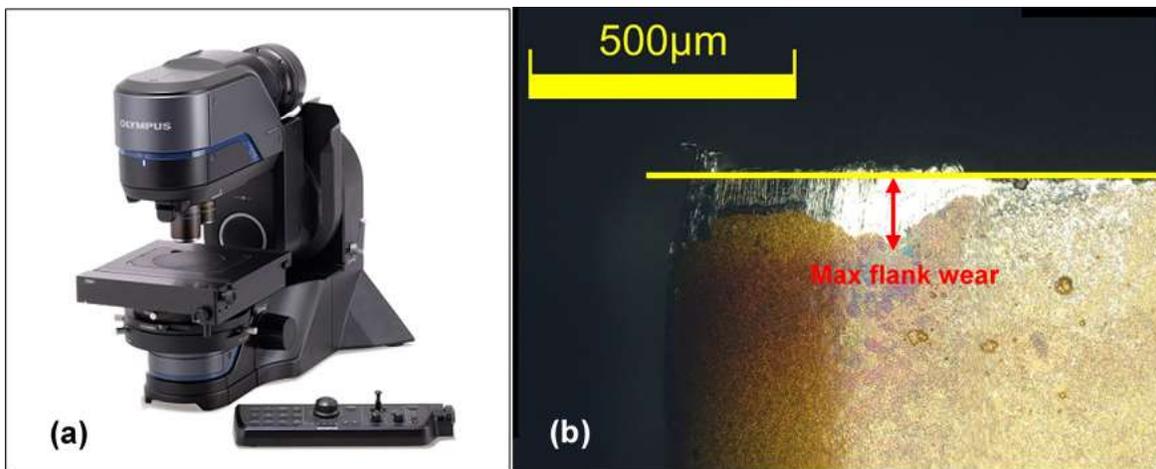


Figure 3. (a) Olympus DSX1000 digital microscope. (b) Digital microscope image of tool wear.

Tool wear measurements were transformed into wear rate denoted as R using **Equation 1** to cater to the effect of reducing the diameter of the workpiece after each cutting pass, which in turn reduces the total distance traveled by the tool over the length of the cut in each successive pass. A negative value of a higher digit for R indicates reduced tool wear (S. I. Jaffery and Mativenga 2009).

$$R = \log \left[\frac{V_B}{l_s} \right] = \log \left[\frac{V_B}{1000 t_m v_c} \right] \quad 1$$

where l_s , V_B , t are the spiral cutting length, tool wear, and cutting time, respectively.

The machine power consumption was measured using a Power Analyzer Model CW-240-F manufactured by Yokogawa (**Figure 4**). The surface roughness was assessed using a TR 110 tester. The SCE was calculated using **Equation 2** (Korkmaz et al. 2023). Importantly, it is worth noting that the SCE remains unaffected by the type or efficiency of machining.

$$SCE(J\ mm^{-3}) = \frac{P_{cut}(W)}{MRR(mm^3s^{-1})} \quad 2$$

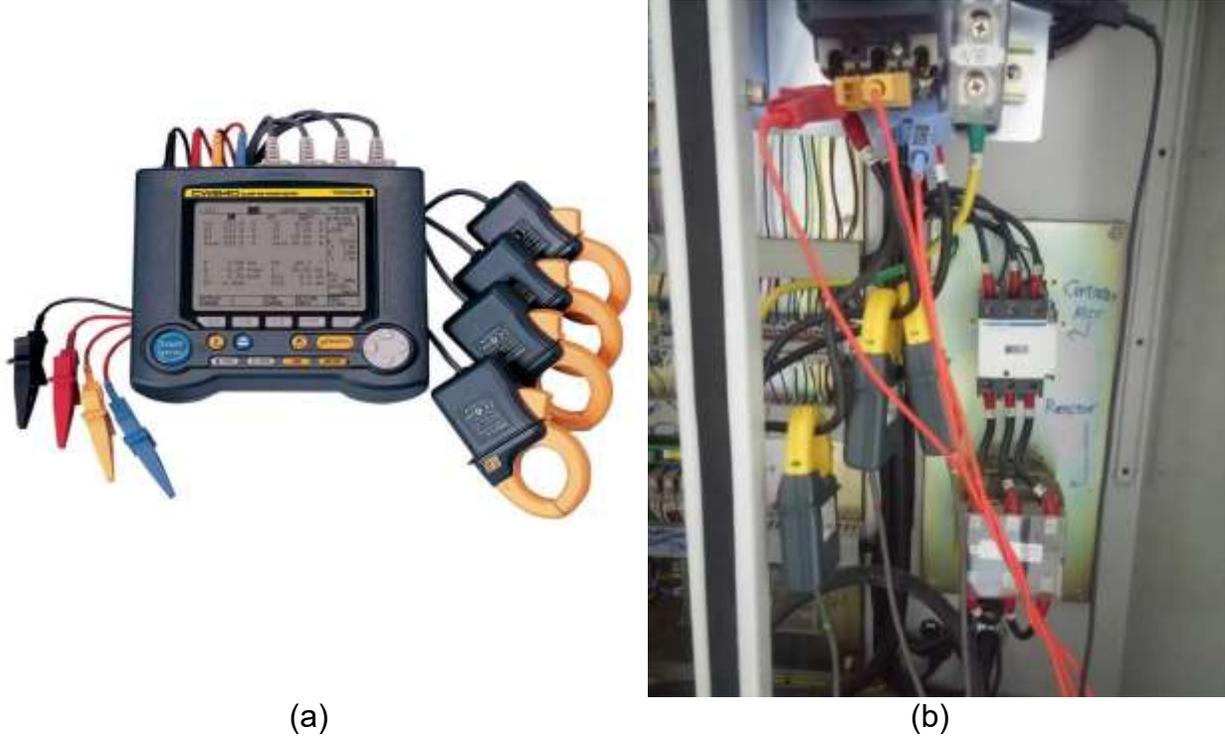


Figure 4. (a) Power analyzer for measuring active power. **(b)** Power meter connections at the main supply of CNC machine.

The calculation of P_{cut} (W) involved a two-cycle methodology, as outlined in **Equation 3** (W. Li and Kara 2011). This approach entails two power measurements for identical input parameters denoted as P_{actual} and P_{air} . Here, P_{actual} signifies the actual cutting power and P_{air} represents the power consumption during the air cut. The difference between these values yields P_{cut} , which denotes the power used during the cutting process. **Figure 5** illustrates two distinct power curves: the blue plot represents P_{actual} , the green plot corresponds to P_{air} . Moreover, material removal rate (MRR), was determined using **Equation 4**.

$$P_{cut}(W) = P_{actual}(W) - P_{air}(W) \quad 3$$

$$MRR = f \times v_c \times a_p \quad 4$$

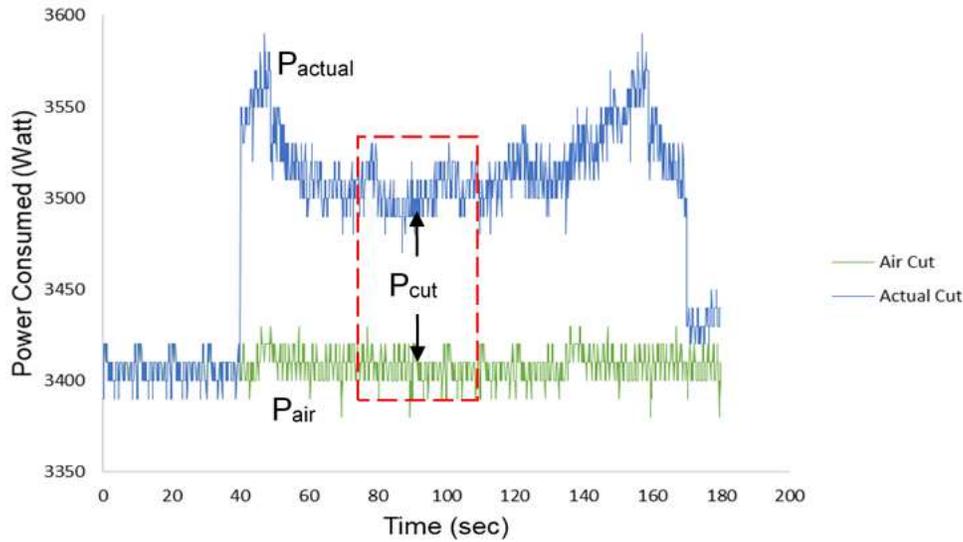


Figure 5 Power consumption plot of machining operation highlighting P_{cut} (as difference of P_{actual} and P_{air})

Carbon emissions refer to the release of carbon dioxide (CO_2) or other greenhouse gases (expressed in terms of CO_2 -equivalents) into the atmosphere as a result of human activities or industrial processes. In machining processes, carbon emissions are primarily associated with energy consumption, as most of the energy used to operate machines is derived from fossil-fuel-based electricity generation, which produces CO_2 . The unit of CE is expressed in kilograms of CO_2 ($kg\ CO_2$) and is typically determined using the following equation:

$$CE = E \times CEF_{source} \quad 5$$

Where:

E: Energy consumption during the process (in kWh).

CEF_{source} : Emission factor of the electricity source (in $kg\ CO_2/kWh$). This factor depends on the energy mix used to generate electricity in a specific region or country. For example: Coal-based energy has a high emission factor (e.g., $0.9\ kgCO_2/kWh$). Renewable energy sources (e.g., solar, wind, or hydropower) have lower or near-zero emission factors.

The carbon emissions resulting from machining processes serve as a key metric for evaluating the sustainability of machining techniques. Machining operations encompass a range of resources, including materials, tools, machinery, cooling fluids, and the energy consumption associated with machining and waste management. These resources contribute to CE in both tangible and intangible ways. The total CE (CE_{Total}) in machining is calculated as the aggregate of CE originating from electricity consumption during machining (CE_{elec}), material production [including cutting tool (CE_{tool}) and coolant ($CE_{coolant}$)], and waste processing [encompassing cutting tool (CE'_{tool}), coolant ($CE'_{coolant}$), and chips (CE'_{chip})]. This summation is mathematically represented by **Equation 6** (Jiang

et al. 2021a). A generalized CNC machining system with carbon emission sources is shown in **Figure 6**. A sample calculation of the carbon emissions for the system is provided in Appendix A for Experiment No. 1 of **Table 5**.

$$CE_{Total} = CE_{Elec} + CE_{Material} + CE_{Waste} \quad 6$$

$$CE_{Material} = CE_{tool} + CE_{coolant} \quad 7$$

$$CE_{Waste} = CE'_{tool} + CE'_{coolant} + CE'_{chip} \quad 8$$

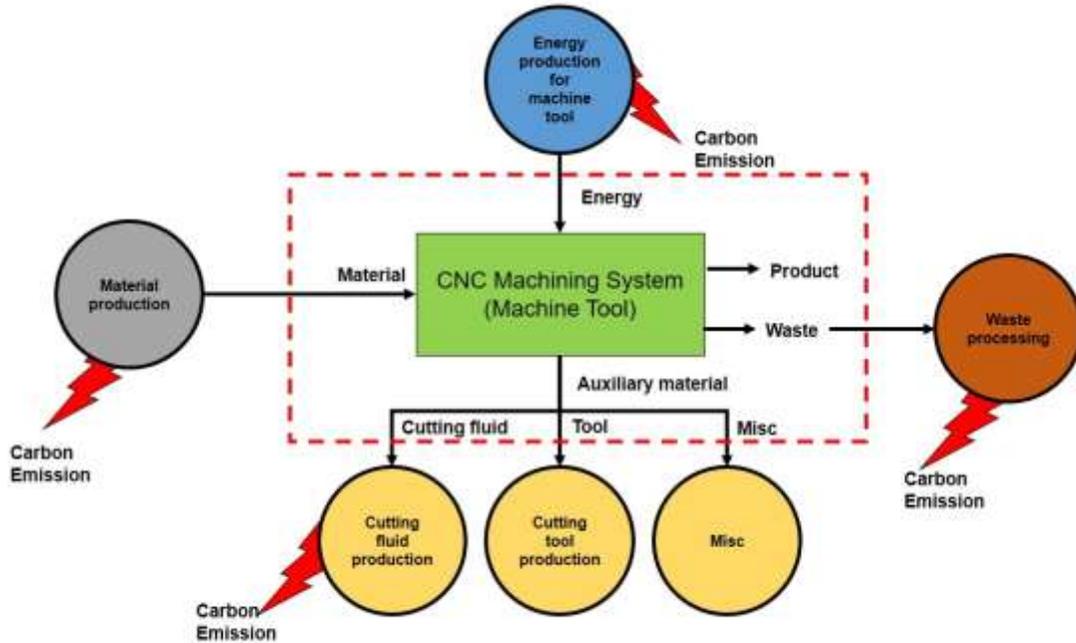


Figure 6. Generalized CNC Machining system with associated carbon emissions

Electricity is the primary power source for CNC machine tools. The CE stemming from the electricity consumption by the machine can be determined using **Equation 9** (Jiang et al. 2021b). This equation involves the electricity CEF for the specific region or country, denoted as CEF_{Elec} . In this case, for Pakistan, the value of CEF_{Elec} is 0.82 kg CO₂ per kWh (NEPRA 2020; Butt, Myllyvirta, and Dahiya 2021). The machine energy consumption, denoted as $EC_{machine}$, is the total energy utilized during various operational phases, including the standby mode, air cut, and cutting operation. This total energy consumption was calculated by summing the energy expended in each phase, as outlined in **Equation 10** (C. Li et al. 2015).

$$CE_{Elec} = CEF_{Elec} \times EC_{machine} \quad 9$$

$$EC_{machining} = \int_0^{T_{sb}} P_{sb} dt + \int_0^{T_{air}} P_{air} dt + \int_0^{t_m} P_m dt \quad 10$$

CE_{tool} represents the fraction of the CE attributed to the tool's operational period, which can be calculated using **Equation 11**.

$$CE_{tool} = \frac{t_m}{T_{tool}} \times CEF_{tool} \times W_{tool} \quad 11$$

The CEF for cutting tools (CEF_{tool}) is determined by considering factors such as the tool mass (W_{tool}), tool life cycle (T_{tool}), and machining time (t_m). In this study, CEF_{tool} is defined 34.16 kg-CO₂/kg (C. Li et al. 2015). The equivalent CE for the coolant $CE_{coolant}$ was calculated using **Equation 12** (Narita, Desmira, and Fujimoto 2008).

$$CE_{coolant} = T \times D \times CEF_{coolant} \quad 12$$

Where, $CEF_{coolant}$ is the CEF for coolant production, T is the coolant usage time during machining, and D is the discharge rate of the coolant. Coolants contribute approximately 0.469 CO₂/L equivalent CE (Narita et al. 2008).

The equivalent CE in waste management of tools, coolants, and chips can be calculated using **Equation (13-15)** (Narita, Desmira, and Fujimoto 2008; C. Li et al. 2015).

$$CE'_{coolant} = T \times D \times CEF'_{coolant} \quad 13$$

$$CE'_{tool} = \frac{t_m}{T_{tool}} \times CEF'_{tool} \times W_{tool} \quad 14$$

$$CE'_{chip} = CEF'_{chip} \times V_{chip} \times \rho_{chip} \quad 15$$

The variables $CE'_{coolant}$, $CEF'_{coolant}$, T , and D represent the CE associated with the disposal of coolant, CEF for coolant disposal, duration of coolant usage during machining, and discharge rate of the coolant, respectively. Similarly, CE'_{tool} , CEF'_{tool} , and W_{tool} denote the CE related to tool disposal, CEF for tool disposal, and tool mass, respectively. Additionally, CE'_{chip} , CEF'_{chip} , V_{chip} , and ρ_{chip} represent the CE for chip recycling, CEF for chip recycling, volume of the chips, and density of the chip material, respectively. CEF'_{tool} and $CEF'_{coolant}$ are specified as 0.013 kg CO₂/kg and 0.261 kg CO₂/L, respectively (Narita, Desmira, and Fujimoto 2008; C. Li et al. 2015).

3.5 Design of experiment

Input variables, including the feed rate, cutting speed, depth of cut, and cooling conditions, exert a significant influence on the machining output response, as highlighted in the literature (Salman Sagheer Warsi et al. 2019). To efficiently explore these variables, a Taguchi design of experiment was employed, chosen over a full factorial design because of its superior efficiency in terms of requiring fewer runs (Ziegel 1997). **Table 4** presents the levels of input parameters selected, aligned with the tool manufacturer guidelines and ISO standards (1993), while **Table 5** presents the Taguchi design of the experiment.

Table 4. Selected machining parameters.

Parameters	V_c (m/min)	f (mm/rev)	a_p (mm)	CC
Level 1	25	0.05	0.4	Dry
Level 2	50	0.10	0.6	Wet
Level 3	75	0.15	0.8	MQL

Table 5. Cutting parameters based on Taguchi design of experiment.

Experiment No	V_c (m/min)	f (mm/rev)	a_p (mm)	CC
1	25	0.1	0.6	Wet
2	50	0.15	0.4	Wet
3	75	0.05	0.8	Wet
4	25	0.05	0.4	Dry
5	50	0.1	0.8	Dry
6	75	0.15	0.6	Dry
7	25	0.15	0.8	MQL
8	50	0.05	0.6	MQL
9	75	0.1	0.4	MQL

4. Results and discussion

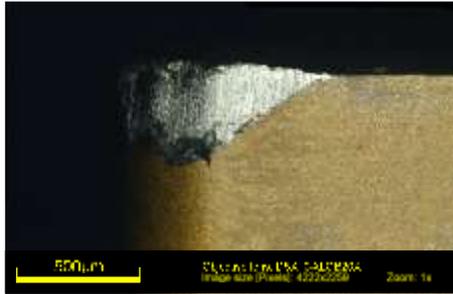
The results, as outlined in **Table 6**, include the measurement of each response twice to ensure precision through repeated experimental runs. Within the range of cutting parameter combinations, the best and worst values for each response were identified both independently and in relation to each other. To extract meaningful insights from the experimental data, each response was plotted and analyzed individually.

Table 6. Experimental results of response parameters.

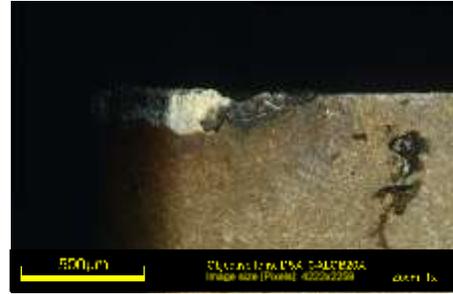
Run	Sustainability parameters				Productivity parameters			
	SCE (J/mm^3)		CE (Kg CO ₂)		Wear rate (R)		Ra (μm)	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
1	23.371	21.919	1.477	1.192	-3.074	-3.099	1.09	1.02
2	20.753	21.894	0.604	0.784	-2.843	-2.86	1.16	1.10
3	14.507	14.688	1.058	1.151	-3.03	-3.016	0.97	1.02
4	11.559	11.133	0.897	0.965	-2.95	-2.93	1.09	1.03
5	14.214	13.552	0.371	0.442	-2.734	-2.712	1.24	1.31
6	15.023	15.557	0.149	0.119	-2.551	-2.531	1.49	1.43
7	25.64	25.058	0.618	0.797	-2.808	-2.835	1.31	1.25
8	12.882	13.478	0.670	0.539	-3.054	-3.04	0.91	0.97
9	14.297	15.082	0.411	0.344	-2.838	-2.863	1.15	1.09

4.1 Effects on tool wear

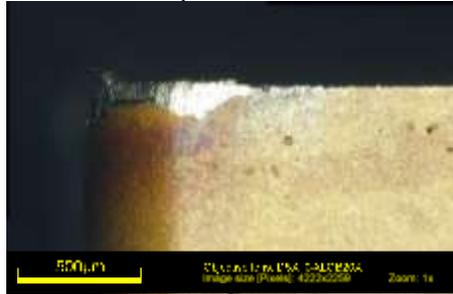
The flank wear (V_B) in each machining run was measured using a digital microscope (**Figure 7**) and the tool wear rate (R) was calculated using **Equation 1**. **Figure 9(a)** illustrates the main effects plot of the tool wear rate, indicating an increase in the wear rate with increasing cutting speed and feed rate. However, the response of the depth of



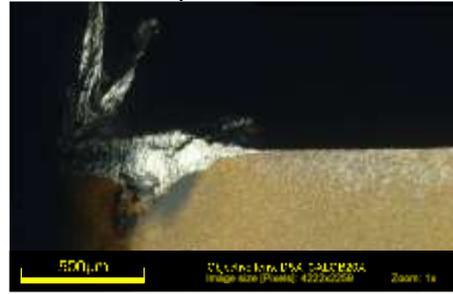
Experiment 1



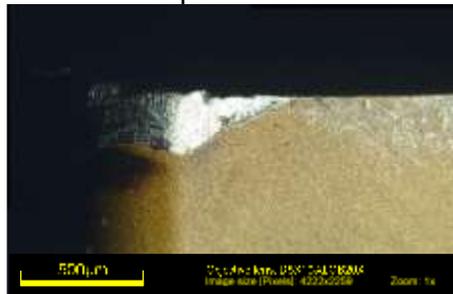
Experiment 2



Experiment 3



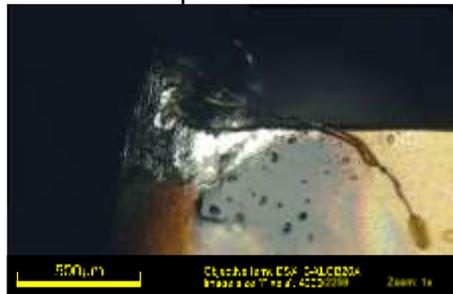
Experiment 4



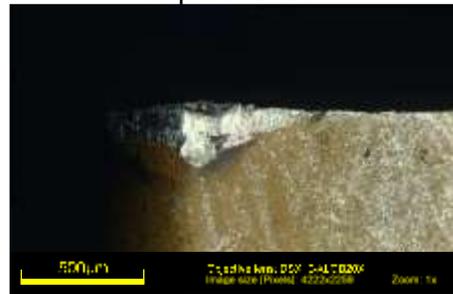
Experiment 5



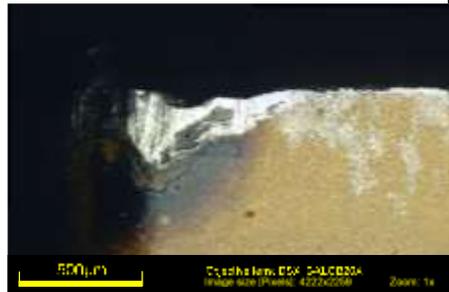
Experiment 6



Experiment 7



Experiment 8



Experiment 9

Figure 7. Digital microscope image of tool wear for Taguchi L9 DOE

cut appears inconsistent and initially decreases before increasing. In terms of cooling conditions, wet cutting resulted in lower wear rates than MQL and dry cutting.

Inconel, renowned for its limited thermal conductivity, undergoes significant heating during machining, resulting in increased tool wear, particularly at elevated cutting speeds, particularly under dry conditions (Birmingham et al. 2012; Pereira et al. 2020). The heightened wear observed at increased feed rates can be ascribed to diminished heat dissipation, augmented forces, and heightened vibrations at the interface between the tool and workpiece (Yan and Li 2013). The superior performance under wet cooling conditions is attributed to its effective heat dissipation capabilities compared to MQL and dry cutting. Research supports this, with wet cutting demonstrating better tool life than MQL and dry conditions (Khanna et al. 2021; Kamata and Obikawa 2007).

Analysis of variance (ANOVA) was employed to evaluate the influence of the individual factors on tool wear, as shown in **Table 7**. The primary influential factor affecting tool wear was found to be the feed rate, accounting for 44.20%, followed by cooling condition at 41.50%, with cutting speed contributing 13.05%. However, depth of cut had insignificant contribution, as depicted by P value and contribution 0.84%.

Table 7. Tool wear ANOVA.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Cutting speed	2	0.0627	13.05%	0.062938	0.03146	141.04	0
Feed rate	2	0.2122	44.20%	0.212559	0.10627	484.30	0
Depth of cut	2	0.0040	0.84%	0.004038	0.00201	9.16	0.007
Cooling condition	2	0.1993	41.50%	0.199607	0.09980	454.79	0
Error	9	0.0019	0.42%	0.001999	0.00022		
Total	17	0.4811	100.00%				
S= 0.014802, R-sq= 99.59%, R-sq(pred)= 98.36%							
DF: Degrees of freedom, Seq SS: Sequential sum of squares, MS: Mean squares, S: Standard error, R-sq: R-squared, R-Sq (Pred): Predicted R-squared							

4.2 Effects on specific cutting energy

Figure 9(b) presents the relationship between the SCE and the input parameters. This illustrates that higher cutting speeds correspond to decreased SCE, whereas both feed rate and depth of cut exhibit an increasing trend in SCE. Additionally, dry cutting demonstrated lower power consumption than the wet and MQL methods.

The decrease in cutting forces at higher speeds can be attributed to factors such as the reduction in the contact surface area and the potential softening of work materials due to elevated temperatures generated during machining. This aligns with observations by (Salman Sagheer Warsi et al. 2018), who reported a reduction in cutting force with increasing cutting speed. Moreover, (Frifita et al. 2020) identified the depth of cut as a significant factor influencing the specific energy, with a higher depth of cut leading to increased power consumption. In addition, the cutting force, which serves as a crucial determinant of energy consumption, is significantly affected by the selected cooling conditions. (Pervaiz et al. 2014) emphasized the significance of thermal softening, noting that its impact is more notable in dry machining than in MQL and wet conditions, consequently leading to reduced SCE values.

Table 8 displays the ANOVA results for SCE. The analysis revealed that feed rate exerted the most substantial influence, accounting for 45.35% of the variance, followed by cooling conditions (29.85%), cutting speed (20.40%), and depth of cut (3.67%).

Table 8. SCE ANOVA.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Cutting speed	2	78.315	20.40%	78.315	39.157	124.61	0
Feed rate	2	174.077	45.35%	174.077	87.038	276.98	0
Depth of cut	2	14.076	3.67%	14.076	7.037	22.4	0
Cooling condition	2	114.573	29.85%	114.573	57.286	182.3	0
Error	9	2.828	0.74%	2.828	0.314		
Total	17	383.868	100.00%				

S= 0.560576, R-Sq= 99.26%, R-Sq(pred)= 97.05%

4.3 Effects on surface roughness

Surface roughness is of paramount importance in machining processes, particularly when dealing with difficult-to-machine materials such as Inconel 718. **Figure 9(c)** illustrates that increasing the feed rate and depth of cut results in elevated Ra values, whereas the influence of cutting speed on Ra seems to vary inconsistently.

The cutting speed plays a pivotal role in the surface roughness during the turning of the Inconel 718. As the cutting speed increases, factors such as elevated tool wear and thermal loading contribute to the increased surface roughness (Pineiro et al. 2021b). Increased feed rates tend to exacerbate the surface roughness, a phenomenon attributed to microgroove formation and higher peaks and crests over the machined surface (Mia and Dhar 2016). In turning operations, the influence of the depth of cut on surface roughness remains debatable. While some studies show a linear relationship between depth of cut and Ra (Frifita et al. 2020), others found no significant impact (Duong, Truong, and Minh-Duc 2013). Coolant systems significantly affect the surface roughness. Conventional cooling generally offers a superior surface finish compared with MQL or dry conditions (Iturbe et al. 2016; Chaabani et al. 2020). However, there are exceptions in which MQL outperforms conventional methods (Kumar, Singh, and Kalsi 2017).

The ANOVA results for surface roughness are presented in **Table 9**. Feed and cooling conditions were the most influential parameters, with 57.12% and 30.37% contribution ratio respectively. The cutting speed contribution was 4.33% and depth of cut showed 4.10% contribution.

Table 9. Surface roughness ANOVA.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Cutting speed	2	0.01934	4.36%	0.0195	0.00967	5.18	0.032
Feed rate	2	0.25743	57.12%	0.2553	0.12767	67.79	0
Depth of cut	2	0.01833	4.36%	0.0195	0.00974	5.17	0.032
Cooling condition	2	0.13511	30.37%	0.1357	0.06787	36.04	0
Error	9	0.01635	3.79%	0.0169	0.00188		
Total	17	0.44656	100.00%				

S= 0.0433974, R-Sq= 96.21%, R-Sq(pred)= 84.83%

4.4 Carbon emissions

Insights into the relationship between the machining parameters are shown in **Figure 9(d)**. The data illustrate that increasing the feed rate tends to decrease carbon emissions, whereas higher depths of cut result in elevated carbon emissions. The cutting speed displays a decreasing trend in CE owing to reduced energy consumption. The cutting speed decreases CE owing to reduced energy consumption, as reported by other researchers as well (Ic et al. 2018). Among the cooling conditions, dry cutting exhibited the lowest carbon emissions, followed by MQL, whereas wet cutting methods contributed the most to emissions.

An increase in feed rate corresponds to a decrease in carbon emissions, supporting the idea of efficiency and environmental benefits associated with higher feed rates owing to quicker task completion and reduced consumption of electricity and coolant (Sihag and Sangwan 2018). Conversely, an increase in the depth of cut, as noted by (Ic et al. 2018), leads to the generation of a larger volume of removed material and power requirements, consequently resulting in higher CO₂ production. Coolant production and disposal significantly contribute to CO₂ emissions. Therefore, dry machining which eliminates coolant usage, is the most environmentally friendly option.

The ANOVA results for CE are summarized in **Table 10**. Cooling condition emerged as the most significant parameter, contributing 45.83%, followed by cutting speed at 32.38%. Feed rate showed contribution of 17.18%, and depth of cut showed insignificant contribution.

Table 10. Carbon emissions ANOVA.

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Cutting speed	2	0.76801	32.38%	0.7680	0.3840	37.09	0.000
Feed rate	2	0.40752	17.18%	0.4075	0.2037	19.68	0.001
Depth of cut	2	0.01617	0.68%	0.0161	0.0080	0.78	0.487
Cooling condition	2	1.08714	45.83%	1.0871	0.5435	52.50	0.000
Error	9	0.09318	3.93%	0.0931	0.0103		
Total	17	2.37202	100.00%				

S= 0.101751, R-Sq= 96.07%, R-Sq(pred)= 84.29%

Figure 8(a) shows the carbon emissions due to energy consumption for the Taguchi design of experiment for wet, dry, and MQL cooling conditions. The carbon emissions associated with energy consumption (CE_{elec}) vary significantly across machining environments. Wet machining resulted in lower CE_{elec} values in Experiments 2 and 3. In contrast, dry machining exhibited the highest CE_{elec} values, reflecting the absence of a coolant-induced cooling efficiency. MQL machining provides a balanced approach, indicating its potential to optimize energy usage while maintaining machining performance. Carbon emission values due to materials (cutting tools and cutting fluid) for wet, dry, and MQL conditions are presented in **Figure 8(b)&(c)**. Coolant usage significantly influenced carbon emissions ($CE_{coolant}$), with wet machining recording the

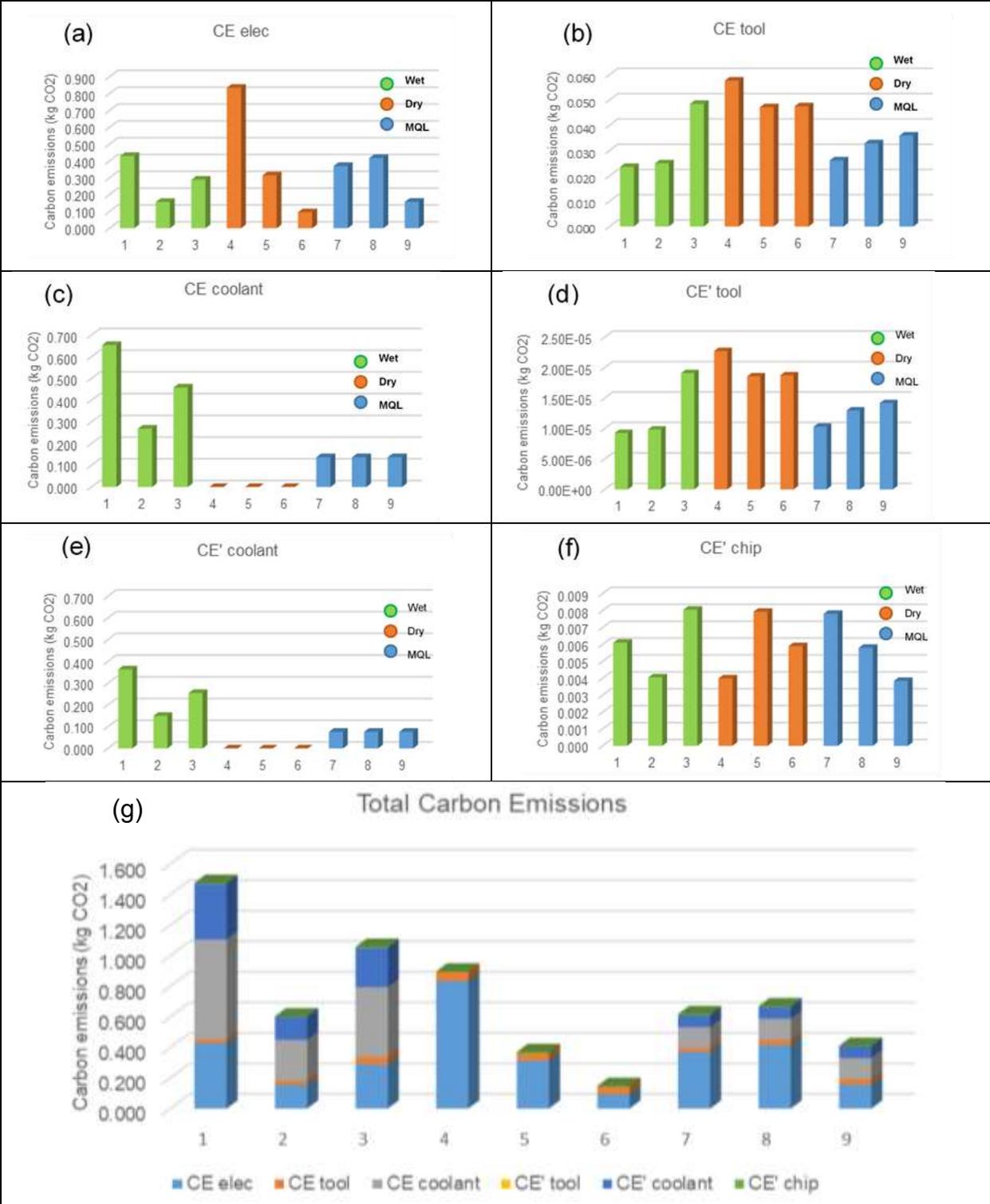


Figure 8. Carbon emissions comparison for Taguchi DOE under wet, dry and MQL conditions.

highest emissions owing to coolant consumption. Conversely, dry machining did not contribute to the CE coolant because no coolant was used. MQL machining demonstrated reduced emissions, highlighting its efficiency in minimizing coolant-related environmental impacts compared with wet machining. The carbon emissions calculated for waste processing are shown in **Figure 8(d-f)**. The carbon emissions attributed to tool disposal (CE'_{tool}) were minimal across all the experiments. The carbon emissions associated with coolant disposal (CE'_{coolant}) were highest in wet machining because of the substantial quantity of coolant used. MQL machining exhibited lower emissions due to reduced coolant usage, while dry machining did not contribute to CE'_{coolant} , offering an advantage in coolant disposal sustainability. The carbon emissions from chip processing (CE'_{chip}) were relatively consistent across all the machining environments. The total carbon emissions (CE_{Total}) highlight the combined environmental impact of all machining components, as shown in **Figure 8(g)**. Wet machining demonstrated the highest CE_{Total} values, primarily because of coolant usage. Dry machining significantly reduced CE_{Total} and MQL machining offered a balanced approach, showing its potential to optimize sustainability while delivering efficient machining performance.

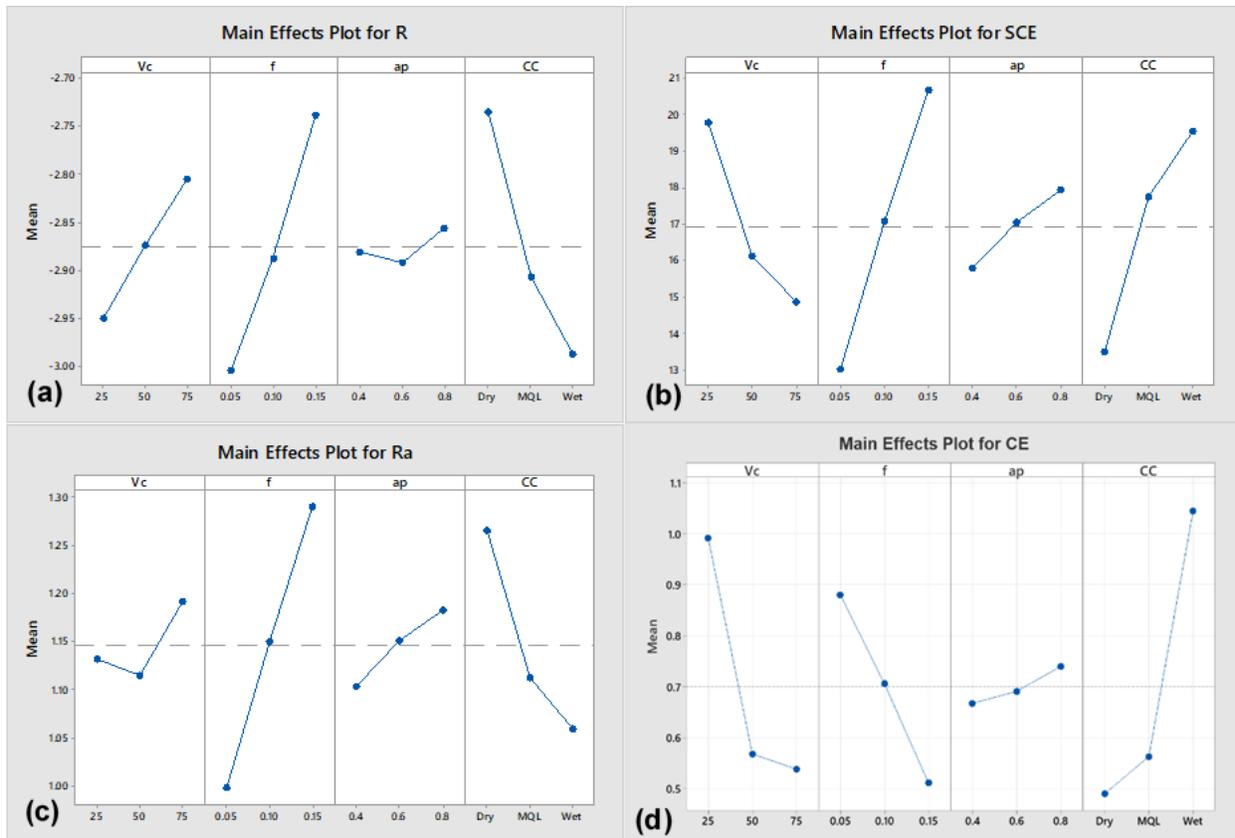


Figure 9. (a) Main effects plot for R. (b) Main effects plot for SCE. (d) Main effects plot for Ra. (d) Main effects plot for CE.

4.5 Validation Experiment

The main objective of this study is to investigate the machining response by primarily focusing on the cooling conditions along with other essential machining parameters. Initially, the methodology involved identifying the significant contributions of the key input parameters and selecting specific values conducive to favorable outcomes. This study focused on parameters such as tool wear, SCE, surface roughness, and CE, following the smaller-the-better model. The predicted values of the best and worst input conditions for the individual response parameters derived from the Taguchi method are presented in **Table 11**.

Confirmatory tests were subsequently conducted at the best and worst combinations of machining parameters to check the results. The results of these confirmatory tests were compared with the best outcomes obtained initially through Taguchi analysis and are presented in **Table 12**. The validation tests notably confirmed the trends anticipated by the statistical analysis and Taguchi Design of Experiments. Digital microscope images illustrating the conditions corresponding to the lowest and highest wear rates are shown in **Figure 10**.

Table 11. Best and worst machining conditions for each response parameters.

Responses	Condition	Cutting Parameters			
		V_c (mm/rev)	f (m/min)	a_p (mm)	CC
Wear Rate (R)	Best	25	0.05	0.6	Wet
	Worst	75	0.15	0.8	dry
SCE (Jmm ⁻³)	Best	75	0.05	0.4	Dry
	Worst	25	0.15	0.8	Wet
Ra (μ m)	Best	50	0.05	0.4	Wet
	Worst	75	0.15	0.8	Dry
Carbon Emission (CE)	Best	75	0.15	0.4	Dry
	Worst	25	0.05	0.8	Wet

Table 12. Validation test results compared to initial experimental runs.

Responses	Condition	Validation test	Initial runs	% difference
Wear Rate (R)	Best	-3.905	-3.099	23%
	Worst	-2.303	-2.531	9%
SCE (Jmm ⁻³)	Best	9.574	11.133	15%
	Worst	26.409	25.640	3%
Ra (μ m)	Best	0.84	0.91	8%
	Worst	1.56	1.49	5%
Carbon Emission (CE)	Best	0.105	0.119	12%
	Worst	1.538	1.477	4%

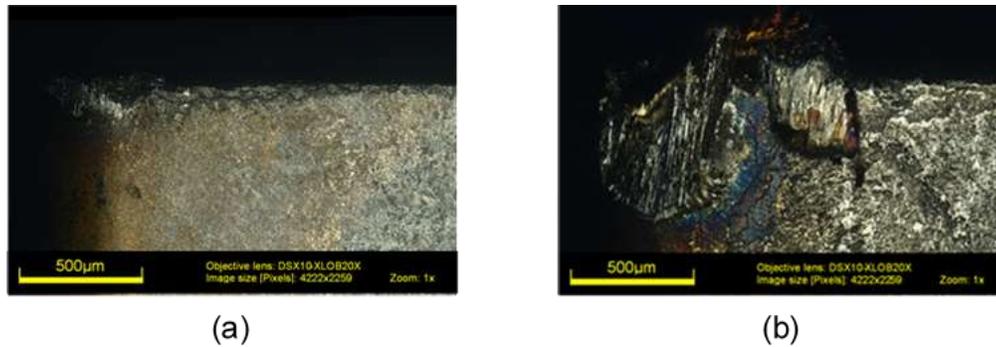


Figure 10. Digital microscope image to tool wear (a) Min wear at $V_c=25$ mm/rev, $f=0.05$ m/min, $a_p=0.6$ mm, wet. (b) Max wear at $V_c=75$ mm/rev, $f=0.15$ m/min, $a_p=0.8$ mm, dry.

5. Conclusion

In this study, dry, MQL, and wet turning techniques were employed to machine Inconel 718, with a focus on enhancing the sustainability and productivity of the machining process. SCE and CE were chosen as indicators of sustainability and efficiency, whereas tool wear rate and surface roughness represented productivity aspects. Based on the results obtained in this study, the following conclusions can be drawn:

- **Tool life improvement:** The findings suggest that both wet and MQL conditions significantly reduced the tool wear rates, with wet machining yielding the lowest wear. This improvement in wear resistance under wet conditions was noted to be 11% better than dry machining, with a notable 23% enhancement in tool life observed under optimal wet machining parameters. Feed rate emerged as the primary contributor (44.20%) to tool wear, followed closely by the CC (41.50%), and cutting speed (13.05%).
- **Specific cutting energy optimization:** In terms of SCE, dry machining exhibited lower energy consumption compared to MQL and wet techniques, with a notable 15% improvement achieved through optimal machining parameters. Feed rate played a significant role in SCE, contributing 45.35%, followed by cutting speed (20.40%) and coolant medium (29.85%), whereas depth of cut had a minimal impact (3.67%).
- **Surface quality enhancement:** Surface roughness was found to increase with higher feed rates, although the application of coolant enhanced the surface quality, primarily because of its effective lubricating properties. Wet machining with optimal parameters resulted in 8% enhancement in surface roughness compared to other conditions.
- **Carbon emissions reduction:** Significant reductions in CE were observed during dry machining, with the cooling medium identified as the primary contributor (45.83%), followed by cutting speed (32.38%), feed rate (17.18%), and insignificant contribution is shown by depth of cut. Notably, CE improved by 12% under optimal machining conditions.

This study advances sustainable manufacturing by analyzing the effects of various machining environments on the critical productivity and sustainability metrics of Inconel 718. These findings provide practical insights for industries, highlighting the balance between tool wear, surface quality, specific cutting energy (SCE), and carbon emissions

(CE). Although the Taguchi method effectively identified optimal machining parameters, its limitations in capturing nonlinear interactions underscore the need for advanced approaches, such as Response Surface Methodology (RSM) or machine learning-based models. These approaches are currently under consideration in ongoing research to provide a deeper understanding of these interactions. To build on the findings of this study and further contribute to the field, several key areas for future research are identified.

Future research directions include the integration of multi-criteria decision-making (MCDM) approaches, such as TOPSIS, to provide a systematic ranking of machining environments for improved decision-making. The development of energy consumption maps tailored to Inconel 718 machining is another critical focus designed to serve as a practical visual guide for selecting energy-optimal parameters while excluding machine-tool-specific energy data. Further exploration is needed to analyze the economic implications of energy efficiency and carbon emission reduction, along with the potential of advanced cooling strategies, such as cryogenic and hybrid systems. These efforts aim to strengthen the connection between sustainability, productivity, and operational cost-effectiveness of machining processes.

Disclosure statement

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Author contributions

M.A.K: Experimentation, Data curation, Micrography, Formal analysis, Investigation, Visualization, Writing – original draft; **R.A:** Conceptualization, Funding acquisition, Methodology, Supervision, Resources, Validation of results, Writing – original draft, Writing – review & editing; **S.H.I.J:** Conceptualization, Methodology, Experimental setup design, Resources, Supervision, Writing, Design of experiments – review & editing; **S.I.B:** Supervision, Statistical analysis, Writing - original draft, Writing - review & editing; **M.S.K:** Software, Validation, Visualization, Writing - original draft, Writing - review & editing; **D.Z:** Resources, Software, Sensor interfacing, Data acquisition, Validation, Writing - review & editing.

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