Investigation of Turning Parameter of Machining Inconel 718

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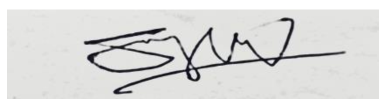
Thesis Supervisor’s Signature: 

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I would like to thank my parents and teachers for guiding me through this work. They were the ones to help me out every time I felt difficulty. I acknowledge their patience. They have contributed the most to my study.

Dedicated to my parents for their support

Abstract

Sustainable manufacturing systems depends upon two important elements i.e., economy and productivity. While economy is associated to the processes that are energy efficient having high output to input ratio, productivity focuses on the quality and quantity. Due to high energy loss and tool wear, machinability of hard to cut materials such as nickel alloys are always challenging. Usage of cutting fluids have positive effect on tool life, surface quality while reducing the cutting forces and temperature. In this study, the effect of input cutting parameters including feed, speed, cutting depth, and three different types cooling conditions (dry, MQL and wet) on surface roughness, specific cutting energy and tool wear during turning of Inconel 718 was investigated. Taguchi design of experiment has been employed for experimental design. To find out the influence of each input parameter on various output responses Analysis of Variance was conducted. When machining at optimal machining conditions obtained through ANOVA, energy consumption was reduced by 27%, while improvement of 30% and 15 % was observed in tool wear and surface roughness, respectively.

Key Words: *Inconel 718, turning, surface roughness, tool wear, specific cutting energy, minimum quantity lubrication, ANOVA*

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1 CHAPTER 1: INTRODUCTION

In recent years, researchers have directed their efforts towards increasing the overall productivity and efficiency of industrial processes. One of the main contributors to these developments is environmental degradation resulting from the release of carbon dioxide (CO_2) by the industries, which results in 26% of total carbon dioxide emissions [1]. Approximately 50% of the carbon dioxide (CO_2) emissions can be attributed to the manufacturing sector. The research focus in manufacturing processes is primarily centered on sustainability, economy, and productivity, driven by the growing environmental concerns and the complexities associated with energy security. The aforementioned challenges motivated researchers to pursue the goal of process optimization, wherein input parameters are precisely chosen to improve the output parameters.

Nickel-based alloys comprise approximately 70% of the total alloys utilized in aero engines [2]. Table 1 demonstrates the exceptional attributes of Inconel 718, including its elevated hardness, strength, temperature resistance, fatigue resistance, and corrosion resistance. The corrosion and wear resistance of Inconel 718 can be attributed to the presence of iron, chromium, nickel, and other elements [3], [4]. Inconel 718 is utilized in several industries such as aerospace and marine due to its unique properties. The utilization of Inconel 718 in the production of gas turbine blades for aviation engines is due to its ability to withstand the severe conditions of elevated pressure and temperature. In contrast to steel and aluminum alloys, which experience softening at elevated temperatures, Inconel 718 maintains its strength and toughness across an extensive range of temperatures [2]. Furthermore, the challenging machinability of Inconel 718 can be linked to its low heat conductivity value, as well as its elevated work hardening and strain rates, which therefore result in elevated cutting temperatures and forces. These properties lead to higher amounts of tool wear, greater power consumption, and surface damages [5, 6].

Dry cutting is often chosen in the manufacturing sector due to the significant expense involved with the utilization of coolants, which can account for around 17 percent of the entire manufacturing cost [7]. Furthermore, the utilization of dry cutting techniques not only reduces manufacturing expenses but also eliminates the adverse environmental impacts associated with the use of lubricants [8]. While dry cutting is generally preferred over the use of oil-based coolants due to environmental considerations, the challenging nature of cutting nickel alloys necessitates the use of cooling media to enhance the efficiency, quality, and productivity of the workpiece. The proper utilization of cutting fluid in machining operations has been found to enhance various aspects of the process, including tool life, power usage, dimensional accuracy, and surface quality. It is important to consider the expenses related to the utilization of coolants in relation to their benefits, as they constitute approximately 20% of the whole manufacturing cost [9], [10]. Numerous authors underscore the significance of this characteristic. To optimize tool life during machining operations, it is imperative to carefully consider the selection of appropriate machining conditions and the utilization of coolant [11]. The use of suitable coolant together with optimized machining parameters has the potential to enhance both productivity and economic efficiency. Researchers have conducted optimization of different output responses on various work pieces by taking into consideration a number of input parameters [12]. In several studies, Khan et al. conducted optimization experiments to observe the effects on R, SCE, and Ra during the cutting process of Ti-6Al-4V in three separate cutting conditions [13]–[16]. In another study, Sheheryar et al. observed the impact of input parameters, namely feed rate, depth of cut, and cutting speed, while micro-milling the Inconel 718. The objective was to optimize the burr formation, tool wear and surface roughness. To accomplish their objective, the researcher employed three different tool coatings [17]. In their investigation, Khan et al. conducted optimization of R in the process of machining titanium alloy. This optimization was carried out in dry and cryogenic cutting conditions [18].

As a result of a range of health and environmental concerns, the researcher shifts their focus towards a more sustainable and ecologically friendly machining technique, namely minimum quantity lubrication (MQL). The implementation of this approach resulted in a decrease in both machining costs and coolant consumption. MQL is believed to provide improved environmental conditions with reduced levels of pollutants, oxidation, and enhanced stability [19].

MQL, often referred to as micro-lubrication or near-dry lubrication, is characterized by its use of a much-reduced quantity of lubricant when compared to the standard approach of flooded lubrication [20], [21]. In the field of MQL, compressed air is employed to disperse a minimal quantity of lubricating oil within the cutting zone in the form of an aerosol, while maintaining a flow rate ranging from 10 to 100 ml/h [8], [22]. Several studies have conducted a comparative analysis of the outcomes of MQL machining in relation to machining performed under dry and wet circumstances, revealing notable enhancements [21], [23]. Kamata and Obikawa et al. conducted a research and found that usage of Minimum Quantity Lubrication (MQL) conditions yielded more favorable outcomes in terms of surface finish and tool life when compared to both dry and flooded cutting conditions during the turning process of Inconel 718 [24]. Thakur et al. conducted research on machining of nickel alloy, examining influence of cutting parameters on several performance indicators including tool wear, cutting pressure, force and temperature, and surface finish. Study employed a tungsten carbide tool for the machining process [25]. Cantero et al. [26] while finish turning Inconel 718, observed the pattern of tool wear. In their study on the turning of nickel alloy, Yazid et al. observed the impact of machining variables and lubrication/cutting conditions on work-piece surface quality. They found out that minimum quantity lubrication (MQL) resulted in a superior surface finish as compared to cutting under dry conditions, particularly at various flow rates [8].

Table 1.1; Aerospace alloys properties at room temperature

Property	Material				
	AI 7075-T6 Alloy	Titanium	Ti-6Al-4V	Ti-10V-2Fe-3Al	Inconel 718
Yield strength (MPa)	503	140	880	900	1170
Ultimate Tensile Strength (MPa)	572	220	950	970	1350
Ductility (%)	11	54	14	9	16
Thermal Conductivity ($W\ mK^{-1}$)	130	17	6.7	7.8	11.4
Hardness (HRC)	~7 (equivalent)	10-12 (equivalent)	30-36	32	38-44
Modulus of elasticity (GPa)	71.7	116	113.8	110	200
Fracture toughness ($MPa\ m^{1/2}$)	20-29	70	75	-	96.4
Max. operating temperature (°C)	-	150	315	315	650
Density ($g\ cm^{-3}$)	2.81	4.5	4.43	4.65	8.22

1.1 Aim of research work

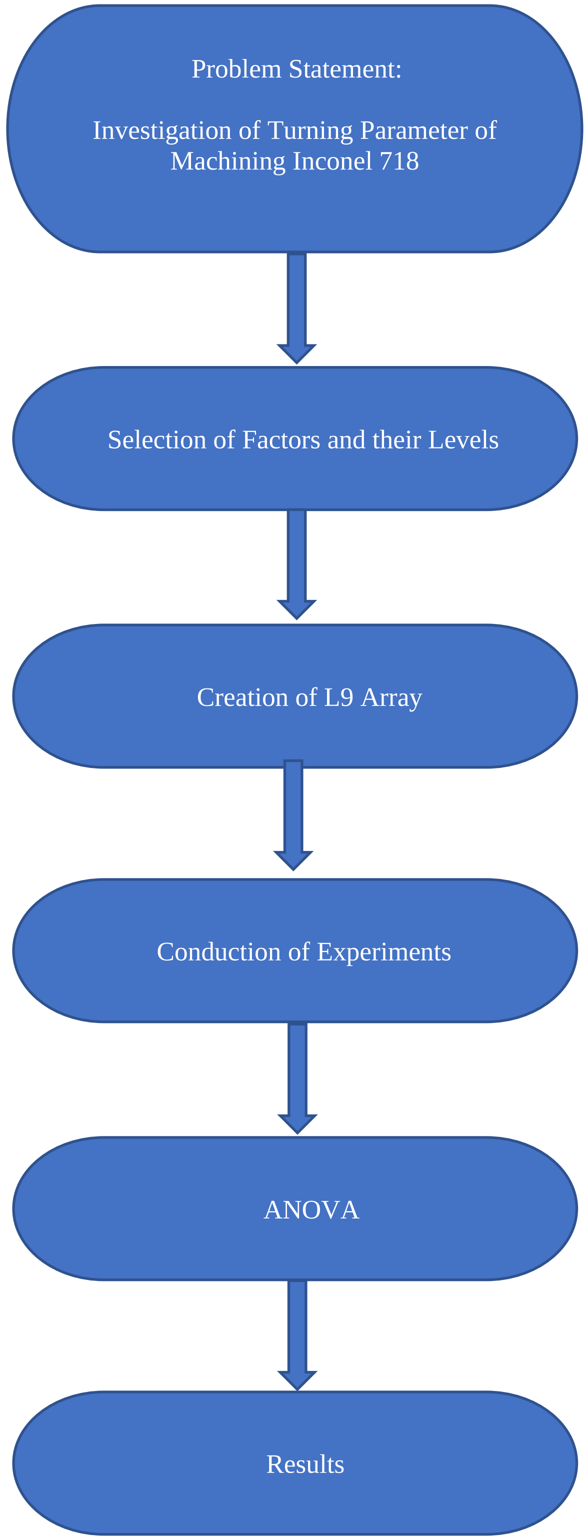
Aim of this research is to increase manufacturing quality of aerospace-grade materials such as Ni-based superalloys. This can be improved by simultaneously enhancing the sustainability, efficiency, and productivity by optimizing the outputs responses in terms input machining parameters. Sustainability can be defined in terms of SCE while efficiency and productivity can be measured as R and Ra, respectively. Main objectives of current study are mentioned below:

- To examine the behavior of nickel alloys under a different combination of input parameters.
- To studied different cooling conditions effects on turning performance.
- To evaluate the Ra, SCE and Ra while machining Inconel 718.

1.2 Application of work

Inconel 718 is mainly used in various industries including defense, automotive, electronics etc. It has different range of applications in jet engines, power plants, automotive, electronics, turbine blades, aircraft engines etc. Moreover, this study also helps us to achieve various sustainable development goal (SDG).

1.3 Research Methodology



1.4 Thesis Layout

Chapter 1 gives the introduction of the topic and briefly describes the aim, area of application, and research methodology of the study.

Chapter 2 discusses the process of reviewing previous literature on the subject and presents the findings.

Chapter 3 describes the experimental process, methodology, and design of the experiment. Also, discuss the different cutting parameters in detail.

Chapter 4 presents the experimental results as well as ANOVA results and their discussion

Chapter 5 concludes the Thesis. It focuses on the conclusions of the study and future recommendations.

2 CHAPTER 2: LITERATURE REVIEW

In this chapter, prior research articles on important overview of the machining process, tool geometry parameters, machining of nickel alloys are discussed. In addition, research is being done on workpiece surface integrity and the application of different cooling conditions for improvement in tool life and energy consumption in the turning of Inconel 718. In light of the above literature assessment, further research is needed to fill in the gaps in our knowledge.

2.1 Machining: An Overview

According to a study conducted by researchers, manufacturing industries globally account for around 20% of the overall energy usage. The energy usage has significant negative effects on the environment, as indicated by a 90 percent. According to a study [55], the implementation of optimal cutting parameters, as well as the design of appropriate tools and tool paths, has the potential to decrease energy consumption by a range of 6% to 40% in machining processes. Furthermore, within the industrial sector, there is a growing need for energy efficient operations due to the rising energy demands and carbon emissions. In the field of machining, turning has emerged as a cost-effective and highly efficient technology for the machining of complex components, enabling higher production rates while requiring less complex setup.

In their study on effect of cutting processes on surface roughness and machining performance, Outeiro et al. observed that uncoated carbide tools produce higher levels of surface residual stresses compared to coated tools [56]. In their research on the wear of tools during the turning process of Inconel 718, Grzesik et al. [57] determined that the utilization of titanium aluminum nitride coated tools resulted in an improvement in tool life. Dudzinski et al. [58] have verified that tool wear is a significant challenge encountered during the machining of Inconel 718. Several studies have documented a reduction in cutting force when Minimum Quantity Lubrication (MQL) is employed during the machining process of Inconel 718, as reported by several researchers [59]–[61].

2.2 Research Motivation

To improve the sustainability and productivity of manufacturing systems, it is necessary to optimize key output variables, including Ra, SCE, and R. Objective of current study is to optimize the responses in terms of input parameters to promote sustainability, efficiency, and productivity simultaneously. The addition of MQL, combined with other machining conditions, offers advantages in terms of promoting green manufacturing and sustainability. The significance of this matter can be assessed by considering the achievement of various sustainable development goals (SDGs) [28].

2.3 Superalloys based on nickel: an overview

The alloys that are manufactured for use in high-temperature environments have been commonly termed as "superalloys." The main qualities of a super alloy are its ability to withstand high level of stresses near to its melting point, its long-term resistance to mechanical degradation, and its resilience in adverse operating conditions. The yield and ultimate tensile strength are static properties [62]. Fracture toughness can be defined as a static property. Consequently, nickel-based superalloys have emerged as the most optimal material for high-temperature applications, specifically in the exhaust stream of gasoline, turbines, and jet engines [63]. Figure 2.1 illustrates the exceptional creep and stress rupture resistance exhibited by nickel-based superalloys. The aluminum, titanium, and magnesium alloys employed in the manufacturing of airplanes are known for their comparatively low weight.

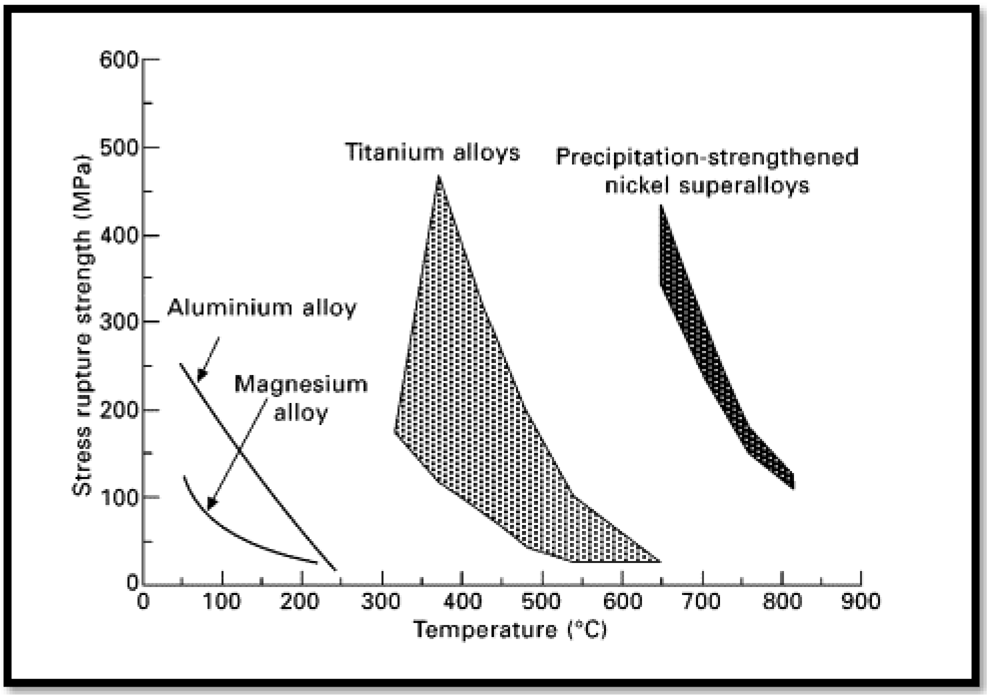


Figure 2.1; Stress rupture curves for various aerospace alloys [64]

Nickel-based superalloys typically have a nickel composition of approximately 50% in terms of weight. Chromium, titanium, aluminum, and cobalt are frequently utilized as alloying elements in a variety of superalloys, with chromium typically comprising 10-20 percent, titanium and aluminum collectively accounting for up to 8 percent, and cobalt constituting 5-15 percent. Little quantities of molybdenum, tungsten, and carbon are additionally present. Table 2.1 presents a comprehensive list of various nickel-based superalloys used in jet engines.

Table 2.1; Composition of various nickel-based alloys [64]

	Composition									
Alloy	Ni	Fe	Cr	Mo	W	Co	Nb	Al	C	Other
Astroloy	55.0	–	15.0	5.3		17.0	–	4.0	0.06	
Hastelloy X	49.0	18.5	22.0	9.0	0.6	1.5	3.6	2.0	0.1	
Inconel 625	61.0	2.5	21.5	9.0	–	–	–	0.2	0.15	<0.25 Cu
Nimonic 75	75.0	2.5	19.5	–	–	–	–	0.15	<0.08	1 V
Inconel 100	60.0	<0.6	10.0	3.0	–	15.0	–	5.5	<0.08	2.9 (Nb+Ta)
Inconel 706	41.5	37.5	16.0	–	–	–	5.1	0.2	0.12	<0.15 Cu
Inconel 716	52.5	18.5	19.0	3.0	–	–	5.2	0.5	0.05	0.1 Zr
Inconel 792	61.0	3.5	12.4	1.9	3.8	9.0	–	3.5	0.04	
Inconel 901	42.7	34	13.5	6.2	–	–	–	0.2	0.16	0.3 V
Discaloy	26.0	55	13.5	2.9	–	–	3.5	0.2	0.15	0.5 Zr
Rene 95	61.0	<0.3	14.0	3.5	3.5	8.0	–	3.5	0.14	
Rene 104	52.0	–	13.1	3.8	1.9	182	1.4	3.5	0.03	2.7 Ta
SX PWA1480	64.0	–	10.0	–	4.0	5.0	–	5.0		2 Hf
DS PWA1422	60.0	–	10.0	–	12.5	10.0		5.0		

In the oil and gas industry, Inconel 718 is frequently employed as a highly utilized austenitic superalloy, characterized by its composition of nickel and chromium. At elevated temperatures, Inconel 718 has exceptional strength and demonstrates remarkable resistance to corrosion. The high-temperature mechanical properties of Inconel 718 make it well-suited for the different applications, including various fields of biomedical, automotive, and aerospace [65,66]. Machining nickel alloy presents challenges due to its low thermal conductivity, which promotes the BUE formation during turning process, as well as its inherent hardness and strong affinity towards tool materials. During the process of machining, the limited heat conductivity of Inconel 718 results in a significant increase in the temperature of the cutting zone, hence imposing limitations on the life the tool.

Historically, turbine discs and blades have been manufactured using nickel-based superalloys. Usage of Inconel 718 has gained a lot of popularity in the realm of high-temperature applications, particularly when compared to other available superalloys. Additional applications of this material encompass usage in gas turbine engines for maritime vessels, industrial operations, and automobiles, as well as in the production of rocket engine components. Furthermore, it finds application in nuclear power facilities, turbine casing engine mounts, rocket propulsion systems, pumps, and chemical equipment [67].

2.3.1 Machinability of Inconel 718

Nickel superalloys are commonly employed in numerous aero-engine applications owing to their outstanding properties, including elevated thermal strength, exceptional fatigue, and corrosion resistance. The low value of thermal conductivity and high hardness of these alloys pose several challenges in the machining process. The presence of hard abrasives inside the microstructure, coupled with the potential for a reaction with the tool material, exacerbates the challenges faced during the machining process. Consequently, the exceptional tensile and yield strength of the material can be ascribed to the formation of precipitate hardening through the secondary phase strengthening mechanism involving Ni3Nb. During the process of machining, the rapid strain hardening shown by these alloys can lead to higher cutting temperatures and forces. According to previous research [68,69], it has been observed that machined nickel alloys exert approximately twice the amount of stress on cutting tools compared to steels, even when the cutting speed is nearly the same. It has been reported that nickel superalloys have been subjected to machining operations at velocities of 300m/s, while being exposed to elevated temperatures of up to 1000 °C [70]. The aforementioned elements possess the potential to exert a substantial influence on both the tool life and surface quality of the components.

2.3.2 Surface Roughness

The manufacturing process of nickel-based superalloys presents significant challenges in achieving desired output and quality standards. Furthermore, the aerospace sector is obligated to uphold stringent quality standards for machined components because of safety rules and regulations. The significance of surface integrity in nickel alloy machining has been a subject of great importance due to the critical role that nickel alloys play as components in aero-engines [71]. The concept of "surface integrity" refers to the correlation between the different properties including metallurgical, mechanical, chemical and topographical, properties of a surface of the manufactured component as well as part's overall functional performance. Most of both typical and modern machining techniques result in surface changes, and the extent of these changes is dependent upon the severity of the operating conditions [72]. Nickel alloys have been seen to exhibit plastic deformation, the formation of cracks, significant changes in microhardness, the presence of residual stresses, and modifications in microstructure on the machined surface when subjected to typical machining techniques. The mechanical and metallurgical qualities of aerospace industry surfaces necessitate investigation in order to assess their potential impact on fatigue strength, stress-corrosion resistance, and life of the machined component. Previous studies conclusion indicate that fatigue strengths of Waspalloy, 410 SS and titanium are reduced by approximately 50% when subjected to electrical discharge machining (EDM) as compared to mechanical milling [73].

2.3.3 Specific Cutting Energy

To evaluate the effectiveness of cutting process and to defines the machinability of the material, SCE is the good indicator. The concept of SCE is established by calculating the ratio between power cut and the rate at which material is removed during the cutting process. SCE is not dependent upon on machine type, size, power rating or efficiency [35].

2.3.4 Tool Wear Rate

R is an indicator of material machinability [39], is a notable output parameter that has been found to be associated with Ra and SCE [40][41]. In their research Jaffery et al. [42] performed a statistical analysis on the dry micro-milling process of titanium alloy. The study determined that the feed rate exhibited the largest contribution ratio (41%) in influencing tool wear. The impacts of process factors during titanium alloy turning in cryogenic conditions were analyzed by Khan et al. [43]. The predominant factor influencing R was determined by the fluctuation in v, accounting for 44% of the overall contribution. A research was done to investigate the impact of cutting parameters on tool wear in a dry environment using titanium alloy. The findings of the study revealed that by employing optimal machining settings, a reduction in tool wear of around 7% can be achieved.

2.4 Cooling Conditions

Three type of cutting conditions (dry, MQL, and wet) are employed during the experimental procedure. In wet conditions, the water-based oil coolant known as Shell Dromus B flows through the cooling system of a CNC machine. This circulation was facilitated by a 0.8kW coolant pump, which ensured a consistent flow rate of 6L min^{-1}. The mist sprayer system developed by COOLRUN was utilized in the experimental investigation of Minimum Quantity Lubrication (MQL). The system is comprised of a mixing chamber that is connected by two flexible pipes, each equipped with a nozzle at both the intake and outlet. Compressed air is introduced into the system using a single flexible inlet pipe, which is securely connected to the compressor. Another pipe is then coupled to the container containing the coolant. The flow rate of MQL was regulated using adjustable controls that were located on the mist sprayer. Both flexible nozzles were pointed towards the cutting zone, as depicted in Figure 2.

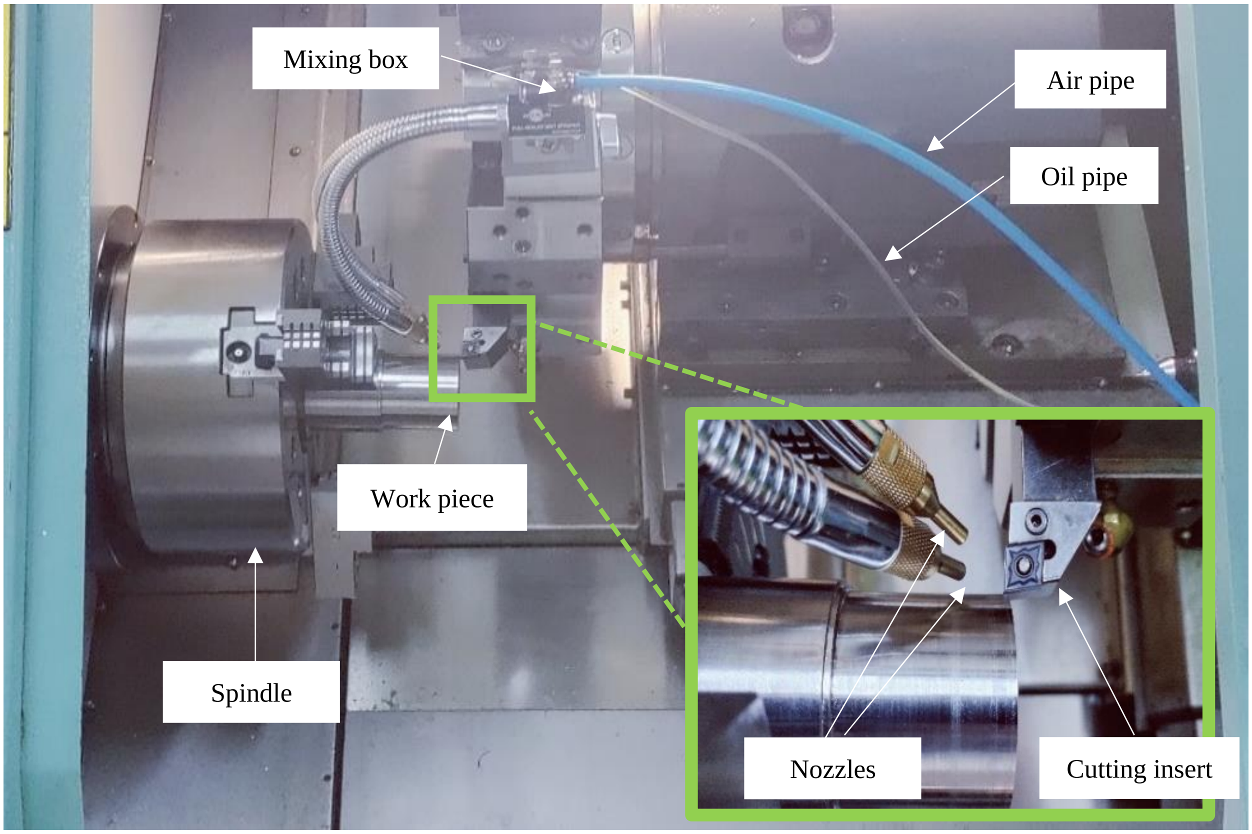


Figure 2.2; MQL setup on CNC Machine

3 CHAPTER 3: DESIGN OF EXPERIMENT AND METHODOLOGY

This chapter presents the experimental investigation of turning on nickel-based superalloy i.e., Inconel 718 in dry, MQL and wet lubricating conditions. This work was investigated under various cutting parameters including speed (v), feed (f), and cutting depth (d), and cooling conditions (CC). The cooling conditions and machining parameter effects on surface finish/roughness, energy consumption as well as tool wear are also studied.

3.1 CNC Machine setup and detail

The turning studies of Inconel 718 were carried out on highly precise YIDA manufactured CNC Turning Center (ML-300) having the spindle speed of 3500 RPM and rated power of 26kW. Pictorial of CNC machine is shown in Figure 3.2.

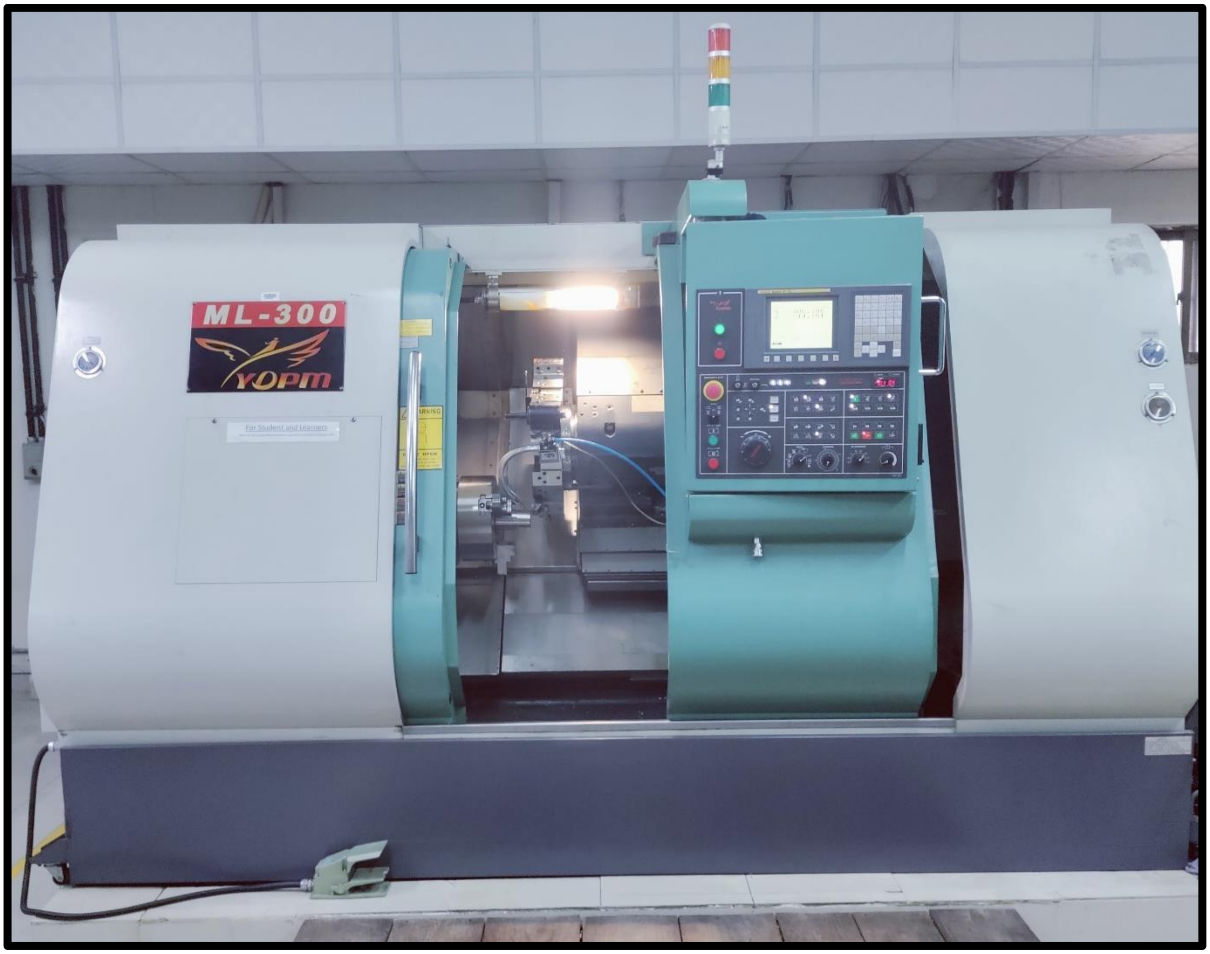


Figure 3.1; Pictorial view of CNC Turning machine

3.2 Design of Experiment

The effects of 04 input variables on Ra, R, and SCE were examined because selected input variable greatly influence the output responses. These input variables are as follows.

a) Three different cooling conditions
b) Three levels of feed (f)
c) Three levels of speed (v)
d) Three levels of cutting depth (d)

Table 3.2.1 shows the input machining variables with their levels. L9 array obtained through Taguchi technique of design of experiment is show in Table 3.2.2. All the input variable levels are defined as per ISO standard (1993) and recommendations of manufacturer of cutting insert (Laminar Technologies). All experiments are repeated twice to cater for any variability and repeatability of results. Length of cut for each experimental run was kept at 50mm.

Table 3.1.1; Machining variable details

Cutting Parameter	f (mm/rev)	v (m/min)	d (mm)	CC
Level 1	0.05	25	0.6	Dry
Level 2	0.10	50	0.8	MQL
Level 3	0.15	75	1	Wet

Table 3.2.2; L9 Array of input cutting variables

Exp. Run	f (mm/rev)	v (m/min)	d (mm)	Cooling conditions*
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1
*1= dry, 2=MQL, 3=Wet				

3.3 Workpiece characteristics

For experimentation Inconel 718 rod of 73mm diameter and 200mm length was used. The rod was manufactured as per ASTM B637. HRC of rod is around 55. Table 3.3 shows the chemical composition of work piece.

Table 3.3; Inconel 718 Chemical Composition (wt%)

Ni	Cr	FeCr	Mo	Co	Al	Si	Mn	Cu	C
50-55	17-21	15.65	2.8-3.3	1.0	0.85	0.35	0.35	0.3	0.08

3.4 Cutting tool specifications

PVD coated tungsten carbide inserts are utilized during experimentations. CNMG 120404NN inserts were manufactured and supplied by Laminar Technology. These inserts have the nose radius of 0.4mm. Only one face of the insert was used for each experimental run for analysis and for record purpose. Inserts used in experimentation has been figure. 3.2.

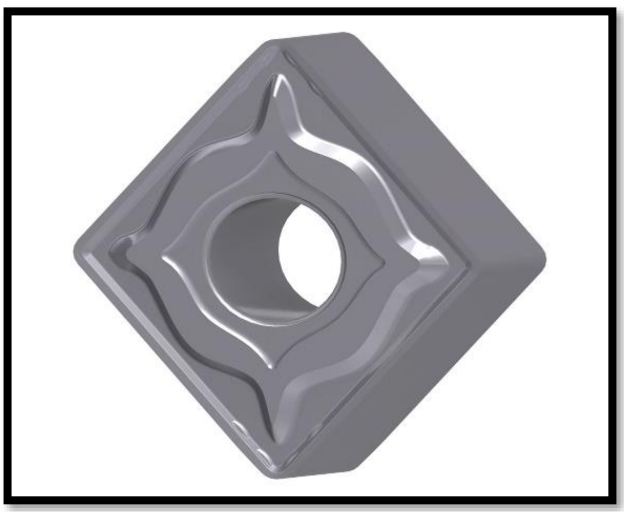


Figure 3.2; Pictorial view of cutting insert used in study

3.5 Surface roughness measurement

Surace roughness Ra values after each experimental trial was measured with the help of TR 110 roughness tester as shown in Figure 3.3. This roughness tester has the measuring range of 0.05 to 10 μm. The length of contact between work piece and meter is 40mm. After each run Ra was measured thrice and averaged to cater for any error in the reading.

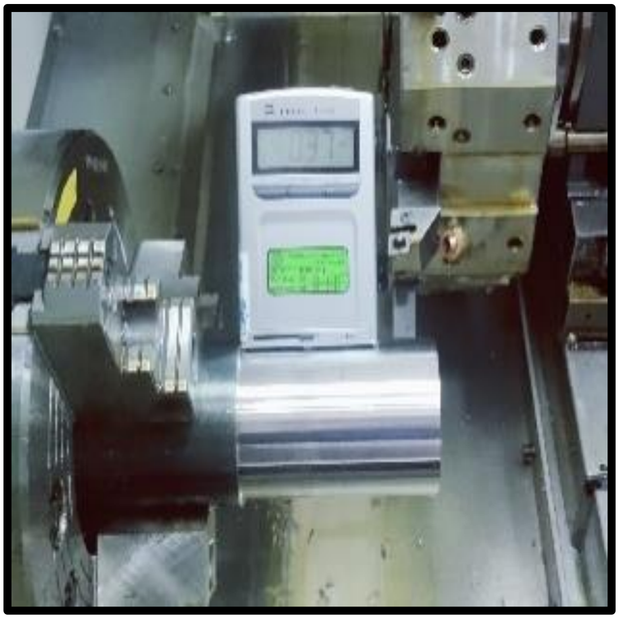


Figure 3.3; Pictorial view of TR 110 Roughness meter

3.6 Specific cutting energy measurement

Specific cutting energy measurement was carried out using CW-240-F Power Analyzer meter manufactured by YOKOGAWA Electric Corporation as shown in Figure 3.4. Power consumption during each trial was measured. 04 clamp of the power meter were attached to the CNC machine. Power meter can instantaneously measure the current, voltage, power factor and power data with the measuring interval of 0.1s. Two steps procedure was followed. In first step power of the air cut was measured with all components of the machine being activated. In the second step actual power was measured when actual experiment is being conducted. Difference of both powers will give us the cutting power of the specific experiment as shown in the Equation 1. SCE is finally calculated with the help of Equation 2.

$$P_{cut}(W) = P_{actual}(W) - P_{air}(W) \quad (1)$$

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

In above equation MRR is the rate of material removal and is the measured of v, f and d as shown in Equation 3.

$$MRR = f \times v \times d \quad (3)$$

Figure 3.4; CW-240-F Power Analyzer

3.7 Tool wear measurement

Measurement of R was done by Olympus DXS1000 digital microscope as shown in Figure 3.5. The flank face wear measurement was used to predict the tool wear because it is the good indicator of tool wear because flank wear indicates the work piece accuracy and quality [30]. ISO 3685 (1993) was used for which is the standard of single point turning and it defines the criteria that is either the average of 0.3 or 0.6 mm.

Tool wear R was calculated with the help of Equation 4. In this equation greater the negative value of R depicts the lower tool wear.

$$R = \log\left[\frac{VB}{l_s}\right] = \log\left[\frac{VB}{1000tv}\right] \quad (4)$$

ls is spiral cut length, v shows the speed and t is time of the cut.

Figure 3.5; Digital Microscope DXS1000

3.8 Methodology

The present study utilized the ANOVA method to assess the impact of various factors on the variables Ra, SCE, and R. Additionally, the Taguchi method was employed to identify the optimal criteria for minimizing Ra, SCE, and R. S/N ratio calculation varied depending on the type of data. Three distinct formulas were utilized to calculate the S/N ratio, namely the lower, nominal, and greater values considered acceptable. In this study, smaller values of Ra, SCE, and R were preferred for the calculation of S/N ratios due to their relevance to the research objectives.

$$\frac{S}{N} ratio = -10 \log_{10}\left(\sum_{i=1}^{n} Y_i^2 / n\right) \quad (5)$$

It was determined the mean S/N ratio at each level, and the optimal parameters were chosen by selecting those with a maximum mean S/N ratio.

4 CHAPTER 4: RESULTS AND DISCUSSION

In turning of Inconel 718 superalloys, this study examined the impact of various cooling conditions, cutting parameters on Ra, SCE and R. Analyzing the statistical relevance of the turning on surface roughness, energy consumption, and tool-wear was done using the ANOVA method. The mechanism of R while turning of Inconel 718 was studied using digital microscopic. Studies of energy consumption during experimentation and subsurface integrity were examined. This chapter presents the details of the results obtained from this research.

4.1 Results

4.1.1 ANOVA Results

To verify / examine the significance of each input cutting parameter on output responses the ANOVA was done by using the Minitab software. Finding of ANOVA shows the significance of each input parameter on each of Ra, SCE and R. Table 4.1 to 4.3 depicts the results.

Table 4.1; ANOVA for Ra

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	CR
f (mm/rev)	2	10.8291	10.8291	5.41457	4470.75	0.000	86.09%
v (m/min)	2	0.8254	0.8254	0.41269	340.75	0.000	6.56%
d (mm)	2	0.4005	0.4005	0.20024	165.33	0.000	3.18%
CC	2	0.5128	0.5128	0.25641	211.71	0.000	4.08%
Error	9	0.0109	0.0109	0.00121			0.09%
Total	**17**	**12.5787**					**100.00%**
SD=0.0348010, R-Sq=98.57%, R-Sq (pred)=95.65%							
DF degrees of freedom, SS Sum of squares, MS mean squares, F – F value, P – P value, CR contribution ratio (%), SD standard deviation, R-Sq. (Pred) – predicted R2							

Table 4.2; ANOVA for SCE

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	CR
f (mm/rev)	2	109.86	109.865	54.932	523.94	0.000	10.15%
v (m/min)	2	200.93	200.930	100.465	958.23	0.000	18.56%
d (mm)	2	84.25	84.248	42.124	401.78	0.000	7.78%
CC	2	686.83	686.831	343.416	3275.48	0.000	63.43%
Error	9	0.94	0.944	0.105			0.09%
Total	**17**	**1082.82**					**100.00%**
SD= 0.323797, R-Sq=98.91%, R-Sq (pred)= 96.65%							

Table 4.3; ANOVA for R

Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	CR
f(mm/rev)	2	0.191255	0.191255	0.095628	71.48	0.000	82.63%
v (m/min)	2	0.015363	0.015363	0.007682	5.74	0.025	6.64%
d (mm)	2	0.005851	0.005851	0.002925	2.19	0.168	2.53%
CC	2	0.006956	0.006956	0.003478	2.60	0.128	3.01%
Error	9	0.012041	0.012041	0.001338			5.20%
Total	**17**	**0.231467**					**100.00%**
SD=0.0365774, R-Sq=97.80%, R-Sq (pred)= 91.19%							

4.1.2 Experimental results

The results reported from the experiment for Ra, SCE and R, are all displayed in Table 4.4. There were multiple runs of each experiment, and the average of those runs was used in the study. The different between results from the first and second runs is due to differences in machine noise, tool quality, human error during measuring, and setting the DOC.

Table 4.4; Experimental design using L9 array and measured experimental responses

Sr. No.	R		SCE (J/mm 3)		Ra (µm)	
	Trail A	Trail B	Trail A	Trail B	Trail A	Trail A
1	-8.8865	-8.8552	8.80	8.58	0.22	0.25
2	-8.9662	-8.9915	5.47	5.80	0.21	0.20
3	-8.9919	-9.0263	13.28	12.96	0.37	0.34
4	-8.8553	-8.7932	26.40	27.60	0.75	0.71
5	-8.8147	-8.8003	1.56	1.68	0.81	0.78
6	-8.8135	-8.9218	3.20	3.33	0.89	0.91
7	-8.7128	-8.6894	2.92	3.20	2.04	2.09
8	-8.6895	-8.6546	10.53	10.80	1.53	1.45
9	-8.7590	-8.6980	0.73	0.66	2.83	2.74

4.2 Discussion

Machining parameters affect aspects of surface quality, sustainability, and economy in terms of surface roughness Ra, SCE and R respectively. Based on ANOVA and experimental result, detailed discussion of various machining parameter on Ra, SCE and R, are given in this section.

4.2.1 Surface Roughness

The Ra value holds significant importance since it is related to the overall product quality. Figure 4.1 illustrates a positive correlation between f and Ra. The two additional input variables, namely v and d, exhibit conflicting effects on the Ra. The rise in Ra, or surface roughness, due to feed is attributed to the formation of microgrooves on the material's surface caused by a high feed rate. These microgrooves lead to stretching and an increase in surface roughness [48]. The value of Ra increases at higher feed rates as a result of the formation of high peaks and crests on the machined surfaces (49). Furthermore, the greater value of Ra at elevated feed values might also be attributed to the concurrent rise in vibrations [39].

In dry condition value of Ra is highest, while the lowest Ra value was observed under wet conditions, with the MQL condition falling in between. The presence of coolant might contribute to improved surface roughness due to its lubricating properties, which facilitate smoother sliding interactions between surfaces [50]. Furthermore, the coefficient of friction is notably altered by the presence of coolant between sliding surfaces between the tool-workpiece [51]. Several researchers have independently observed and documented the occurrence of coolant penetration [49], [52], [53]. Mia et al. found that a high Ra value in dry cutting can be attributed to increased tool wear, which counteracts the thermal softening effect.

The study of contribution factors is presented in Table 4.3. The factor that has the highest contribution ratio, accounting for 86.09%, is feed. It is followed by speed, cooling conditions, and cutting depth.

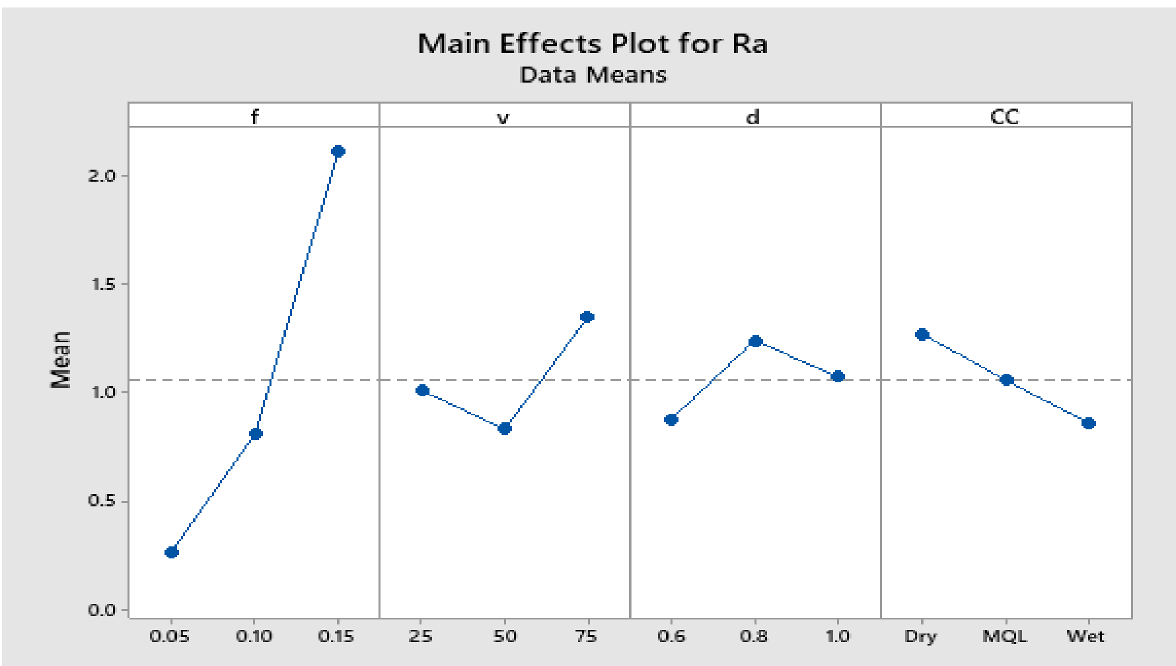


Figure 4.1; Ra main effect plot

4.2.2 Specific Cutting Energy Analysis

Figure 5 displays the main effects plots depicting the relationship between the SCE measured in Jmm^{-3} and input machining parameters. The plot demonstrates that with the rise in speed leads to a decrease in SCE. The observed phenomenon can be due to a decline in cutting forces at the interface between the tool and workpiece. This decrease is primarily caused by the thermal softening of Inconel 718 at elevated temperatures, which is a result of the lower value of thermal conductivity shown by nickel alloys. Parida and Hao et al. (44, 45) observed a reduction in cutting forces during the machining of Inconel 718, correlating this phenomenon with an increase in machining speed. The relation between cutting forces and SCE is direct [46]. Therefore, a drop in cutting forces will reduce the SCE. An increase in the shear angle of nickel alloy with increasing v results in reduction in forces.

SCE exhibits a pattern of initial increase followed by a subsequent decrease as the feed increases. This pattern, as depicted in the main effect plots presented in Figure 4.2, demonstrates an inconsistency. The power consumption associated with Minimum Quantity Lubrication (MQL) is comparatively lower when compared to that of flooded cooling. The observed patterns align with the findings presented in a prior study conducted by Pinherio et al. machining of a nickel super alloy, specifically Inconel 718 [47]. In machining operations, the cutting force serves as a primary measure of energy consumption and is subject to the influence of cutting and lubricating conditions. The trials clearly demonstrated that the use of MQL resulted in significantly lower cutting forces as compared to the flooded situation.

An ANOVA was conducted to examine the impact of each input cutting parameters on SCE. Results of this analysis can be found in Table 4.2. The influence of all input machining factors on the output response is demonstrated by the P value. The findings of the analysis indicate that the cooling and lubricating condition is the most influential element, accounting for 63.43% of the observed effects. Following this, speed is identified as the second most influential factor, contributing to 18.56% of the observed effects.

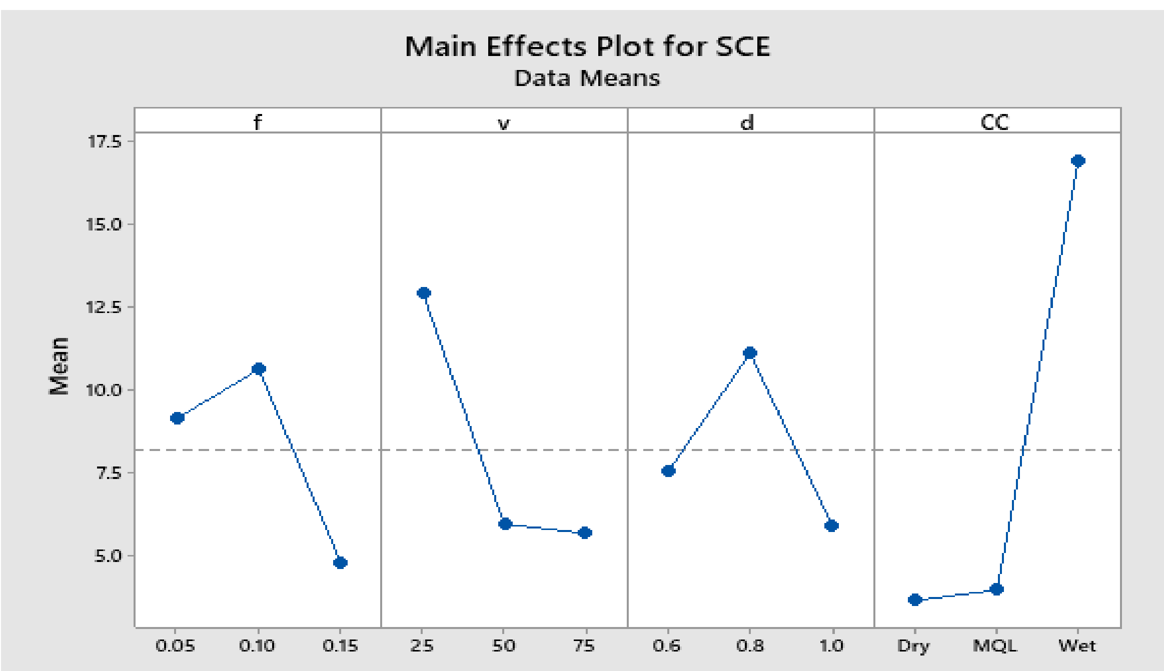


Figure 4.2; The main effect plot for SCE

4.2.3 Tool Wear Analysis

The measurement of flank wear (VB) of cutting insert was done for each experimental run. The calculation of tool wear rate was performed using Equation 4. Figure 4.3 illustrates the primary effects plot pertaining to tool wear (R). The plot demonstrates a positive correlation between wear rate and feed rate, indicating that wear rate rises as feed rate increases. Conversely, wear rate exhibits an opposite relationship with cutting speed, suggesting that wear rate drops as cutting speed decreases. However, with regards to depth of cut, the relationship is more complex, as wear rate initially decreases and then increases, displaying an inconsistent pattern of response. In relation to coolant and lubrication conditions, the value of R is lower in MQL as compared to dry and wet cutting.

The reason for rise in R as the f increases is attributed to the reduction in the tool-chip interface contact area. Reduction in contact area results in a rise of temperature in proximity of the cutting edge [37]. The observed phenomenon of increased tool wear when the feed rate is raised can be attributed to two main factors: a decrease in the rate of heat dissipation [38] and an increase in vibration at tool-workpiece interface [39]. The reduction in R observed with rise in v can be attributed to the less thermal diffusion or heat transfer occurring between tool-workpiece at elevated cutting rates. Furthermore, the decrease in tool wear can be attributed to the reduction in the production of Build-up-edges (BUE) and the thermal softening of Inconel-718 at higher v. This is because the temperature of Inconel 718 can reach levels between 1100°C and 1300°C as the cutting speed increases, as indicated in literature [40], [41], and [42]. In their research, Anthony et al. [43] observed that the usage of MQL resulted in improvement in tool life at lower cutting rates in comparison with both dry and wet conditions.

Results of analysis of variance (ANOVA) are displayed in Table 4.3. This table provides information regarding the significance of each input factor on the variable R. The S and R-Sq values suggest that the experimental data may be employed to make predictions for subsequent data points. According to the data shown in Table 4.1, f accounts for the largest proportion of influence on wear rate (82.63%), followed by cutting speed (6.64%). These parameters are identified as the primary contributors to variations in wear rate (R).

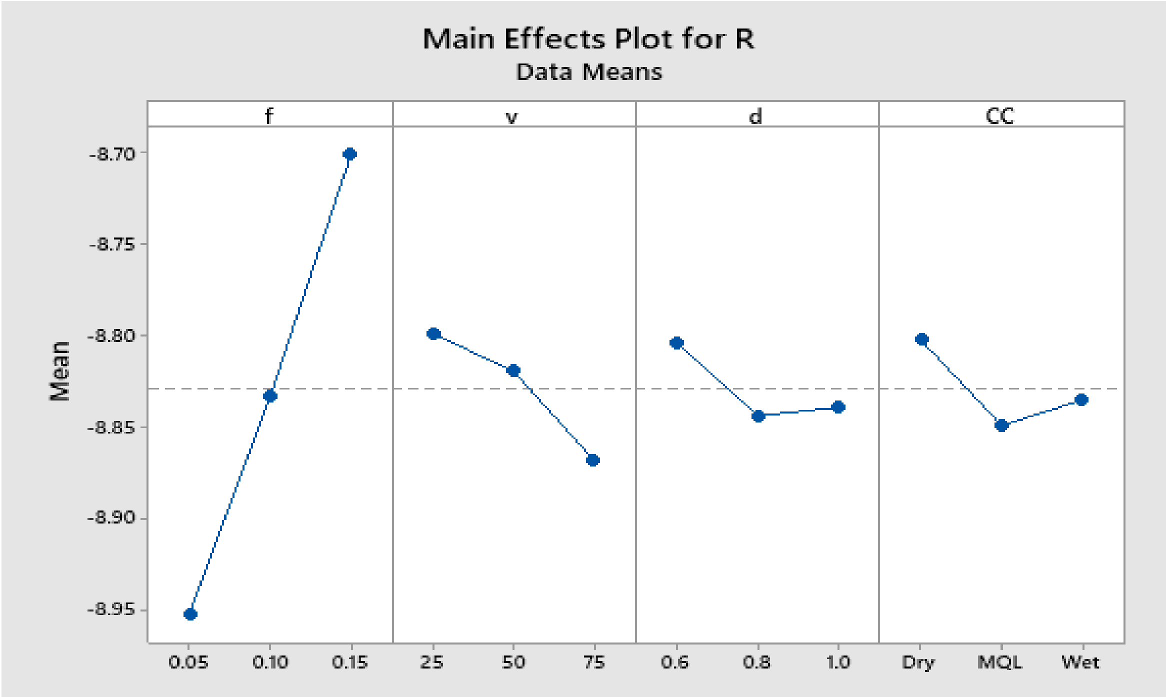


Figure 4.3; The main effect plot for R

4.2.4 Confirmatory Experimentation

The aim of current research is to examine the machining responses by using cooling conditions as an input cutting parameter in conjunction with other machining variables. The study methodology aims to observe the individual influence of each input variable and subsequently select specific values based on their respective contributions, to achieve favorable outcomes. In the current study, the output responses of Ra, SCE, and R were chosen on the principle of smaller being better. Taguchi technique is employed to forecast the optimal input parameter values, as seen in Table 4.5.

The validation of experimental data was conducted through confirmatory tests using both the optimal and worst combinations of input cutting parameters. The outcomes of confirmatory trials are compared with the most favorable and least favorable outcomes, specifically those achieved using Taguchi Analysis, as presented in Table 4.6. Results presented in Table 4.6 demonstrate the consistency of the confirmatory tests with the predicted patterns derived from the Taguchi Design of Experiments and ANOVA. Figures 4.4 and 4.5 depict the microscopic images corresponding to the situations of maximum and minimum tool wear, respectively.

Table 4.5; Best and worst response machining conditions

Output Response	Machining parameter				
		f (mm/rev)	v (m/min)	d (mm)	*CC*
R	Best	0.05	75	0.8	2
	Worst	0.15	25	0.6	1

SCE (J/mm^3)	Best	0.15	75	1	1
	Worst	0.10	25	0.8	3
Ra (µm)	Best	0.05	50	0.6	3
	Worst	0.15	75	0.8	1

Table 4.6; Comparison of initial runs result with the confirmatory test results

Responses	Conditions	Confirmatory test	Initial run	Percentage difference
R	Best	-9.122	-9.0263	30%
	Worst	-8.0871	-8.6546	58%
SCE (J/mm^3)	Best	0.48	0.66	27%
	Worst	27.60	27.60	0%
Ra (µm)	Best	0.17	0.2	15%
	Worst	2.83	2.83	0%

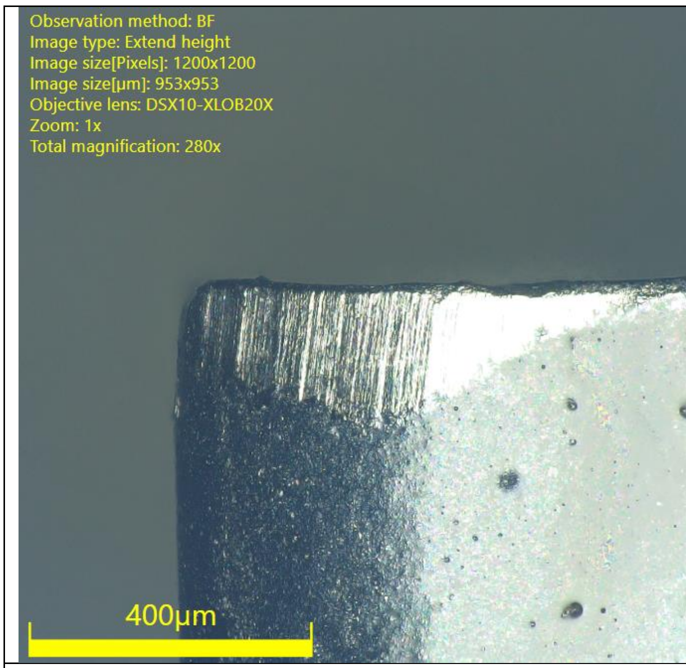


Fig.4.4: Optical image of Maximum wear (f=0.05, v=25, d=0.6, dry)

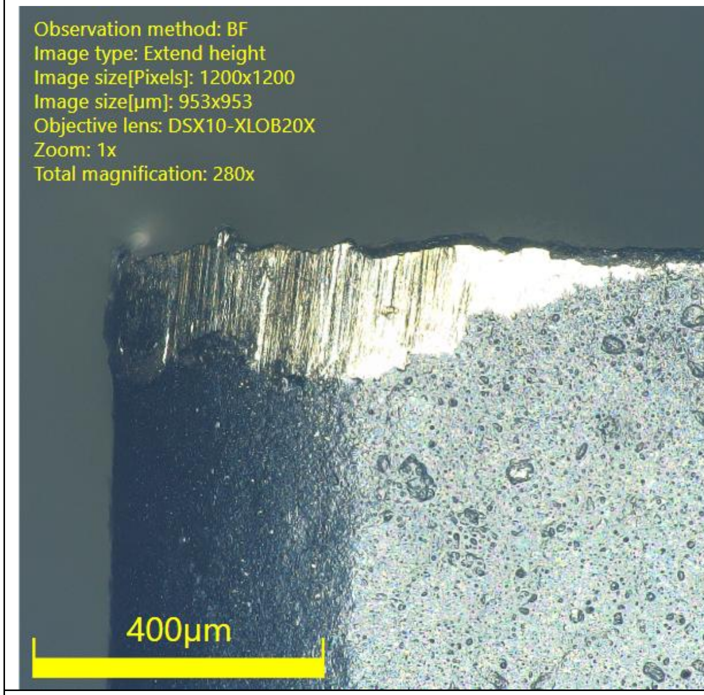


Fig.4.5: Optical image of Minimum wear (f=0.05, v=75, d=0.8, MQL)

5 CHAPTER 5: CONCLUSION

This study involved the turning of Inconel 718 in dry, MQL, and wet cutting conditions. The primary emphasis of this research centers on the examination and analysis of the sustainability, efficiency, and productivity aspects pertaining to machining operations. In the context of sustainability, the output parameter of specific cutting energy was chosen, while efficiency and productivity were evaluated based on tool wear and surface roughness. Based on the obtained outcomes, it is possible to draw the following conclusions. ANOVA analysis found that the most important factors to reduce surface roughness were cutting speed and tool coating.

- A substantial decrease in tool wear was seen with the implementation of MQL cooling conditions. Additional improvement of 30% in tool life observed when MQL turning was executed at the most favorable cutting conditions.
- The rate of tool wear was shown to be significantly impacted by the feed rate, which accounted for 82.63%. Cutting speed was also found to have a notable influence, contributing to 6.64% of the observed variation in tool wear.
- In comparison to machining under wet conditions, machining under minimum quantity lubrication (MQL) conditions results in a reduced consumption of specific cutting energy. A reduction of approximately 27% in energy usage was seen when machining operations were conducted using optimal machining settings.
- The cooling condition exhibited the greatest influence on the specific cutting energy (SCE), accounting for 63.43% of the observed variation. Cutting speed followed with a contribution of 18.56%, while feed rate contributed 10.15%. Conversely, the depth of cut had a relatively minor impact, accounting for only 7.78% of the observed variation in SCE.
- The surface roughness is shown to rise when the f increases. However, presence of coolant, which acts as a lubricant, leads to an improvement in surface roughness. A 15% improvement in surface roughness was observed when machining was conducted under wet conditions using optimal machining parameters.
- The feed parameter exhibited a substantial impact on surface roughness, accounting for 86.09% of the overall contribution. In contrast, the contribution ratios of cooling conditions, cutting depth, and speed were 4.08%, 3.18%, and 6.56% respectively.

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