بِسْمِ اللَّهِ الرَّحْمَٰنِ الرَّحِيمِ

Ultrasonic Assisted Micro Milling of Inconel 718

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Thesis Acceptance Certificate

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We hereby recommended that the dissertation prepared under our supervision by **Asim Ali Mirza** (00000274128) titled: "**Ultrasonic Assisted Micro Milling of Inconel 718)**" be accepted in partial fulfillment of the requirements for the MS Design and Manufacturing Degree with (___) grade.

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I certified that this research work titled "**Ultrasonic Assisted Micro milling of Inconel 718**" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledge/referred.

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This Thesis work has been done at School of Mechanical and Manufacturing Engineering (SMME) at NUST, Islamabad under the project *"**Ultrasonic Assisted Micro milling of Inconel-718**"* and is submitted in partial fulfillment of the requirements for the degree of Master of Science program in Design and Manufacturing (DME) at SMME, NUST University.

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DEDICATION

To my Beloved Parents,
Without whom none of my success
would have been possible

&

To my Respected Teachers,
Who acted like compass
that activated the magnets of
curiosity, knowledge and wisdom in me

&

*Engineer **Khush Bakhat** for having Believe in me*
and keep me Motivated thorough out my research

ABSTRACT

A super alloy with high temperature resistance, high corrosion resistance, and high strength is iconel-718, which is based on nickel. In the biomedical, aerospace, marine, and automotive industries, nickel-based super alloys are frequently used. The super alloy inconel-718 is difficult to machine and to cut. For greater surface roughness, little tool wear, and minimal burr formation, which produces better results than conventional micro milling, a methodology using ultrasonic assisted micro milling is developed to address this problem. This experimental investigation uses 0.5mm diameter cutting tools with various coatings, such as TiAlN, TiSiN, and nACo, to evaluate the effects of various machining parameters on surface roughness, tool wear, and burr development. With four levels and five parameters—cutting speed, feed rate, depth of cut, coating, and amplitude of tool vibration—Taguchi L16 array is used to create experiments. The analysis of variance is performed using Minitab software. It provides the percentage influence of each element, and we can identify the best and worst set of parameters to achieve the desired results using main effect plots. For multi-objective optimization, Grey Relational Analysis (GRA) is used to determine the best and worst parameter levels for each of the three answers. Confirmatory experiments revealed that ultrasonic aided micro milling produces better results than traditional micro milling with an amplitude of vibration of 9 m.

Table of Contents

Table of Contents 10
List of Figures 11
List of Tables 12
Chapter 1 Introduction 13
1.1 Research Motivation 14
1.2 Research Objectives 15
1.3 Research Scope 15
1.4 Why research on Burr formation 15
Chapter 2 Literature Review 16
2.01 Types of micro machining 18
2.02 Ultrasonic Machining: 18
2.03 Ultrasonic Assisted Micro Milling 19
Chapter 3 Experimental Setup 21
3.01 CNC Machine Details and Setup 21
3.02 Work piece Material Preparation and Characteristics 23
3.03 Cutting Tool Specifications 24
3.04 Selection of machining parameters: 24
3.05 Measured responses: 25
3.06 Design of Experiments 27
Chapter 4 Results and Discussions 29
Chapter 5 Multi-Objective Optimization 37
Chapter 6 Conclusion and Future Recommendations 51
References 53

List of Figures

Figure 01 A comparison of micro aching and other machining techniques	13
Figure. Development in micro machining	17
Figure 3 Experimental setup used for ultrasonic assisted micromachining	21
Figure 04 Different coated micro tools used in the experiments.	22
Figure 05 Ultrasonic setup	22
Figure 06 Machined Slots	23
Figure 07 Microscopic image cutting edge of Different tool	24
Figure 08 Olympus setup used for measurement of responses	25
Figure 09 Optical image showing maximum burr measurement, tool wear	26
Figure 10 Machined Slots Surface Roughness Microscopic image	27
Figure 11 Methodology	28
Figure 12 Main effect plots for Surface Roughness	30
Figure 13 Main effect Plot for Tool Wear	32
Figure 14 Main effect plots for Burr Down Milling	34
Figure 15 Main effect plots of Burr Up milling	36
Figure 16 Pareto Chart GRG	40
Figure 17 Normal Probability Plot GRG	41
Figure 18 Histogram	41
Figure 19 Contour Plots of GRG	45
Figure 20 Surface Effect plots of GRG	48
Figure 21 Optimized Solution	50
Figure 22 Confirmatrory Slots	50

List of Tables

Table 01 Micro milling capabilities. 18

Table 02 Experimental Setup and Conditions. 23

Table 03 Chemical Composition of Inconel-718. 23

Table 04 Details of Tools are given in table. 24

Table 05 presents the Selected Parameters and their Levels. 25

Table 06 The details of Olympus microscope. 26

Table 07 The best and worst responses obtained from cutting conditions. 29

Table 08 Experiments using L16 orthogonal array and their responses. 31

Table 09 Response for combine signal to noise ratios for down milling burr for smaller is better 33

Table 10 GRC and GRG calculated from responses. 39

Table 11 Analysis of variance of GRG. 42

Table 12 Optimized run-in comparison with the best experimental run. 50

Chapter 1

Introduction

Manufacturing processes and techniques are reorienting toward tiny scale components as technology advances and strives to minimize component size as much as feasible. There is a need for micro- and nanoscale research because of the rising need for small-scale components. The methods of micromachining, which include micro-scale milling, turning, and drilling, removes material in the form of chips from 0.1 m to 100 m in size[1]. The improved precision of tiny scale components requires very accurate tools and machinery. The status of micro machining in relation to other material-removal machining techniques is depicted in Fig. 1 in terms of size and precision. Macro machining equipment, methods, techniques, and materials have been the subject of much research over the past two decades, and transitioning to the micro sector is not as straightforward as scaling down macro domain attributes. Therefore, further research is required to comprehend the technical aspects of micromachining.[2]

Super alloys often contain nickel, chromium, cobalt, or nickel-iron as their basis metal. These materials are employed by the commercial gas turbine, aerospace, and marine turbine sectors, among others. The nickel chromium alloy Inconel 718 offers outstanding mechanical qualities at high temperatures (up to 1300°F),[3] as well as strong strength and durability against corrosion. Because of its high tensile strength and work-hardening properties, it is important to choose the right tool materials, tool coatings, and operating settings. Numerous studies have been conducted on various machining processes for various kinds of materials. Today's market has seen an upsurge in demand for micro components.[4] New alloys have been developed for a long time, but little study has been done on the many elements of micro machining on extremely hard alloys. This research is also being driven by the rise in need for the delicacy of micro components.[5]

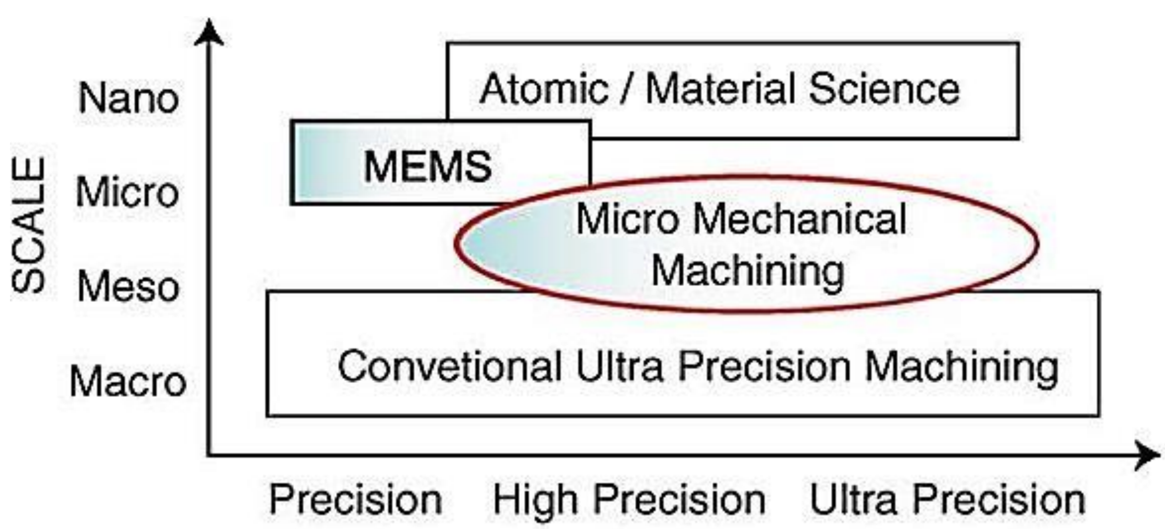


Figure 01 A comparison of micro aching and other machining techniques

1.1 Research Motivation

As the science advances the need for micro parts is always in demand. machining of these micro parts is not easy. We need the micromachining parameters which can give us the best surface finish and tool wear should be minimum with burr formation should also be Reduced.From literature we ca conclude that Ultrasonic assisted micro milling results in better surface finish, less tool wear and reduced burr formation.[6]so Ultrasonic assisted micro milling can be used for micro milling for hard to cut materials like Inconle-718.Burr formation always occurs during mechanical machining, whether it is macro- or micro-machining. Compared to micro-machining, deburring is simple when using macro-machining. Deburring can harm the work piece as well as sensitive micro features in micro components[7]. Additionally, deburring is quite expensive since it necessitates complicated assembly procedures. Therefore, using the deburring procedure to reduce burr is undesirable.[8]

The major issue with mechanical machining is burr formation. It happens during both macro and micro machining processes. In macro machining, burr removal is simple and requires a different technique because of the larger burr size, but in micro machining, burr removal is challenging because of the smaller burr size and the high degree of precision needed to avoid damaging the component during the deburring process. Additional steps are done to reduce burr development during the micro milling process. When burrs formed during the micro-machining of Inconel 718, AJ Mian found that the best conditions were mostly for uncoated and AlTiN Coating tools with a 0.5mm diameter and a minimum chip thickness.[9] Little information was discovered when he researched the micro manufacturing process for a wide variety of cutting speeds on how the cutting speed affects burr development. Therefore, we will use similar cutting speeds with various tool coatings to examine the impact of cutting speed on burr development. According to the literature review, high cutting speed is more efficient for micromachining operations, therefore less information is available on low cutting speed work and more work has been done at high cutting speed.As opposed to high-speed milling equipment, low speed milling setup is more accessible and cost-effective. Therefore, we will focus on slow cutting speed (conventional machining range). Observe how tool coating affects burr development at low cutting speeds.

1.2 Research Objectives

- To do research on the **ultrasonic assisted micro milling processes for different super alloys** provided in the literature.
- To identify the **processing parameters for characterization** of the ultrasonic assisted micro milling.
- To investigate the structural characteristics like **surface roughness, burr formation and tool wear** resulted from the ultrasonic assisted micro milling.
- To **optimize the processing parameters** for improved surface finish, lesser burr formation and minimized tool wear.

1.3 Research Scope

This study is restricted to the Ultrasonic assisted micro-end milling of Inconel 718 utilizing a TiAlN,TiSiN, nACo, And Un-coated, 0.5mm-diameter carbide end mill with a cutting speed between 8 and 12 m/min below 8000 rpm. As opposed to high velocity machining equipment, low speed machining equipment is more accessible and cost-effective. We will thus focus on low cutting conditions (conventional machining range). Observe how tool coating affects burr development at low cutting speeds.

1.4 Why research on Burr formation

In drilling and milling, burrs can develop. The tool life is extended by less burr development. Because burrs on small manufactured components cannot always be removed by post-processing, the reduction of burr growth in micro-machining is crucial.

The use of traditional machining has long been hampered by issues including burrs, poor edge polish, and surface flaws. Through process improvement and post processing, some of these issues have been eliminated. Due to intrinsic material properties or restrictions in component shape, these issues are equally relevant in micromachining and necessitate much closer attention. This is because many times, solutions utilized in macro machining are not applicable due of these issues.

Chapter 2

Literature Review

The requirement of new materials and assembling techniques is highly desired as time goes on and innovation progresses according to plan. As we strive to create small, space-saving parts, the advancement in technology is also pushing us toward the need for tiny, miniature machine parts, which forces us to find a conventional solution to cutting-edge problems. Currently, standard machining techniques have been developed to the stage of micro machining for the needs of miniature parts, and this comes with a lot of benefits that make them better than conventional machining techniques. The creation of tiny components requires special frameworks that can do the required tasks at microscopic scales, so it is undoubtedly a difficult task. Advancements in small-scale machining frameworks are required in order to achieve the high durability, high trustworthiness, greater dependability, and reparability that these small parts must possess.[10]

A machining cycle known as "minuscule machining" can provide us tiny components with dimensions ranging from 1 micrometer to 999 miniature meters, or it can remove material from tiny levels (e: g Micro milling). Researchers have had the option to consider modern miniature machining processes like Ultrasonic helped miniature machining, Electronic Discharge machine, Ultrasonic helped Laser machining, and Electro compound machining to overcome the challenges for the assembly and creation of scaling down of parts as advancements occur in conventional machining processes. Smaller than expected machining procedures have progressed because of the utilization of scaled down parts in enterprises like aviation, biotechnology, medication, and correspondence. We are needing new materials for these applications, for example, hard, fragile, pottery and Super combinations like Titanium compounds and Nickel Alloys (Inconel-718). To machine these materials for miniature parts we really want micromachining strategies. [10]Ultrasonic helped Micro processing is one of the most recent methods for these materials hard to cut materials like Nickel Alloy (Inconel-718).

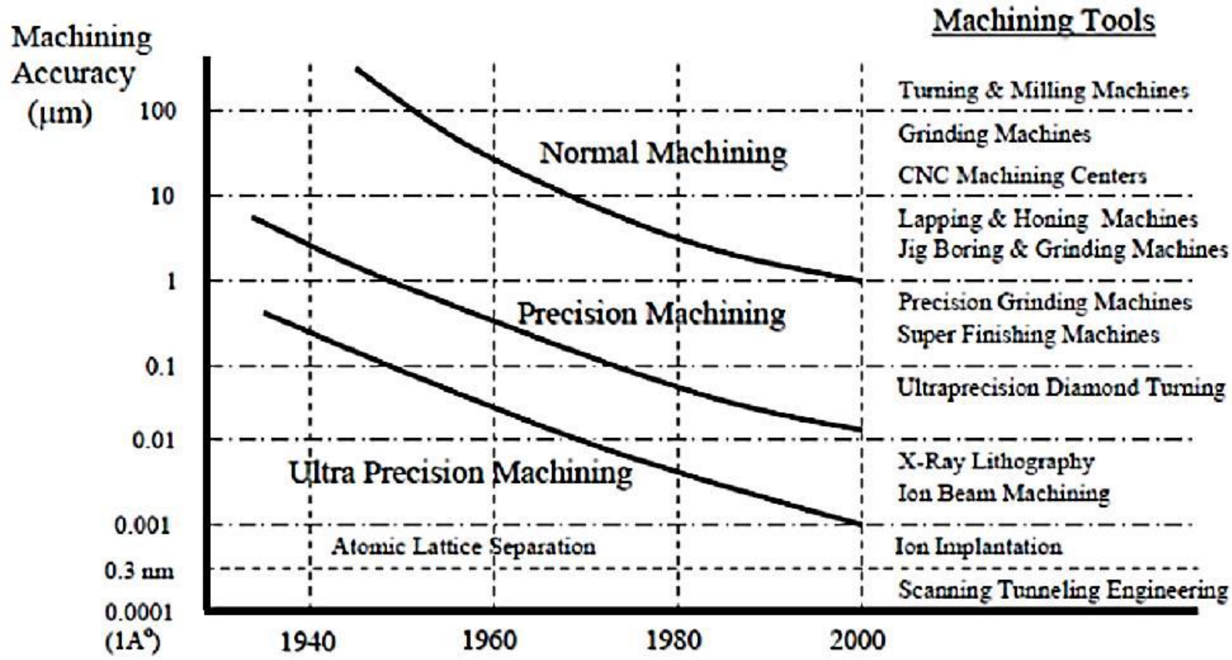


Figure 02 Development in micro machining

Because of the employment of smaller-than-expected parts in industries including aircraft, biotechnology, medicine, and correspondence, machining techniques have advanced. For these uses, we need novel materials, such as hard, delicate pottery and super combinations like Titanium compounds and Nickel Alloys (Inconel-718). Micromachining techniques are what we actually need to process these materials for tiny parts. the use of ultrasound One of the most current techniques for these difficult-to-cut materials, such Nickel Alloy, is micro processing (Inconel-718).[11]In comparison to full-scale produced components, testing, handling, and gathering miniature mechanically made parts is challenging due to their small size. The testing of small mechanically made pieces has not yet been completed in full..[2]For the most part, the following three parameters—DOC (depth of cut), cutting rate, and chip load—are used in miniature processing processes. It also depends on a number of parameters, such as the device material, the equipment covering the work piece, and so on.[12]

Table 1 Micro milling capabilities

Machining Principle	Mechanical ablation (defined cutting edge)	**Removal Rate/Machining Time**	Medium...low/ Hours..days
Tool Type	end-mills	**Minimum Structure Details**	>5 µm (sub-µm for SPD milling)
Tool Material	Carbide, HSS, Diamond	**Maximum Aspect Ratio**	Typ. 10
Min. Tool Size	<50 µm ... 125 µm	**Accuracy**	1...3 µm (sub-µm for SPD milling)
Workpiece material	Ductile materials: polymers, copper, aluminum, graphite, green ceramics, steels	**Surface Finish (Ra)**	<0.1 µm

SPD: single point diamond

2.01 Types of micro machining

Following are different types of micro machining.[5]

1. Laser Technology
2. Micro-Ultrasonic Machining
3. Mechanical Micromachining
4. Micro-Electrochemical Machining

2.02 Ultrasonic Machining:

In the process of ultrasonic machining, external energy is added to the work piece or tool and it is vibrated using ultrasonic repetition. It should be feasible to use ultrasonic machining on a variety of machining processes, including ultrasonic turning, ultrasonic drilling, and ultrasonic milling.[8]

The idea was first presented by R. W. Wood and A. L. Loomis in 1927 and was first Patented by L Balamuth 1945.

If we talk about how ultrasonic machining works, we will see that a transducer that is positioned at the end helps convert electrical energy into mechanical energy. The gadget tip will vibrate longitudinally thanks to this transducer. The Tip gadget vibrates with a frequency of about 20 KHz and a range of up to 50mm. The contact can be improved by using an abrasive slurry. Silicon carbide, boron carbide, and other types of carbide are mixed with either water or oil to create the slurry substance. The tool's vibration causes the slurry particles to move around inside the device and on the work piece, which eventually results in material cutting.[13]

2.03 Ultrasonic Assisted Micro Milling

Processing is a machining cycle where instrument is pivoted and Work piece is static concerning the device development. Likewise, miniature machining is an interaction where miniature devices are utilized for the miniature aspects to accomplish with high close resistance levels. The measurement of hardware in miniature processing is typically in microns as the aspects are. Ultrasonic helped miniature processing is a processing cycle where the processing is finished on miniature level and is finished with the assistance of ultrasonic vibration movement given to the devices or work piece. Ultrasonic helped miniature processing is progressed method for the creation of miniature parts and has extensive variety of use like free structure optic focal point and complex calculations and miniature designs. As these applications requires a complex method on the grounds that a little mistake will the surface of the part. To beat this issue ultrasonic helped miniature processing is finished.[13]

With its unique advantages, such as reduced cutting power, decreased cutting temperature, increased instrument life, improved assembling steadiness, and chip-breaking impact, fast ultrasonic cutting (HUVC) has recently been recognized as a proficient and potent non-traditional slicing interaction to increase the machinability of materials. The appropriateness of HUVC to deliver three different types of difficult-to-machine materials has been established in previous studies. These materials are toughened steel, super alloys based on nickel, and titanium alloys Sui et al. found that, when spinning Ti-6Al-4V at high rates (200-400 m/min), HUVC has a substantial impact on chip breakage and can reduce slicing force by up to 50%[10].

They arrived at the goal that the cutting may be reduced by a restriction of 55%. high cutting rates (200-500 m/min) with high-pressure coolants (HPC) inside seeing HUVC gave 7.3 times the gadget future over customary cutting (CC) exercises.[9]

Nonetheless, to the extent that the author knows, there isn't sufficient information on vibration-helped miniature processing of nickel composite inconel-718. Especially on how vibration impacts with various Tool Coating and Depth of Cut the impact during the UVAM cycle, there hasn't been any distributed exploration. This paper explores an UVAM with Tool vibration. With the vibration given to instrument, we did precise vibration-helped miniature processing investigates Inconel-718 analyze the effects of vibration boundaries alongside other machining boundaries on size impact, surface quality, and Tool Wear and find the best and most awful blend of boundaries for Ultrasonic helped miniature processing of Inconel-718.

Chapter 3

Experimental Setup

3.01 CNC Machine Details and Setup

The Inconel 718 (nickel composite) was the object of the tiny processing experiments, which were carried out using a FANUCMV-1060 standard speed machining focus, as shown in figure 3. A FANUC 0i-MC movement regulator controlled the entire movement between the work piece and processing tool during the micromachining process. A carbide end factory with an 08mm width was used to initially level out the work piece's surface, which was then utilised as a standard. In the z-pivot, a device pre setter was employed to make precise predictions. The device has been subjected to 1D vibrations using a 3-kW piezoelectric transducer, an MPI ultrasonic generator, and high-recurrence electrical stimulation from a 50 KHz electrical source (ACROW MACHINERY MANUFACTURING COMPANY LTD TAIWAN). These beats with a high frequency high- pulses after entering the transducer, are transformed into ultrasonic-frequency mechanical vibrations (23 kHz). Fig 4

Figure 3 Experimental setup used for ultrasonic assisted micromachining

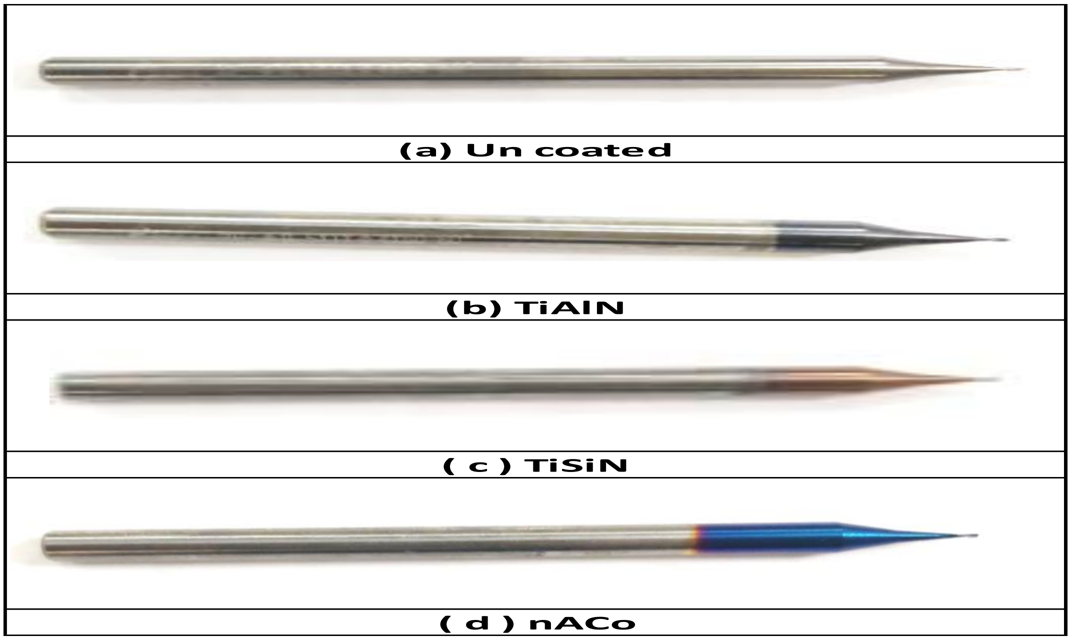


Figure 04 Different coated micro tools used in the experiments.

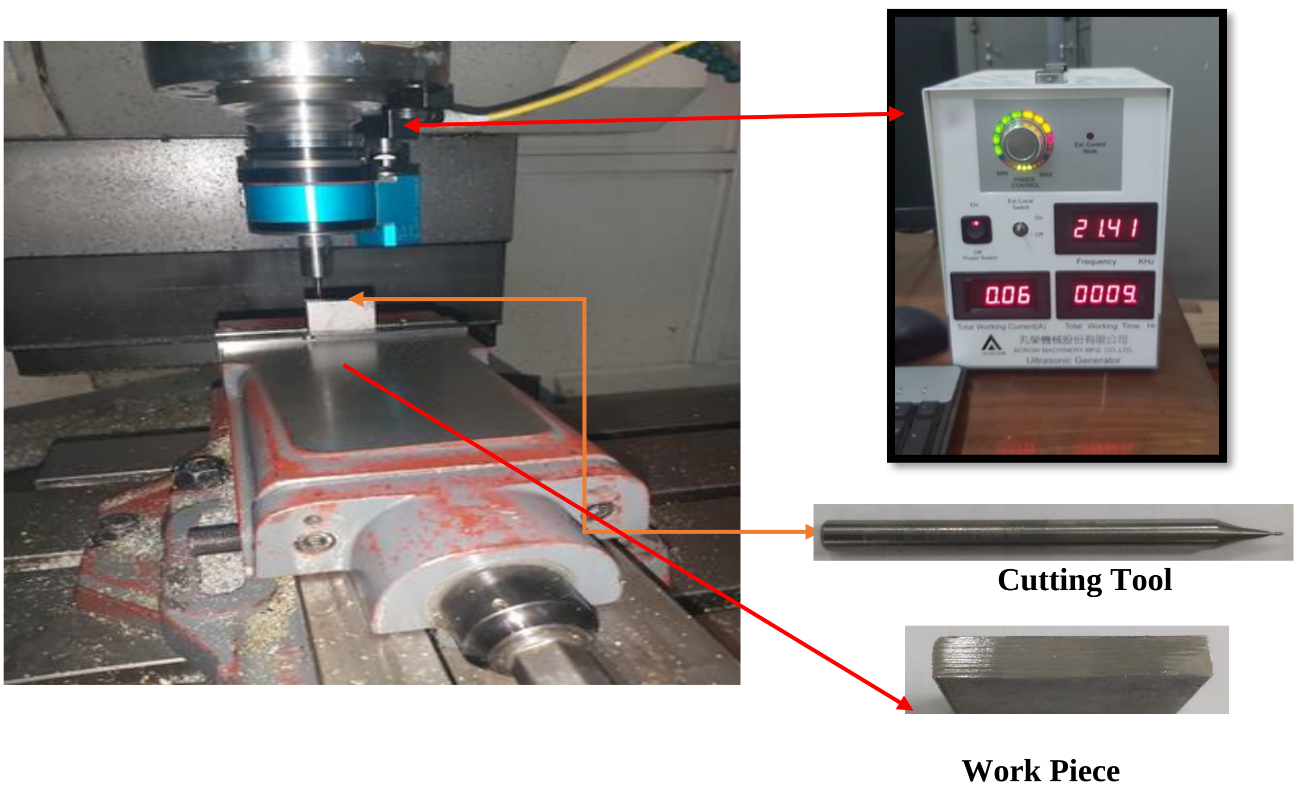


Figure 05 Ultrasonic setup

Table 02 Experimental Setup and Conditions[14]

Work piece Material	**Inconel -718**
Tool Diameter	0.5mm
Number of Flutes	02
Cutting Length	10mm
Cutting Condition	Dry
Milling Type	Full immersion

The work piece was created utilising electric discharge machining and has dimensions of 10 x 50 x 50 mm (EDM). According to Figure 06, the slot's cutting length for the tests was set to 10 mm. Slots are spaced 1 mm apart. Prior to the start of each experiment, the static runout of the cutting tool was measured at the cutting tool's shaft region using a dial gauge. It was discovered that the typical runout values were less than 3mm.

Table 03 Chemical Composition of Inconel-718[8]

Element	**Ni**	**Cr**	**Fe**	**Nb**	**S**	**Ti**
Weight by %	54.59	19.16	18.66	4.85	1.69	1.05

3.02 Work piece Material Preparation and Characteristics

The finished item was first ground and polished. The irritation was then treated with waterless Kalling's chemical for about 5 seconds before being cleansed with water. The Vickers hardness of Inconel 718 was measured using a Vickers Micro hardness tester (HBRVU- 187.5 Times Group Inc., Beijing, China). To verify accuracy, five tests were run in five distinct places. A force of 9800 Nm and a dwell period of 6 s were used in these tests. There was discovered to be 361 HV micro hardness.

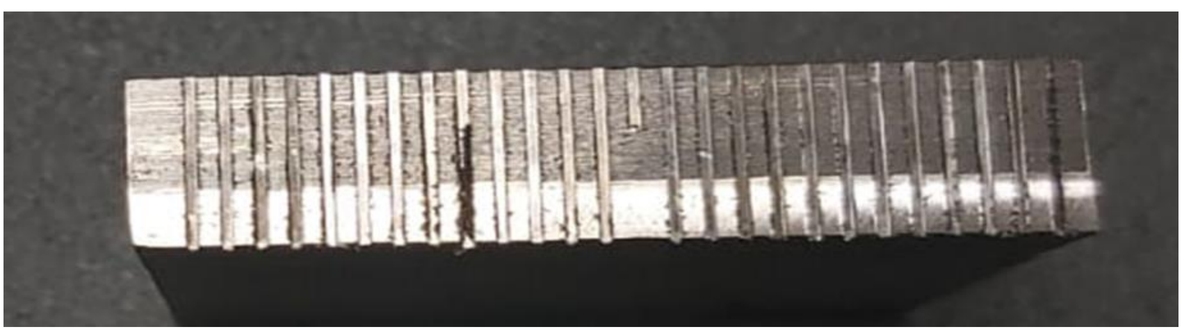
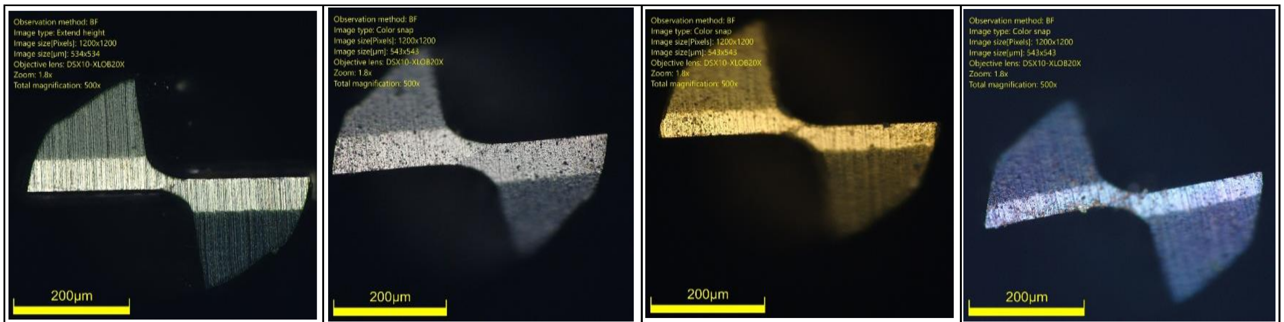


Figure 06 Machined Slots

3.03 Cutting Tool Specifications

Tungsten carbide flat end mills which are Titanium Aluminum Nitride (TiAlN), Titanium Silicon nitride (TiSiN), Aluminum Titanium Nitride + Silicon Nitride (nACo) and Uncoated fig 04 are from China, were used to make the cutting tool, which had a tool diameter of 0.5 mm as shown in figure 07.



(A) Un Coated | (B) TiAlN | (c) TiSiN | (D) nACo

Figure 07 ***Microscopic image cutting edge of Different tool***

Table 04 Details of Tools are given in table.

Detail	Information
Brand Name	Changzhou North Carbide Tool Co
Material	Tungsten Carbide steel
Type	End mill
Number of Flutes	02
Diameter(mm)	0.5
Overall Length(mm)	50
Rockwell hardness (HRC)	60
Coabalt Content (%)	12
Balde Length(mm)	1
Helix Angle	35
Grain Size	0.5
Flexural Length	4300

3.04 Selection of machining parameters:

In this focus, four machining parameters—Speed, Feed, Depth of Cut, and Amount of Hardware Vibration—are evaluated along with three different types of coating—TiAlN, TiSiN, nACo, and uncoated. Surface Roughness, Tool Wear, and Burr Arrangement as Written are Affected by These Boundaries. The levels and ranges of these information boundaries were chosen in consideration of literature [2], [42] pertaining to ISO principles and tool manufacturing guidelines (Cutting

Speed 6-10.5 m/minute, Feed 0.25-0.9 m/tooth, Depth of cut 30-50 m, Amplitude 0-9 m, Coatings TiSiN, TiAlN, nACo, Uncoated).

Table 05 presents the Selected Parameters and their Levels.

Parameters	Level 1	Level 2	Level 3	Level 4
Speed(m/min)	6	7.5	9	10.5
Feed(μm/tooth)	0.25	0.5	0.75	0.9
Depth of Cut(μm)	35	50	70	90
Coating	Uncoated	TiAlN	TiSiN	nACo
Amplitude	0	3	6	9

3.05 Measured responses:

Four reactions are estimated in this concentrate as surface Roughness, Tool Wear, Burr Formation in Up processing and Burr Formation in down processing. Surface harshness, device wear and burr development is estimated utilizing DSX programming utilizing amplification of 200μm.Using a magnifying lens, which empowers the recognizable proof of miniature surface surfaces in processing tasks, the surface unpleasantness of each space was estimated. The ISO 4287 standard is utilized to evaluate surface unpleasantness in micrometers[14]. To gauge these reactions Olympus Digital magnifying lens is utilized figure 06. DSX magnifying lens is utilized for estimation of hardware wear with amplification of 100μm for each Flute edge that has break down and the standard utilized for this is ISO8688-1 and ISO8688-2.as displayed in figure 07.

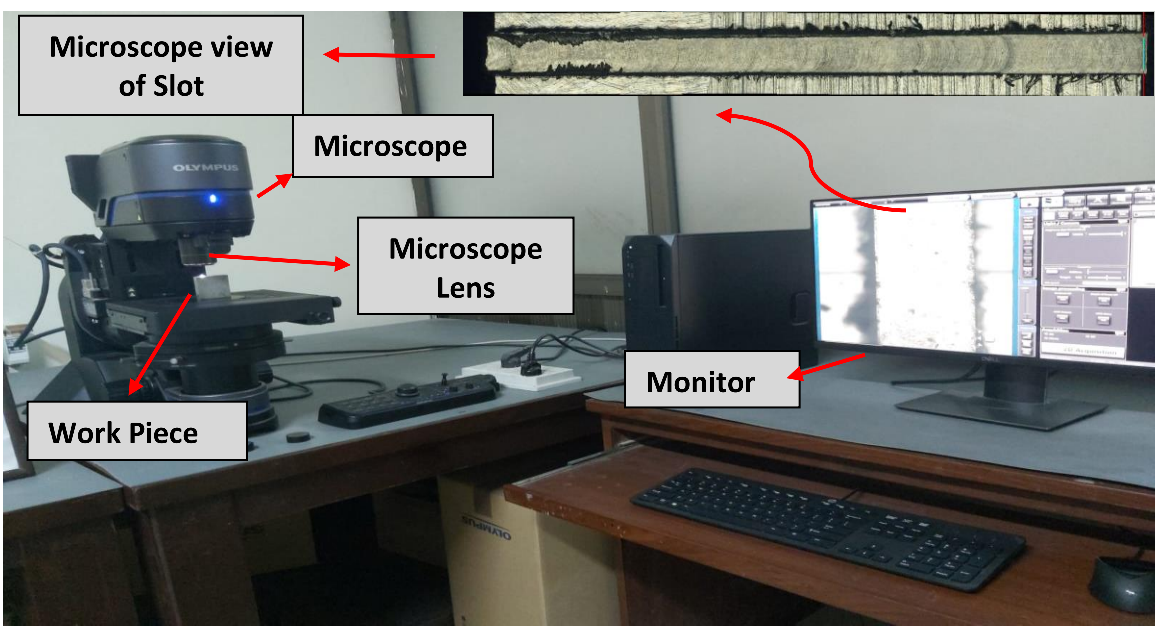
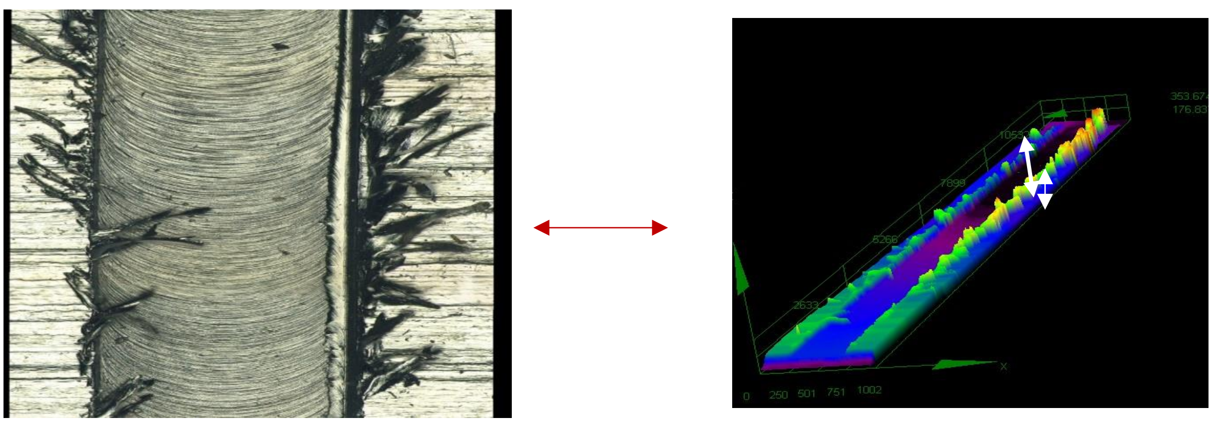


Figure 08 Olympus setup used for measurement of responses

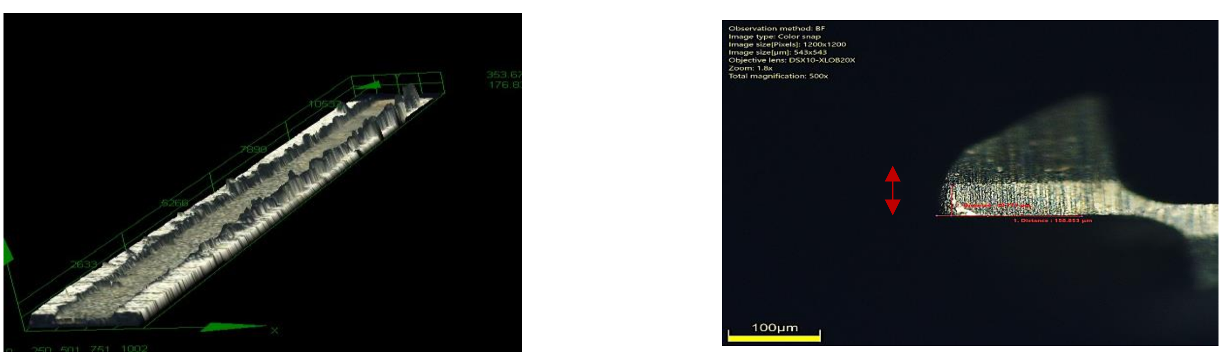
Table 06 The details of Olympus microscope

Brand	**OLYMPUS DSX**
Optical system	Telocentric optical system
Zoom ratio	10X (motorized)
Maximum total magnification (on a 27-inch monitor)	8220X
Working distance (W.D.)	66.1 mm – 0.35 mm
Image sensor	1 / 1.2 inch, 2.35-million-pixel color CMOS
Frame rate	60 fps (maximum)

There are various different burr places that can foster notwithstanding the top, leave, entry, and base burrs. The ebb and flow research focused on estimating the top burr width and level with a checking magnifying lens at different amplifications as per burr width and level. The burr arrangement explores estimated the most extreme burr width and level for each opening as figure.



(a) Maximum Burr Width (b) Maximum Burr Height



(c) 3D Image of Slot (d) Maximum Tool Wear

Figure 09 Optical image showing maximum burr measurement, tool wear

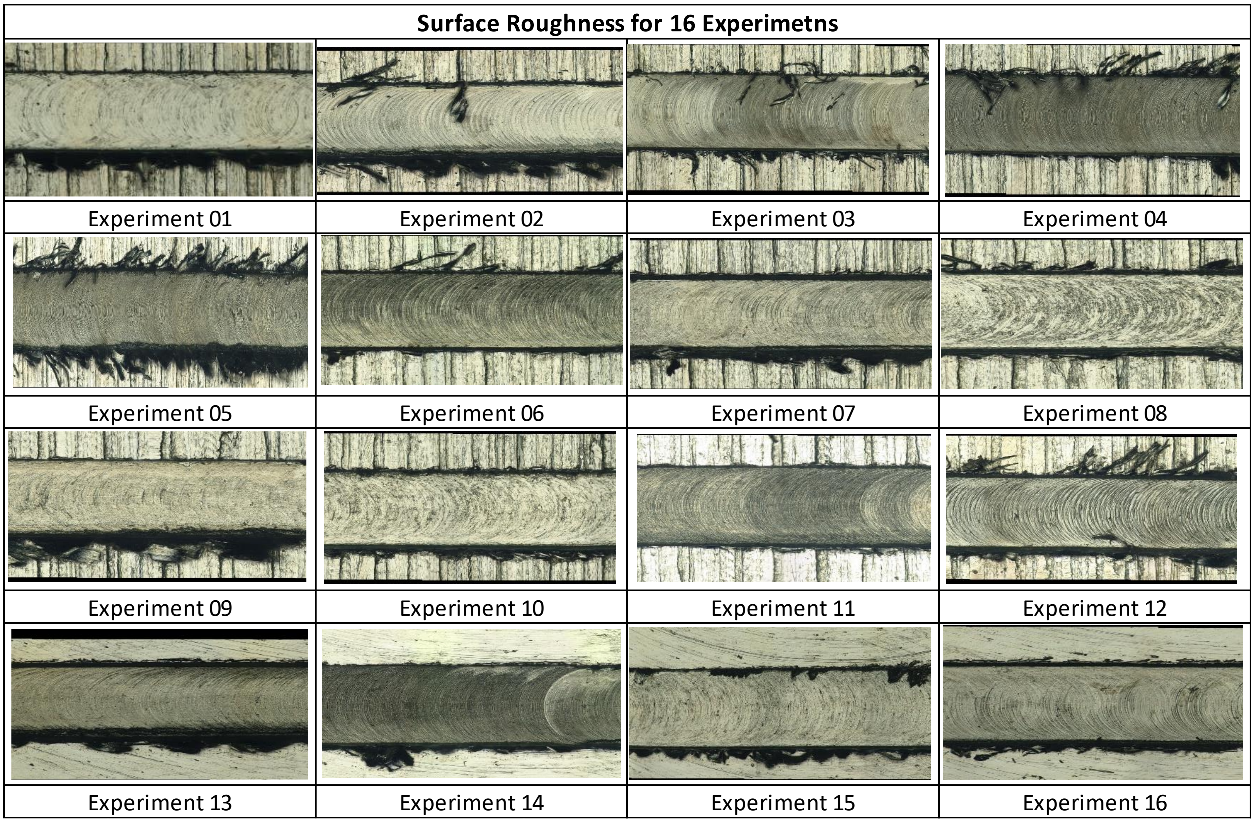


Figure 10 Machined Slots Surface Roughness Microscopic image

3.06 Design of Experiments

An orthogonal L_{16} array was developed using the Taguchi design of experiments [15], [16]. Due to its effectiveness in requiring fewer runs, the Taguchi approach was preferred [17]. It is well known that Taguchi orthogonal arrays that are used in accordance with the factors and their levels give definitive findings [18]. It has been successfully employed by several studies in the past[11], [14], [19] In order to measure responses twice, experimental runs were repeated. Average values of measured responses are shown Table 06 in relation to their combinations of machining parameters[20], [21]. Main effect plots are used for finding of best and worst combination of parameters based on smaller the better as we need minimum value of our responses. In this study, ANOVA is used to find the main machining contributor to responses and its percentages. In this study, the response surface method is used to optimize many answers under different input parameters. First, each response parameter is examined in main effect plot. Using the Grey relational technique, a regression model for the GRG is created. The optimal model condition is then verified.

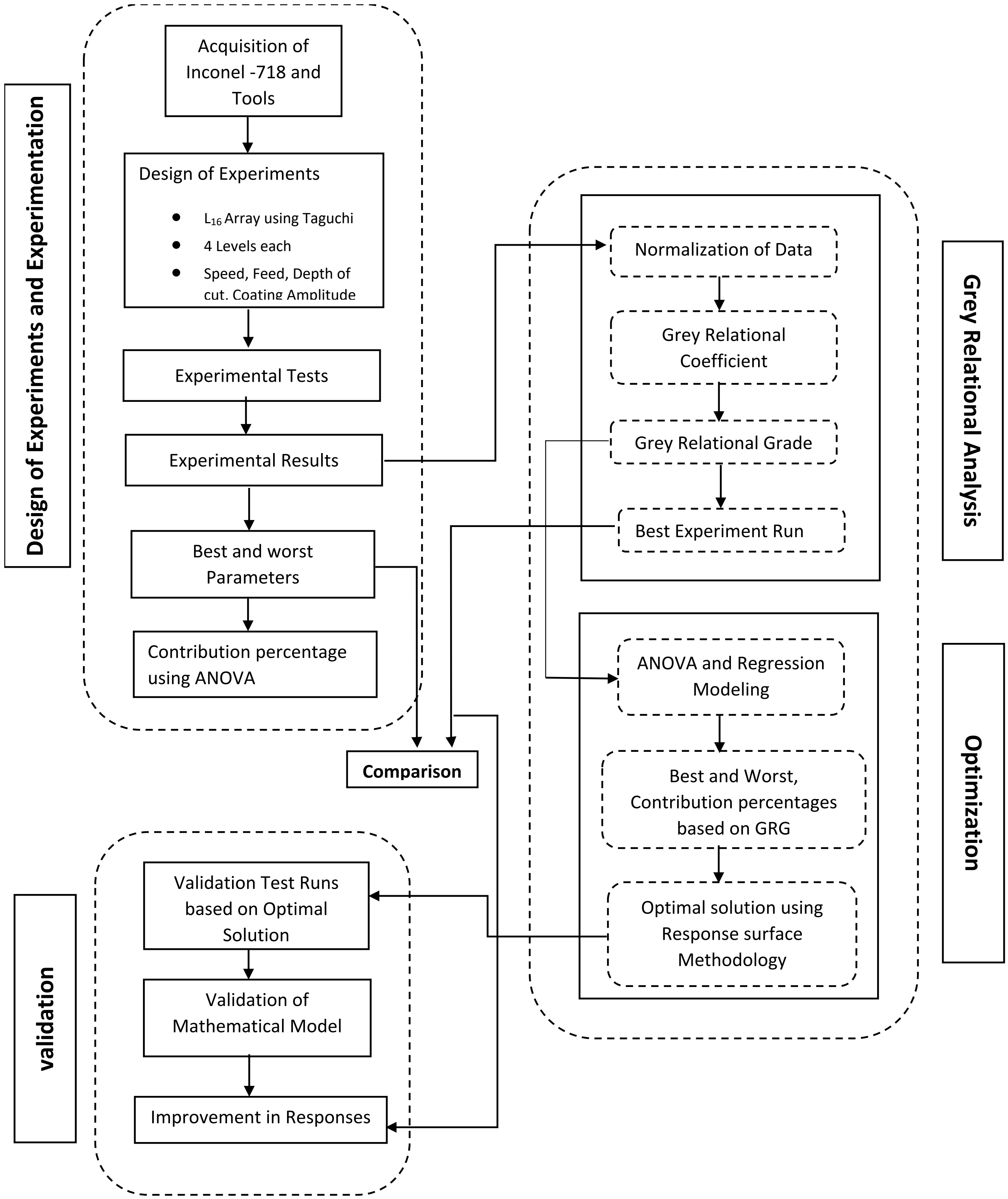


Figure 11 Methodology

Chapter 4

Results and Discussions

4.01 Surface Roughness

Metal surface roughness was influenced by the feed rate to the cutting-edge radius, the speed of the cut, the depth of the cut, and tool coatings.[22] Chip deformation removes the material because most of the feed/tooth are below the radius of the cutting edge and the material heat bends easily. Due to tool friction and chip deformation in the absence of grooves, this type of chip reduces surface roughness and increases burr growth[23]. A nACo-coated tool reduced surface roughness by cutting more quickly. The surface roughness of the TiSiN-coated tool was second-best. The smoothest tools had nACo coating. This is because wear leads to surface roughness, and nACo tools are harder than the other two coatings.[24] The lower surface roughness may be due to the reduced BUE forms on surfaces machined using nACo coated tools. At a greater axial depth of cut, high temperature is produced during micromachining procedures as a result of increased friction between the work piece and the tool's cutting edge. It also intensifies vibration of the tool and cutting force, which elevates surface roughness levels.[25], [26]. A reasonable surface quality is produced up to the minimal chip thickness, but beyond that point, the surface roughness begins to increase due to an increase in ploughing and cutting force. [2] We can see that surface roughness is significant at low speed and improves at high speed, but for feed it first reduces, then increases, and finally improves at the greatest feed level. This is due to the thermal softening effect, as seen in the main effect plots in Figure 11.

Table 07 The best and worst responses obtained from cutting conditions

Responses	**Cutting Conditions**					
		Speed (m/min)	Feed (um/tooth)	Depth of cut(um)	Coating	Amplitude (um)
Surface Roughness	Best	10.5	0.9	50	nACo	6
	Worst	6	0.5	90	uncoated	0
Tool Wear	Best	7.5	0.75	50	Uncoated	9
	Worst	10.5	0.5	90	TiAlN	3
Burr Height Down Milling	Best	6	7.5	70	nACo	9
	Worst	10.5	0.25	30	TiSiN	6
Burr Width Down Milling	Best	6	0.75	30	Uncoated	9
	Worst	10.5	4	90	TiSiN	0
Burr Height up Milling	Best	6	0.9	70	TiAlN	4
	Worst	10.5	0.75	90	nACo	0
Burr Width Up Milling	Best	6	0.9	50	TiAlN	0
	Worst	10.5	0.25	90	nACo	9

Surface roughness is better when cutting at a shallower depth, and it gets worse as the depth of cut grows because the forces and vibration of the tool are smaller at shallower depths, and as a result, the surface roughness gets worse at deeper depths. The interaction between the tool and the work piece decreases as the amplitude rises, which can improve tool wear and surface roughness. According to the Anova study, the contributions for surface roughness are as follows: depth of cut (34.13%), feed (27.03%), coating (14.16%), amplitude (13.26%), and speed (5.81%).

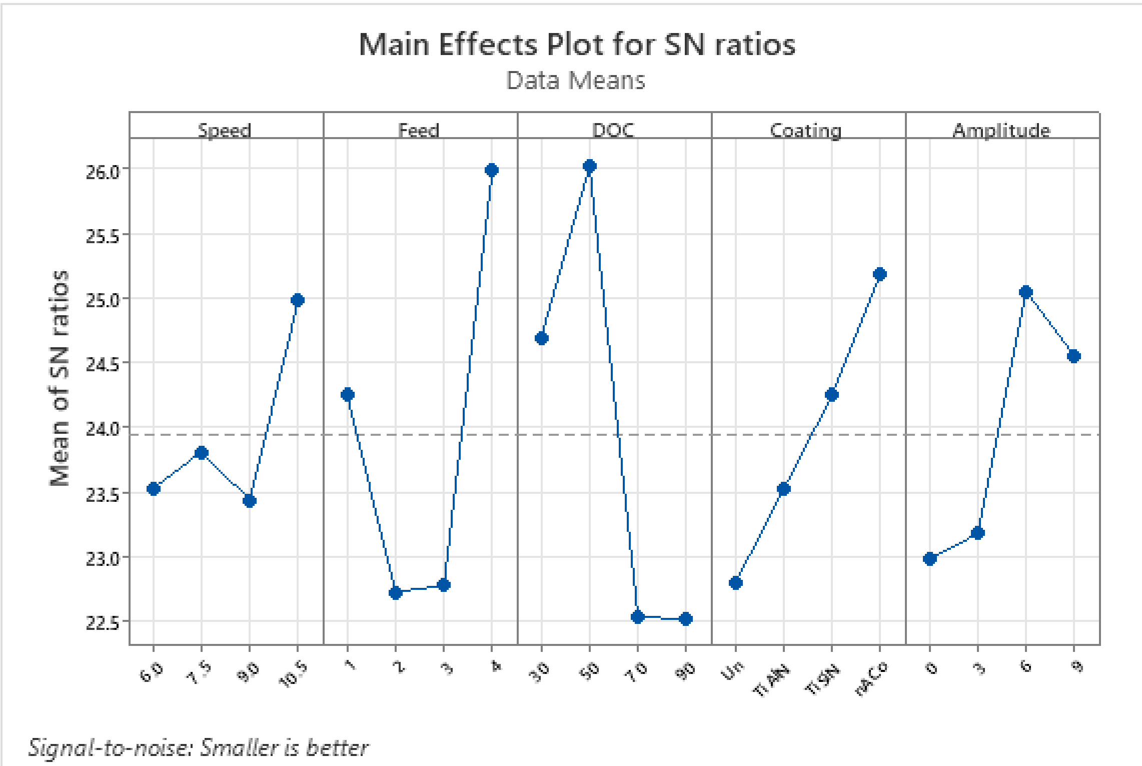


Figure 12 Main effect plots for Surface Roughness

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Speed	3	0.000685	5.81%	0.000685	0.000228	5.54	0.008
Feed	3	0.003184	27.03%	0.003184	0.001061	25.74	0.000
DOC	3	0.004020	34.13%	0.004020	0.001340	32.51	0.000
Coating	3	0.001668	14.16%	0.001668	0.000556	13.49	0.000
Amplitude	3	0.001562	13.26%	0.001562	0.000521	12.63	0.000
Error	16	0.000660	5.60%	0.000660	0.000041		
Total	31	0.011779	100.00%				

4.02 Tool Wear:

The most important tool life indicator, which also affects surface roughness and product quality, is thought to be flank wear[27]. This is a result of the tool flank making direct touch with the newly created work piece surface. In the field of micromachining, tool flank wear therefore becomes increasingly critical due to the importance of surface quality in micro-components. [[18].The micro milling technique's chip adhesion and high temperature inside the tool tip area provide a clear built-up edge[28], [29]. A built-up edge will increase the arc radius of the tool tip[30], enhancing the ploughing impact during the ensuing cutting phase. Preventing the formation of built-up edges is essential for improving surface quality since Wang et al research's [31]indicates that the existence of built-up edges is the main factor affecting surface quality. At a given spindle speed rpm, uncoated tools wore down less quickly than TiAlN, TiSiN, or nACo coated tools. In comparison to other coated tungsten carbide tools, [32] tool wear for uncoated tools can be reduced by increasing spindle speed and depth of cut. Coated instruments, as depicted in Figure 8 of the main effect graphs.

Table 08 Experiments using L16 orthogonal array and their responses

Exp #	Speed (m/min)	Feed (µm/tooth)	DOC (µm)	Coating	Amplitude (µm)	Surface Roughness (µm)	Tool Wear (µm)	Burr Height Down Milling (µm)	Burr Width Down Milling (µm)	Burr Height Up Milling (µm)	Burr Width Up Milling (µm)
1	6	1	30	Uncoated	0	0.075	33.750	170.766	141.733	25.798	152.824
2	6	2	50	TiAlN	3	0.069	37.335	164.276	167.292	16.239	57.334
3	6	3	70	TiSiN	6	0.076	34.250	119.110	180.222	23.079	106.535
4	6	4	90	nACo	9	0.050	36.200	129.046	201.417	101.812	190.467
5	7.5	1	50	TiSiN	9	0.044	31.269	184.505	198.056	46.526	133.519
6	7.5	2	30	nACo	6	0.052	35.059	180.000	202.901	64.904	201.076
7	7.5	3	90	Uncoated	3	0.108	34.251	167.024	179.885	110.847	230.961
8	7.5	4	70	TiAlN	0	0.070	32.880	151.041	212.857	26.811	95.613
9	9	1	70	nACo	3	0.072	39.819	175.143	201.909	102.683	210.885
10	9	2	90	TiSiN	0	0.098	39.800	257.360	276.880	94.875	148.115
11	9	3	30	TiAlN	9	0.069	37.100	119.667	149.045	35.284	138.020
12	9	4	50	Uncoated	6	0.042	34.200	231.984	201.041	41.253	101.319
13	10.5	1	90	TiAlN	6	0.059	40.899	334.601	232.927	132.157	201.532
14	10.5	2	70	Uncoated	9	0.081	39.068	190.068	145.050	55.576	205.248
15	10.5	3	50	nACo	0	0.049	37.140	235.279	209.262	170.513	185.935
16	10.5	4	30	TiSiN	3	0.043	42.746	225.604	251.407	58.293	131.181

This can be explained by the fact that a chemical reaction between the coating and the tool substrate material occurs at high speeds as the temperature rises, which can lead to increased tool wear than uncoated.[33] Instability On the substrate of the tool, co-binder components can lead to molecular diffusion[34][35]. Applying the diffusion technique causes the adhesive contact between the tool substrate surface and the coating layer to progressively disintegrate, beginning the diffusion process. [24]Tool wear for amplitude starts out increasing up to 3 meters before decreasing up to 9 meters. Figure 12 This can be explained by the fact that at 3m amplitude, tool and work piece interactions are more impactful, leading to increased tool wear, but as amplitude increases, the impact between the tool and work piece interactions becomes less, leading to lower tool wear as the tool cools during vibration.[36] Tool wear increases with nine amplitudes of vibration due to the impact of tool wear. But as tool wear begins to decline with an amplitude increment of 3 m to 9 um, which is when surface roughness is most strongly correlated with it, surface roughness may also Anova gives us the contribution as Speed 59.39%, and Amplitude as 8.39% as main contributors.

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Speed	3	233.872	59.39%	233.872	77.957	18.13	0.000
Feed	3	22.595	5.74%	22.595	7.532	1.75	0.197
DOC	3	27.938	7.09%	27.938	9.313	2.17	0.132
Coating	3	7.556	1.92%	7.556	2.519	0.59	0.633
Amplitude	3	33.043	8.39%	33.043	11.014	2.56	0.091
Error	16	68.816	17.47%	68.816	4.301		
Total	31	393.819	100.00%				

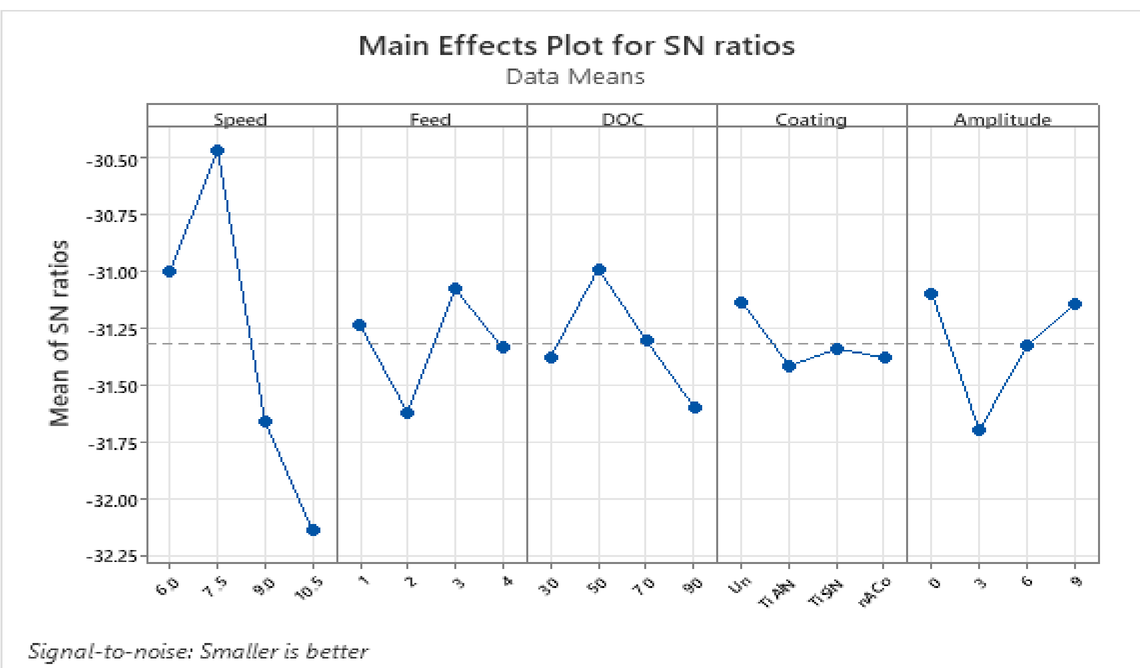


Figure 13 Main effect Plot for Tool Wear

4.03 Formation in Down milling

The researcher enhanced the contact work hardening qualities to create a superior surface quality using traditional micro milling,[37], [38] where tool vibration is 0 and Inconel 718's optimized parameters. The most important factor affecting burr thickness, according to Mian et al. [27], is the proportion of feed per tooth (fz) to cutting edge radius. The majority of the burr was produced during down milling, which is in line with what was stated in the literature. Cutting-edge radius is a crucial cutting parameter in the micro milling process[39], [40]. Due to the greater cutting-edge radius, most of the cutting was done below the required chip thickness, which increased cutting pressures and deformation throughout the machining process and produced a wider burr.[2], [41] As seen in figure 08, burr height and width are optimized under various machining conditions, and our objective is to reduce both for a particular set of machining parameters.[42] As we require both responses to be at a minimum, the smaller the better, we must perform the combined Taguchi analysis for the burr width and burr height of down milling in this case.

$$S/N = -10 * \log(\Sigma(Y^2)/n) \qquad (1)$$

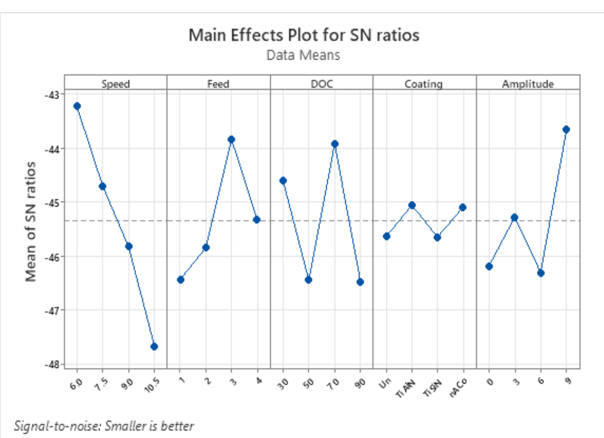
Where Y is value response at given set of parameters.

For burr height in down milling the main contributors are Speed 37.81%, Depth of Cut 19.64%, Amplitude 17.14% and Feed 10.55%. Similarly, for burr Width in Down Milling Coating 29.79%, Speed 16.01%, Depth of cut 15.76%, Amplitude 14.77%, and Feed 13.77%.

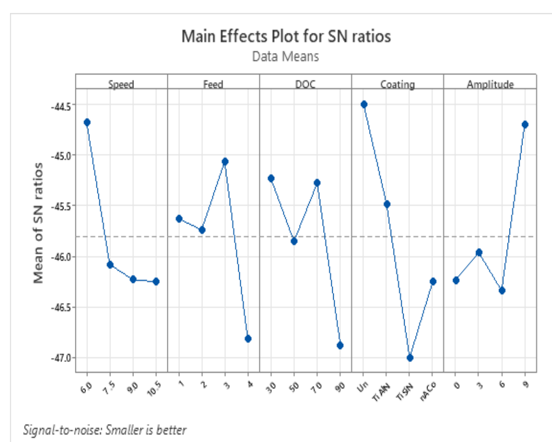
Table 09 Response for combine signal to noise ratios for down milling burr for smaller is better

Level	Speed	Feed	DOC	Coating	Amplitude
1	**-44.20**	-46.17	-45.01	**-45.17**	-46.33
2	-45.52	-45.88	-46.22	-45.47	-45.66
3	-46.11	-44.62	-44.82	-46.46	-46.54
4	-47.11	**-46.27**	**-46.88**	-45.84	**-44.39**
Delta	2.91	1.66	2.07	1.30	2.15
Rank	1	4	3	5	2

According to the above table, speed is the biggest factor in the combined effect of burr width and burr height, followed by amplitude, depth of cut, feed rate, and coating[43]. Table 08 demonstrates that 6 m/min is the ideal speed for low bur formation in down milling, and that burr formation increases as speed does[43], [44]. Cutting temperatures vary according to cutting speeds. Because of the increased temperature created by high-speed machining, the tool's cutting edge bends and widens the burr. The enhanced creation of burrs was helped by material deformation caused by the coated tool's higher coefficient of friction.[31] [2], [40]Burr width reduced as feed/cutting-edge radius rose from 0.3 to 0.5. In earlier Inconel 718 micromachining studies, similar burr root thickness patterns were observed. Burr width reduced as feed/cutting-edge radius rose from 0.3 to 0.5. Prior research revealed the similar pattern when micromachining Inconel 718 burr root thickness. [27] We can see from table 08 that the minimal burr value for depth of cut is at level 3, which is 70 m, and decreases after that because as the depth of cut grows, more material is taken from the slot, causing a thick chip to develop that doesn't shatter,[45] leading to large burr creation. The level 4 parameter, which has a vibrational amplitude of 9 m, is excellent for amplitude. When ultrasonic vibration is used, chip size can be reduced, chip breaking frequency can be increased, and burr size is therefore decreased. [24].[24],[55]



Burr Height Down Milling



Burr Width Doen Milling

Figure 14 Main effect plots for Burr Down Milling

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Speed	3	45346	37.81%	45346	15115.3	14.40	0.000
Feed	3	12650	10.55%	12650	4216.6	4.02	0.026
DOC	3	23557	19.64%	23557	7852.4	7.48	0.002
Coating	3	1027	0.86%	1027	342.2	0.33	0.807
Amplitude	3	20552	17.14%	20552	6850.7	6.53	0.004
Error	16	16794	14.00%	16794	1049.6		
Total	31	119925	100.00%				

Burr Height Down Milling

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Speed	3	7421	16.01%	7421	2473.7	8.62	0.001
Feed	3	6382	13.77%	6382	2127.4	7.42	0.002
DOC	3	7304	15.76%	7304	2434.8	8.49	0.001
Coating	3	13810	29.79%	13810	4603.2	16.05	0.000
Amplitude	3	6846	14.77%	6846	2281.9	7.95	0.002
Error	16	4590	9.90%	4590	286.9		
Total	31	46353	100.00%				

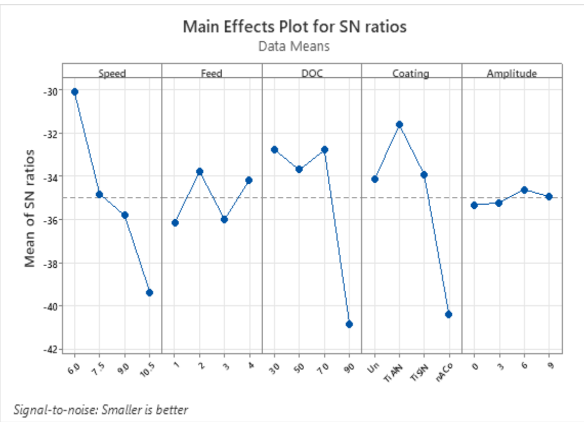
Burr Width Down Milling

4.04 Burr Formation in up milling:

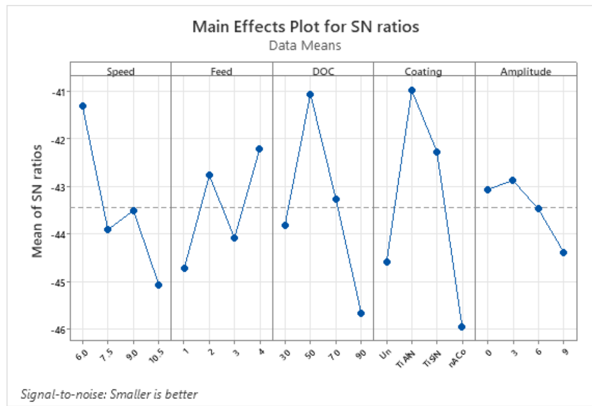
The results of the experiment allow us to draw the conclusion that the up-milling side experiences far less burr formation than the down-milling side. This conclusion is supported by the literature.[14], [46] Figure 08 demonstrates that the optimum and worst burr height and breadth parameters are the same as for up milling, negating the requirement for a combine analysis. Using main effects plots, we can observe that burr rises with speed because of variations in cutting temperature. The work piece flexes and develops a larger burr as a result of increased machining caused by a temperature difference between both the tool's cutting edge and the work material. This encourages chip release.[14] [7], [47].The TiSiN-coated tool's higher coefficient of friction caused the material to bend more easily, which accelerated the production of burrs. A significant influencing factor is the ratio of feed rate and cutting edge radius, which increases then drops as the ratio varies between 0.3 and 0.6, and performs best at maximum feed. Because burr formation reduces as even more material is removed and more thick, hard chips are created, which break and produce burrs, burr formation is lowest at 50 um depth of cut but increases later.[10], [48] Burr development will be at its lowest for 3 m amplitude and afterwards rise as amplitude increases. The key factors in burr height during up milling are depth of cut (32.5%), coating (29.57%), and speed (25.6%). The primary contributions to burr width in up milling are similar: coating

(38.547%), depth of cut (25.35%), and speed (15.48%). According to an ANOVA for burr creation in up milling, the percentage impact of amplitude is insignificant, thus we may disregard the idea that increasing amplitude will have a detrimental effect on burr increment in the up milling process.

The results of the experiment allow us to draw the conclusion that the up-milling side experiences far less burr formation than the down-milling side. This conclusion is supported by the literature.



Burr Height Up Milling



Burr Width Up Milling

Figure 15 Main effect plots of Burr Up milling

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Speed	3	15969	25.65%	15969	5323.0	52.61	0.000
Feed	3	4549	7.31%	4549	1516.5	14.99	0.000
DOC	3	20233	32.50%	20233	6744.5	66.66	0.000
Coating	3	18227	29.27%	18227	6075.7	60.05	0.000
Amplitude	3	1664	2.67%	1664	554.7	5.48	0.009
Error	16	1619	2.60%	1619	101.2		
Total	31	62262	100.00%				

Burr Height Up Milling

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Speed	3	12343	15.48%	12343	4114.4	9.97	0.001
Feed	3	7907	9.92%	7907	2635.6	6.38	0.005
DOC	3	20215	25.35%	20215	6738.4	16.32	0.000
Coating	3	30680	38.47%	30680	10226.5	24.77	0.000
Amplitude	3	1990	2.50%	1990	663.4	1.61	0.227
Error	16	6606	8.28%	6606	412.9		
Total	31	79741	100.00%				

Burr Width Up Milling

Chapter 5

Multi-Objective Optimization

According to Table 07's research, several responses are best at various input varying concentrations. [49]Multi Objective Optimization (MOO) had to be used in this particular situation to balance all of the responses. In the majority of machining operations, enhancing one reaction usually necessitates reducing the other. Multi-objective optimization substantially facilitates making difficult decisions when there are conflicting reactions[50].

5.01 Multi-Objective optimization using gray relational analysis

MOO enables the study's goal of simultaneously producing the best possible number of responses. The research methodology used in this study was created in 1989 by Deng Julong [[27], [51]. The term "grey system" was first used by Deng Julong in 1981 [51], who defined it as everything that is not expressly articulated in black or white and is therefore considered to be grey. The objective was to interpret the available information in a way that supported decision-making. [52]The grey relational grade was first proposed by Wang Ting in 1985. The technique has multiple steps, each of which will be briefly described below[20], [21], [42], [49]

5.02 Data Pre-Processing

The first step in GRA is normalization of Data such that Data is brought to single value between 0 and Formula used is here is equation 2 which is smaller the better as we are optimizing our response on smaller the better.

$$Zij = \frac{\boldsymbol{max(yij, i=1,2,3 \ldots\ldots\ldots, n) - yij}}{\boldsymbol{max(yij, i=1,2,3, \ldots\ldots\ldots, n) - min(yij, i=1,2,3, \ldots\ldots\ldots,)}} \qquad \textbf{(2)}$$

where max (y_{ij}) and min (y_{ij}) are the highest and lowest values found in the experimental results for each response, respectively. Where yij represents the value of response for experiment. The true and normalized values are represented by Zij.

5.03 Calculation of grey relational coefficients (GRC)

The grey relational coefficients (GRC) are then determined using the normalized data and Equation 3. GRC connects the response's ideal value to the results of the experiment.

$$\gamma\left(z_o, z_{ij}\right) = \frac{\Delta min+\varepsilon\Delta max}{\Delta oj(k)+\varepsilon\Delta max} \quad \textbf{(3)}$$

Where $0 < \gamma\left(z_o, z_{ij}\right) \leq 1$

The deviation sequence's maximum and minimum values are Δmax and Δmin, respectively. In the equation above, the deviation sequence, oj(k), can be approximated by

$$\Delta oj(k) = \left|(z_o(k) - z_{ij}(k)\right| \quad \textbf{(4)}$$

where Zo(k) stands for the reference sequence, and Zij for the comparability sequence (k). In this study, the value of the distinguishing coefficient, which has a range of 0 to 1, is taken into account to be 0.5. The estimated GRC values for the four responses are shown in Table 9. Calculation of GRG

In this level, the several diverse objectives are combined into a single grey relational grade (GRG). The best results can be achieved by maximizing the obtained GRG. Using Eq. (5), where r is the weight of the rth objective, GRG is determined. Manufacturers decide on weight based on orders from customers or rules and regulations. The current study gives equal weight to each response.

$$Grade\left(Z_o, Z_{ij}\right) = \sum_{r=1}^{n} \omega_r \left(Z_o, Z_{ij}\right) \quad \textbf{(5)}$$

Where $\sum_{r=1}^{n} \omega_r = 1$

5.04 Calculation of Rank

Rank is calculated on the basis of GRG. The higher the value of GRG will be the rank 1 and will be the best optimal Combination of Parameters while the lowest value of GRG will be the worst combination of parameters.[53] From Grey Relational Analysis table 09 the best combination of parameters is Experiment # 02 with Speed at 6m/mint, Feed 0.5um/tooth, Depth of cut 50µm, coating TiAlN and Tool Vibration Amplitude 3µm.While the worst combination is Experiment

#10 with Speed at 9m/mint, feed 0.5um, Depth of Cut 90µm, Coating TiSiN and Amplitude with 0 Amplitude.

Table 10 GRC and GRG calculated from responses

Exp #	Speed (m/min)	Feed (µm/tooth)	DOC (µm)	Coating	Amplitude (µm)	Surface Roughness (GRC)	Tool Wear (GRC)	Burr Height Down Milling (GRC)	Burr Height Up Milling (GRC)	Burr Width Up Milling (GRC)	Burr Width Up Milling (GRC)	GRG	Rank
1	6	1	30	Uncoated	0	0.500	0.698	0.676	1.000	0.890	0.476	0.707	5
2	6	2	50	TiAlN	3	0.550	0.486	0.705	0.726	1.000	1.000	0.744	1
3	6	3	70	TiSiN	6	0.493	0.658	1.000	0.637	0.919	0.638	0.724	3
4	6	4	90	nACo	9	0.805	0.538	0.916	0.531	0.474	0.395	0.610	8
	7.5	1	50	TiSiN	9	0.943	1.000	0.622	0.545	0.718	0.533	0.727	2
6	7.5	2	30	nACo	6	0.771	0.602	0.639	0.525	0.613	0.377	0.588	9
7	7.5	3	90	Uncoated	3	0.333	0.658	0.692	0.639	0.449	0.333	0.518	12
8	7.5	4	70	TiAlN	0	0.541	0.781	0.771	0.487	0.879	0.694	0.692	6
9	9	1	70	nACo	3	0.524	0.402	0.658	0.529	0.472	0.361	0.491	14
10	9	2	90	TiSiN	0	0.371	0.402	0.438	0.333	0.495	0.489	0.421	16
11	9	3	30	TiAlN	9	0.550	0.496	0.995	0.902	0.802	0.518	0.711	4
12	9	4	50	Uncoated	6	1.000	0.662	0.488	0.533	0.755	0.664	0.684	7
13	10.5	1	90	TiAlN	6	0.660	0.373	0.333	0.426	0.400	0.376	0.428	15
14	10.5	2	70	Uncoated	9	0.458	0.424	0.603	0.953	0.662	0.370	0.578	10
15	10.5	3	50	nACo	0	0.825	0.494	0.481	0.500	0.333	0.403	0.506	13
16	10.5	4	30	TiSiN	3	0.971	0.333	0.503	0.381	0.647	0.540	0.563	11

5.05 Regression model for GRG function

Regression modelling and its optimization were part of an intricate regression analysis that was conducted. Significant contributing parameters were found using analysis of variance. A second-order (Response surface methodology) RSM model was used to create a multi-objective GRG function that closely matches the GRG deduced from the experimental findings. The coating condition was a non-continuous categorical element in the current study, with four unique degrees, namely uncoated, TiAlN, TiSiN, nACo. A separate function for each coating was developed

$$\mathbf{GRG}(\boldsymbol{speed}, \boldsymbol{feed}, \boldsymbol{depth\ of\ cut}, \boldsymbol{Amplitude}, \boldsymbol{Un\ coated}) = 0.6883 - 0.0641\, Speed - 0.0044\, Feed + 0.1631\, DOC - 0.0577\, Amplitude + 0\, Speed + 0.00706\, Feed * Feed - 0.03745\, DOC * DOC + 0.01643\, Amplitude * Amplitude - 0.00342\, Speed * DOC - 0.0064\, Feed * DOC$$

$$\mathbf{G}(\boldsymbol{speed}, \boldsymbol{feed}, \boldsymbol{depth\ of\ cut}, \boldsymbol{Amplitude}, \boldsymbol{TiAlN}) = 0.7040 - 0.0641\ Speed - 0.0044\ Feed + 0.1631\ DOC - 0.0577\ Amplitude + 0.00163\ Speed * Speed + 0.00706\ Feed * Feed - 0.03745\ DOC * DOC + 0.01643\ Amplitude * Amplitude - 0.00342\ Speed * DOC - 0.0064\ Feed * DOC$$

$$\mathbf{GRG}(\boldsymbol{speed}, \boldsymbol{feed}, \boldsymbol{depth\ of\ cut}, \boldsymbol{Amplitude}, \boldsymbol{TiSiN}) = 0.6654 - 0.0641\ Speed - 0.0044\ Feed + 0.1631\ DO - 0.0577\ Amplitude + 0.00163\ Speed * Speed + 0.00706\ Feed * Feed - 0.03745\ DOC * DOC + 0.01643\ Amplitude * Amplitude - 0.00342\ Speed * DOC - 0.0064\ Feed * DOC \quad \textbf{(09)}$$

$$\mathbf{GRG}(\boldsymbol{speed}, \boldsymbol{feed}, \boldsymbol{depth\ of\ cut}, \boldsymbol{Amplitude}, \boldsymbol{nACo}) = 0.6118 - 0.0641\ Speed - 0.0044\ Feed + 0.1631\ DOC - 0.0577\ Amplitud + 0.00163\ Speed * Speed + 0.00706\ Feed * Feed - 0.03745\ DOC * D + 0.01643\ Amplitude * Amplitude - 0.00342\ Speed * DOC - 0.0064\ Feed * DOC \quad \textbf{(10)}$$

The above equations are developed using response surface regression model with R-Square of 99.74% and R square adjusted 98.05%. From the equations it is found that best performing categorical factor is TiAlN. which will be optimized solution using response regression model given by these equations. The applicability of the developed model is only limited to ultrasonic assisted micro milling Inconel-718; using uncoated and coated tools, within the conditions (6 m/min ≤ speed ≤ 10.5 m/min), (0.25 mm/rev ≤ feed ≤ 0.

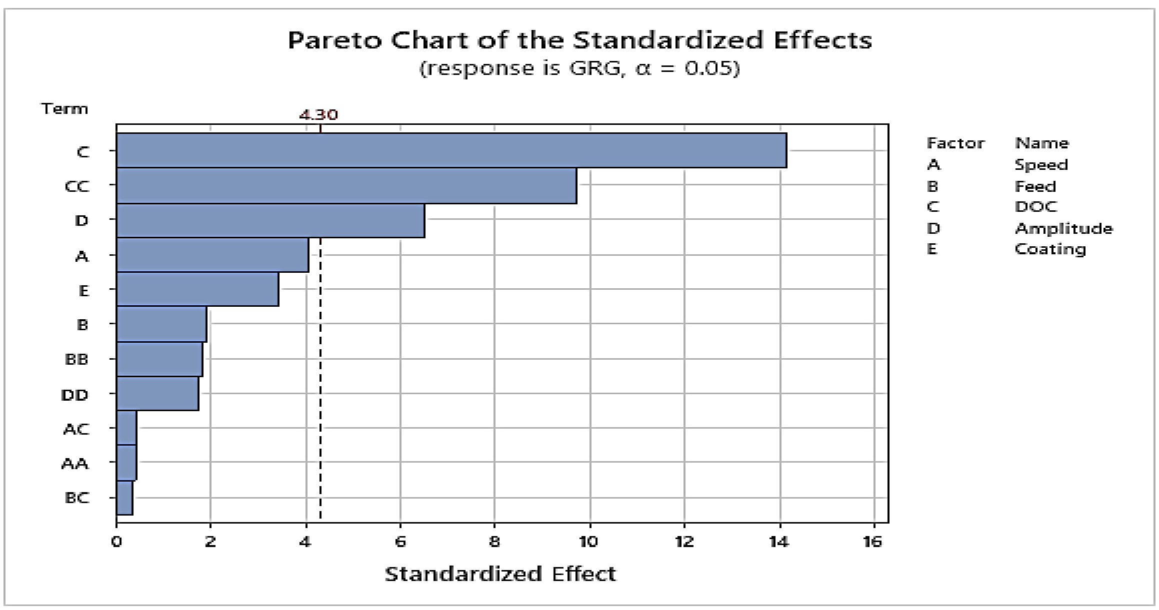


Figure 16 Pareto Chart GRG

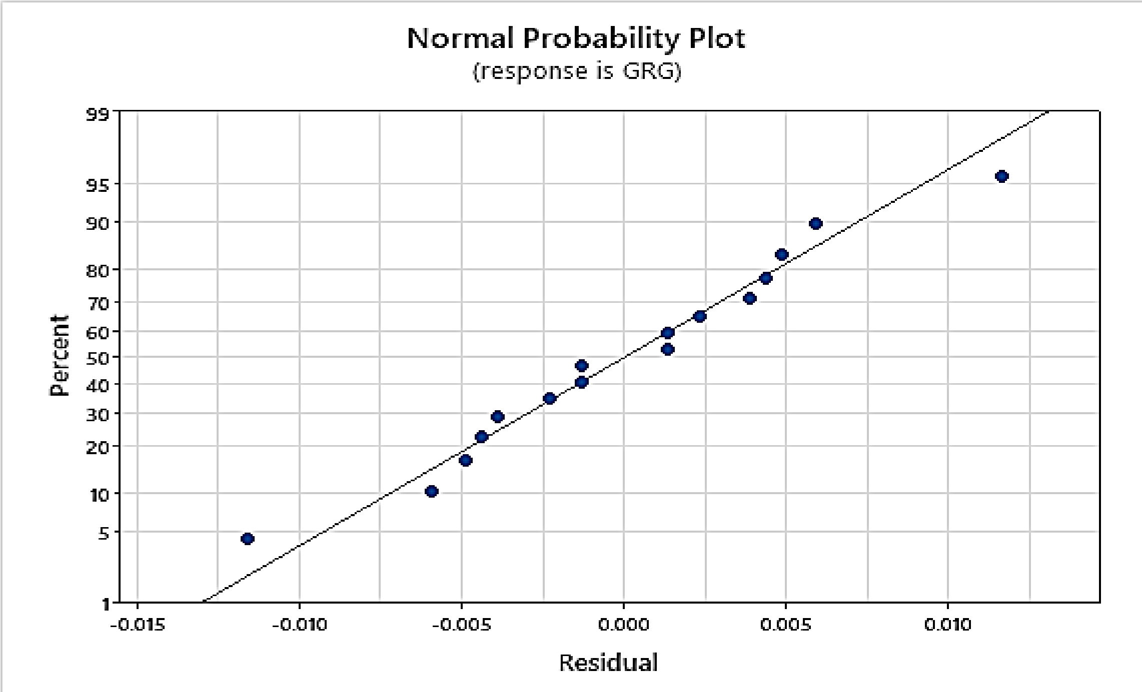


Figure 17 Normal Probability Plot GRG

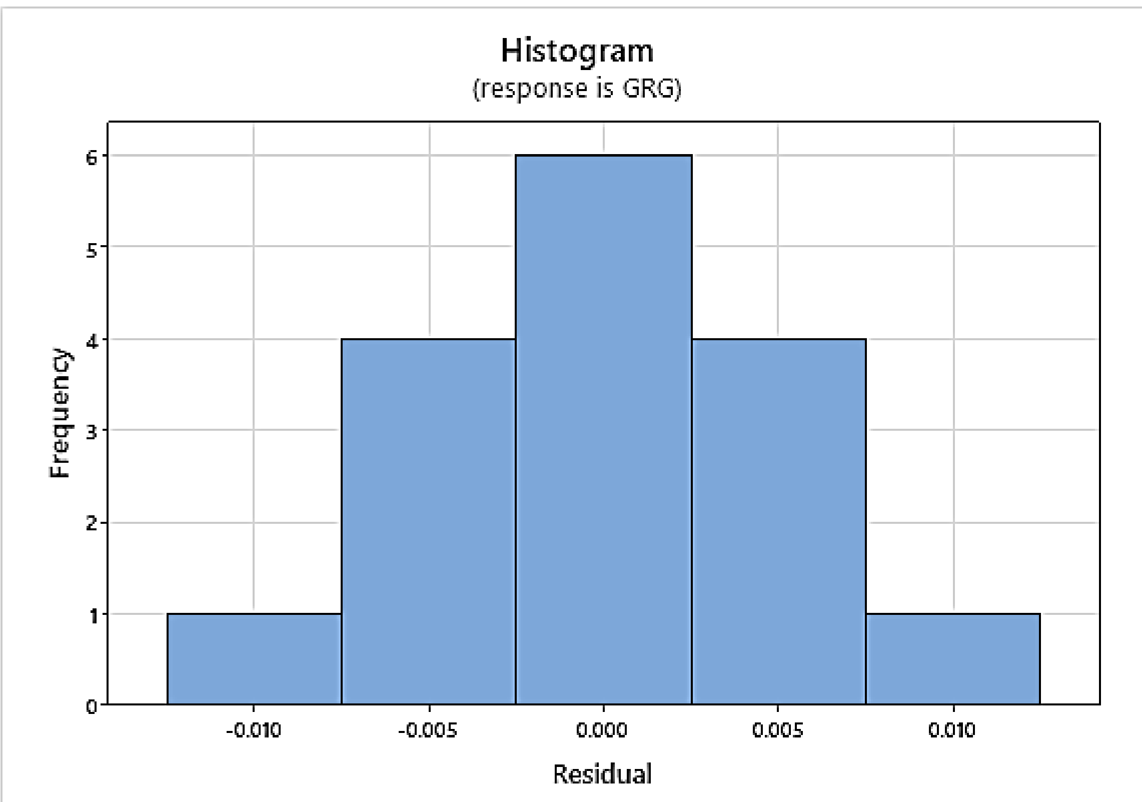


Figure 18 Histogram

5.06 Analysis of Variance of GRG

The MINITAB® software was used to perform an ANOVA at a 95% confidence level in order to evaluate the efficiency of the cutting parameters (speed, feed, depth of cut, coating, and amplitude). According to anova table 10, individual factors have a greater overall impact on machining responses (85.38%), followed by the square of individual responses (14.32), and the interaction of individual answers (which has a small impact).[54]

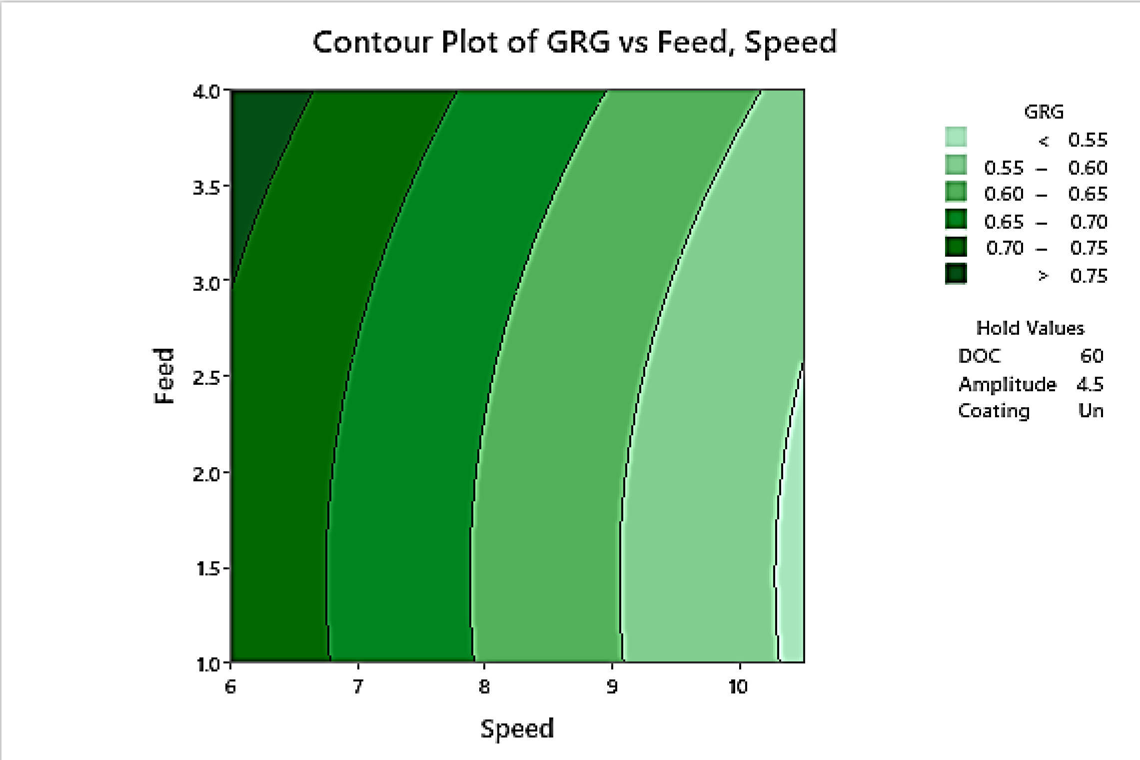
Additionally, speed is seen to provide the most amount to machining replies, at 37.86%. As shown in the table, the other most important characteristics are depth of cut (26.09%), depth of cut x depth of cut (12.32%), coating (10.92%), amplitude (6.97%), and feed (3.54%). The amplitude, DOC x DOC, DOC, and Speed are significant parameters, according to the P-Value of the anova table.

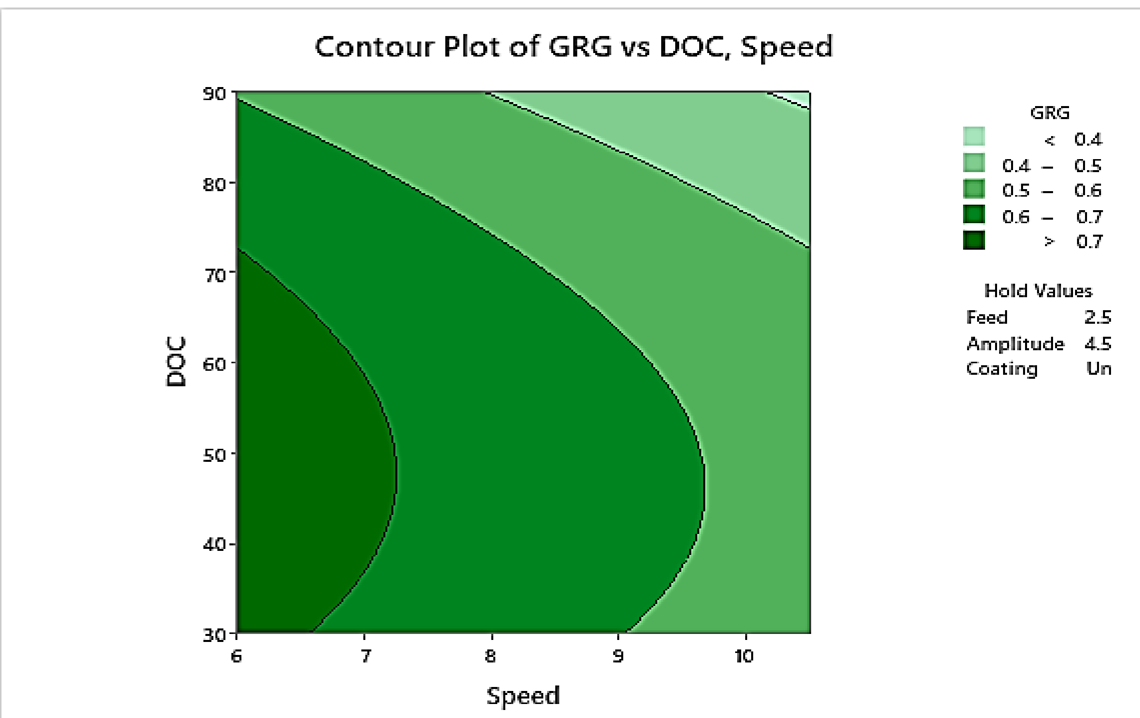
Table 11 Analysis of variance of GRG

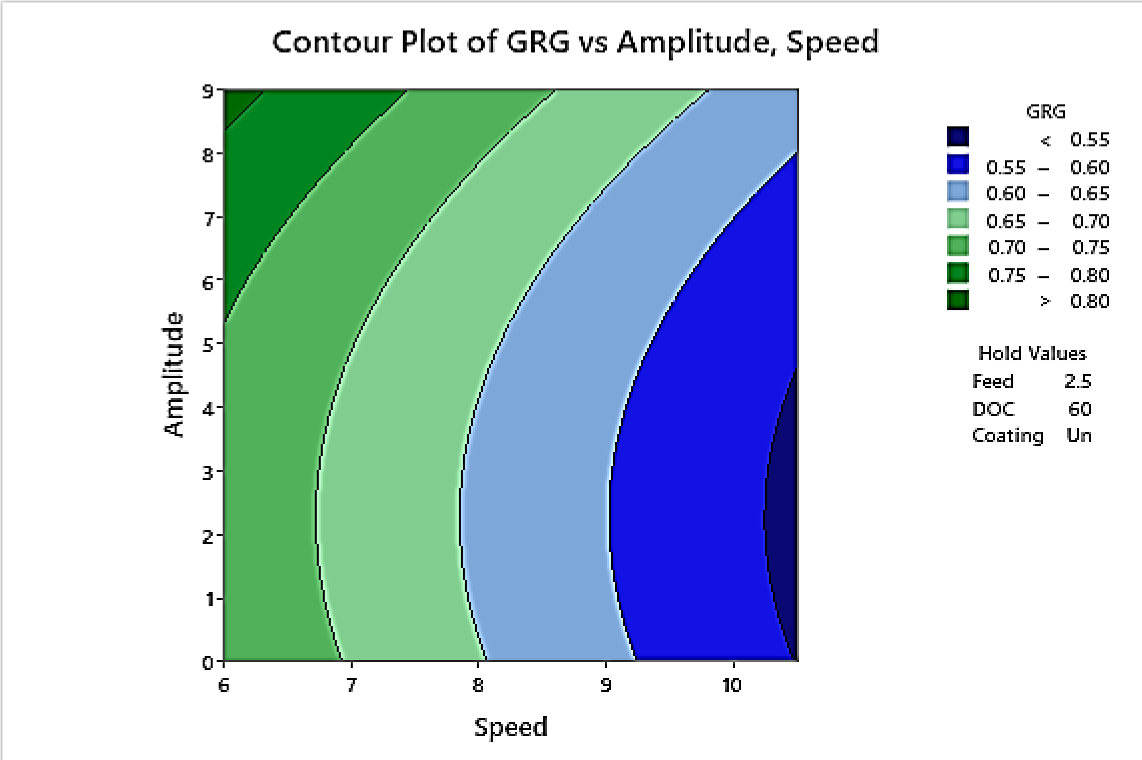
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	13	0.181676	99.74%	0.181676	0.013975	59.06	0.017
Linear	7	0.155514	85.38%	0.116128	0.016590	70.11	0.014
Speed	1	0.068959	37.86%	0.003914	0.003914	16.54	0.055
Feed	1	0.006441	3.54%	0.000875	0.000875	3.70	0.194
DOC	1	0.047521	26.09%	0.047521	0.047521	200.82	0.005
Amplitude	1	0.012703	6.97%	0.010019	0.010019	42.34	0.023
Coating	3	0.019890	10.92%	0.008854	0.002951	12.47	0.075
Square	4	0.026082	14.32%	0.024002	0.006000	25.36	0.038
Speed*Speed	1	0.000043	0.02%	0.000043	0.000043	0.18	0.712
Feed*Feed	1	0.000798	0.44%	0.000798	0.000798	3.37	0.208
DOC*DOC	1	0.022441	12.32%	0.022441	0.022441	94.83	0.010
Amplitude*Amplitude	1	0.002801	1.54%	0.000720	0.000720	3.04	0.223
2-Way Interaction	2	0.000080	0.04%	0.000080	0.000040	0.17	0.856
Speed*DOC	1	0.000047	0.03%	0.000047	0.000047	0.20	0.700
Feed*DOC	1	0.000033	0.02%	0.000033	0.000033	0.14	0.745
Error	2	0.000473	0.26%	0.000473	0.000237		
Total	15	0.182149	100.00%				

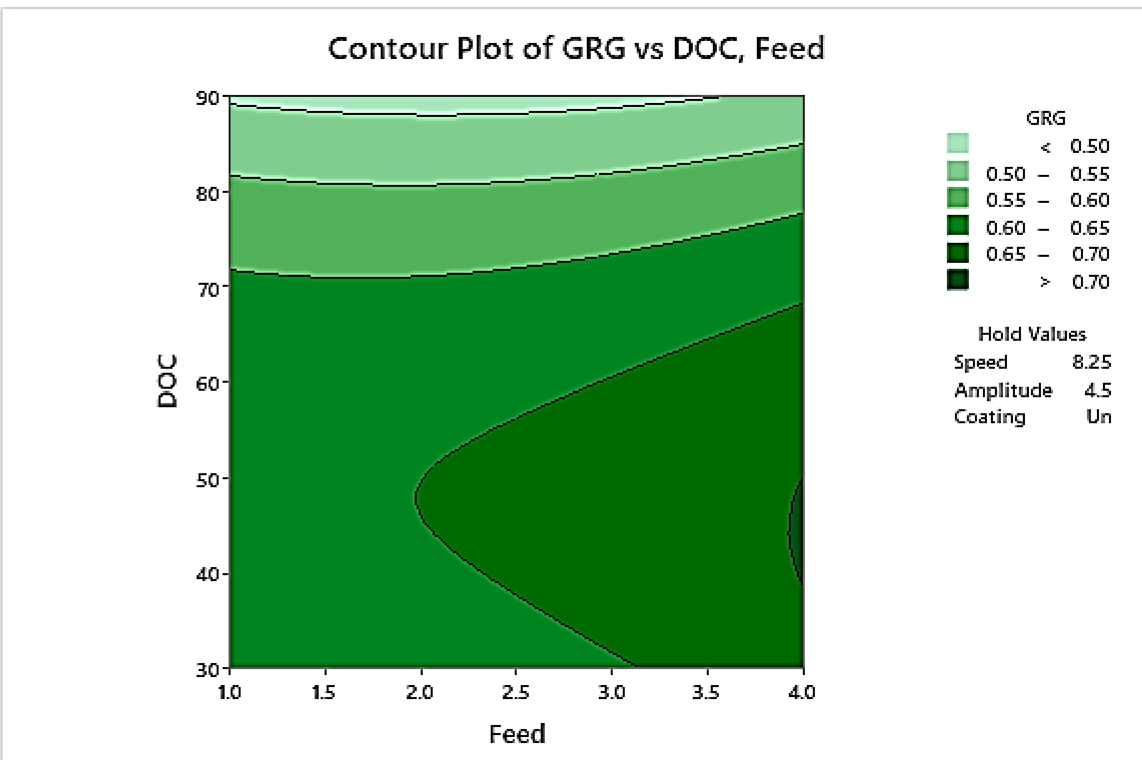
DF, degrees of freedom; SS, sum of squares; MS, mean squares; F, F value; P, P value; CR, contribution ratio (%); S, standard deviation; R-Sq.(pred) predicted R2

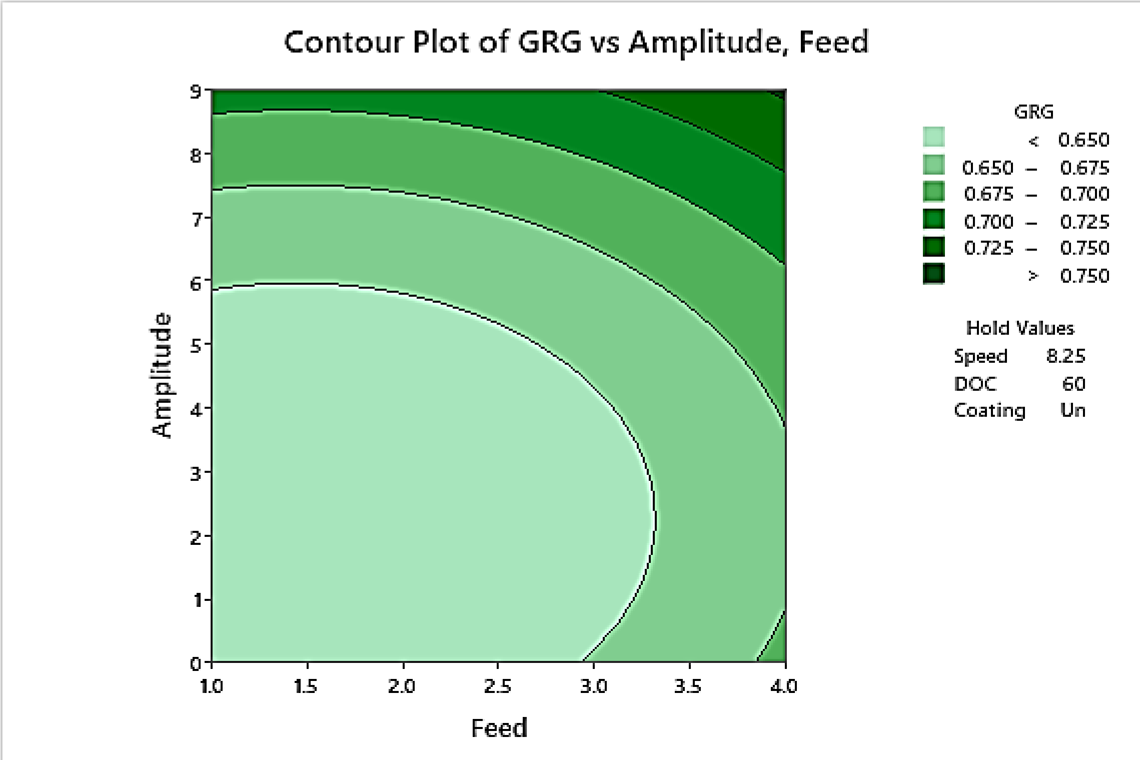
Figure 19 displays surface effect charts that illustrate the impact of various machining settings on GRG using the RSM regression model and regression equations. Maximum GRG can be seen at low speed, high feed, short depth of cut, and big amplitude, as shown by the surface effect plots. which, as already demonstrated by [2] and [24], can be supported by literature.






Contour Plot of GRG vs Amplitude, Speed
Amplitude
Speed
0
1
2
3
4
5
6
7
8
9
6
7
8
9
10
GRG
< 0.55
0.55 – 0.60
0.60 – 0.65
0.65 – 0.70
0.70 – 0.75
0.75 – 0.80
> 0.80
Hold Values
Feed 2.5
DOC 60
Coating Un


Contour Plot of GRG vs DOC, Feed
DOC
Feed
30
40
50
60
70
80
90
1.0
1.5
2.0
2.5
3.0
3.5
4.0
GRG
< 0.50
0.50 – 0.55
0.55 – 0.60
0.60 – 0.65
0.65 – 0.70
> 0.70
Hold Values
Speed 8.25
Amplitude 4.5
Coating Un



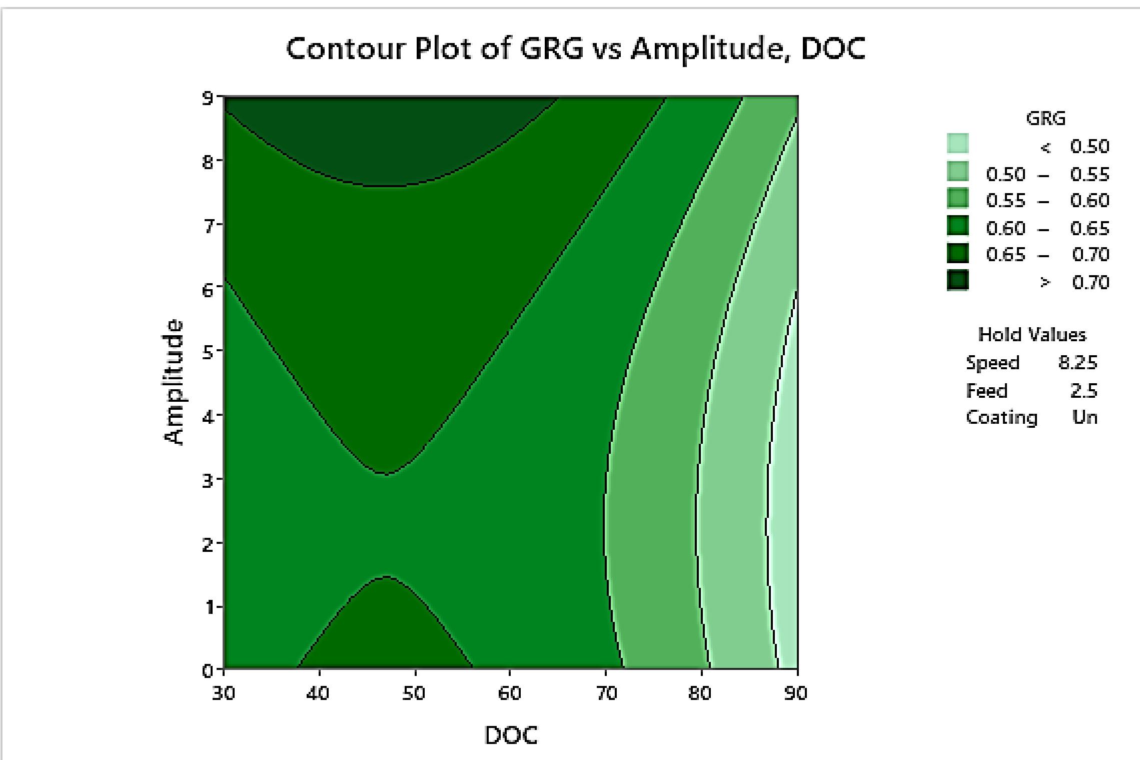
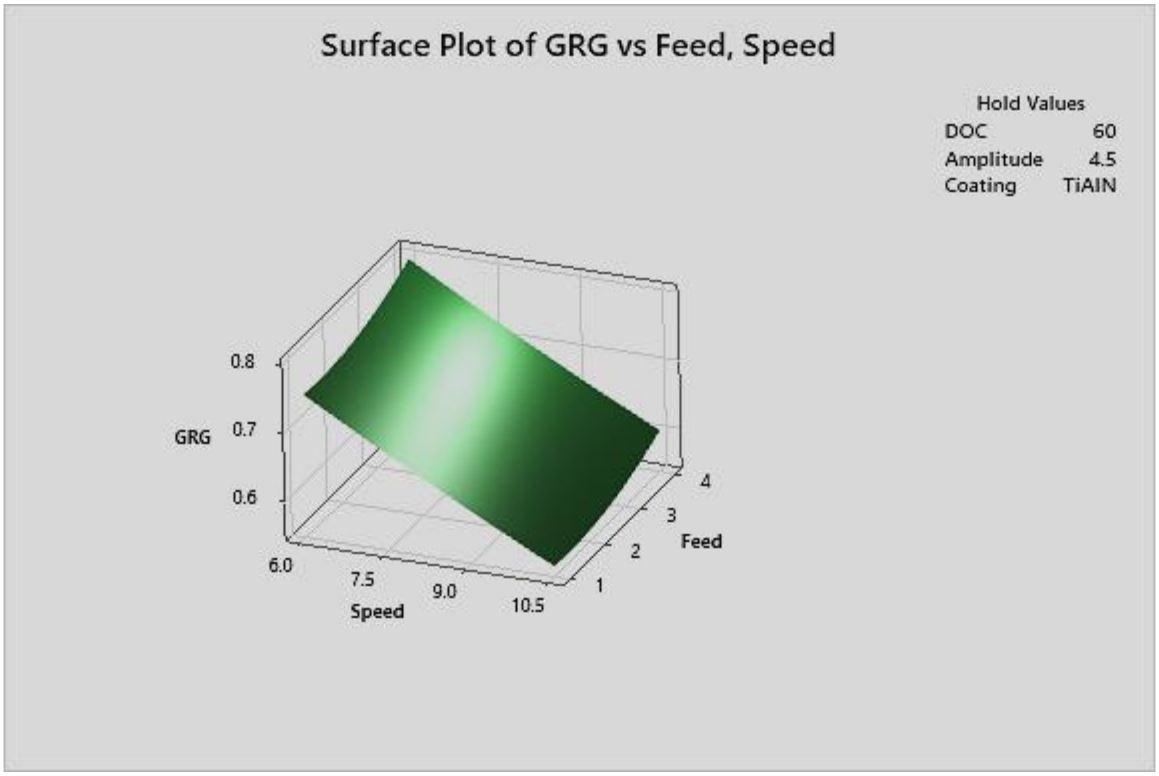
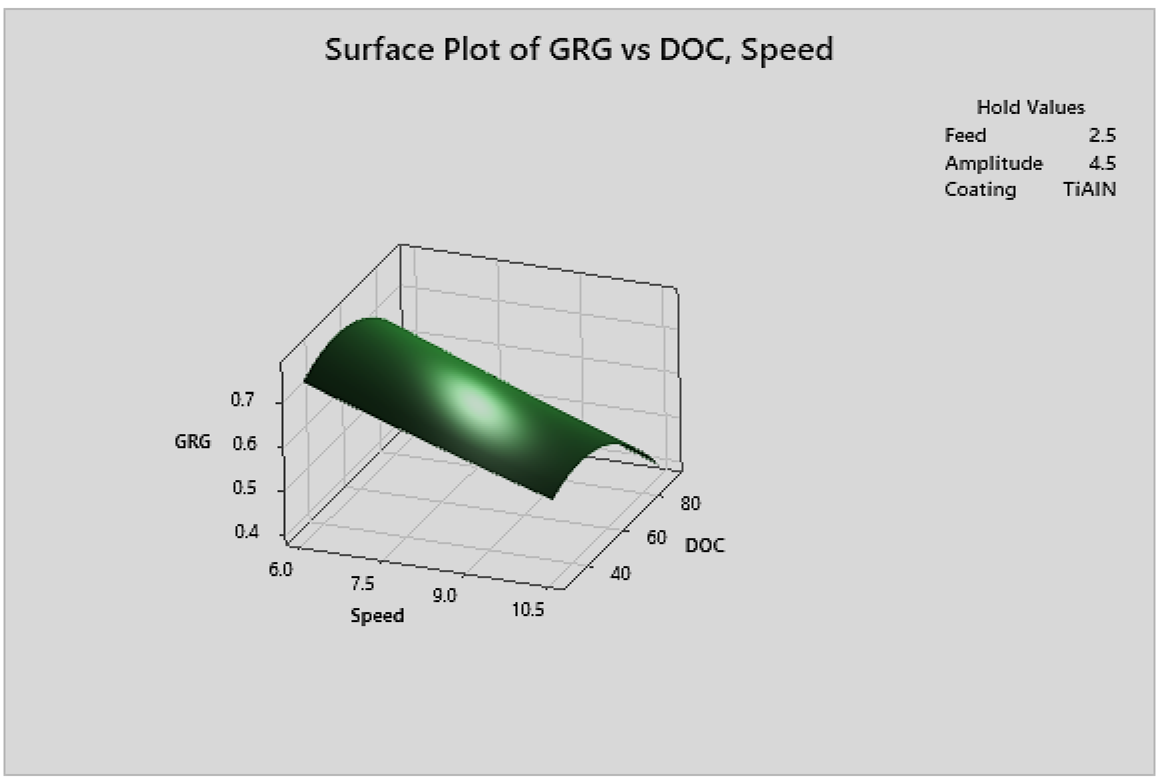
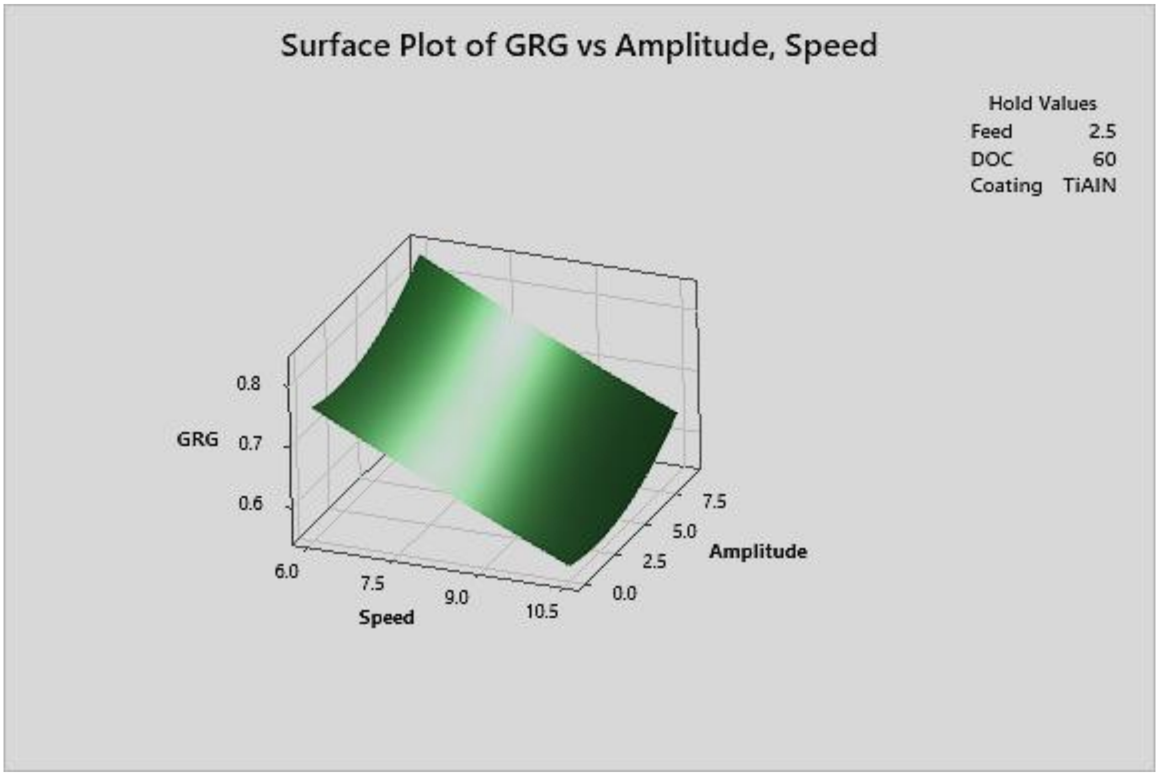
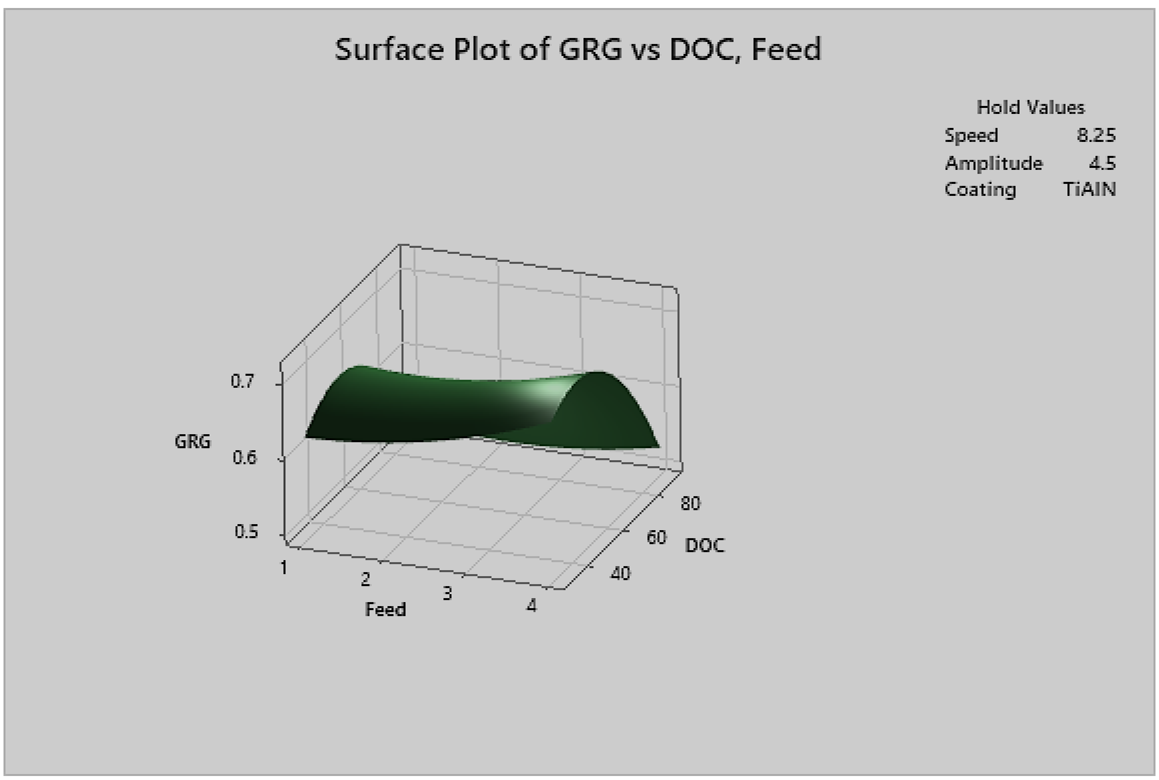


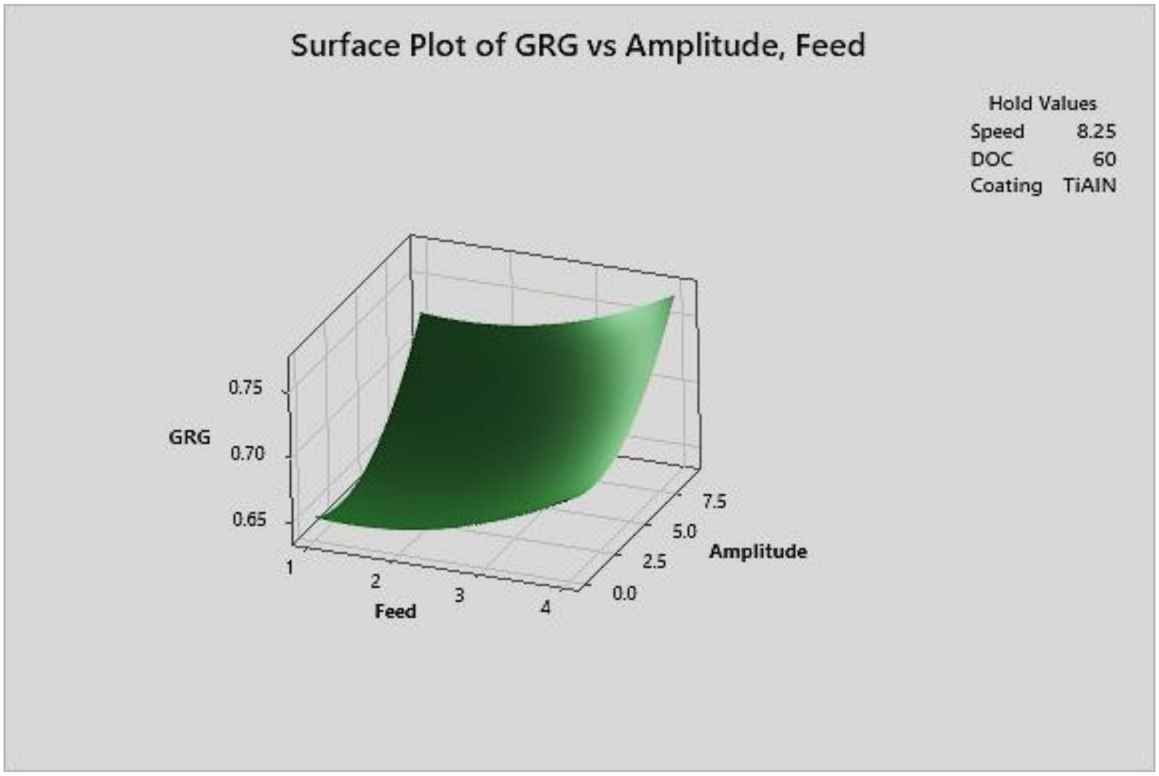
Figure 19 Contour Plots of GRG


Surface Plot of GRG vs Feed, Speed
Hold Values
DOC 60
Amplitude 4.5
Coating TiAIN
0.8
GRG 0.7
0.6
6.0
7.5
9.0
10.5
Speed
1
2
3
4
Feed


Surface Plot of GRG vs DOC, Speed
Hold Values
Feed 2.5
Amplitude 4.5
Coating TiAIN
0.7
GRG 0.6
0.5
0.4
6.0
7.5
9.0
10.5
Speed
40
60
80
DOC


Surface Plot of GRG vs Amplitude, Speed
Hold Values
Feed 2.5
DOC 60
Coating TiAIN
GRG
0.8
0.7
0.6
6.0
7.5
9.0
10.5
Speed
0.0
2.5
5.0
7.5
Amplitude


Surface Plot of GRG vs DOC, Feed
Hold Values
Speed 8.25
Amplitude 4.5
Coating TiAIN
GRG
0.7
0.6
0.5
1
2
3
4
Feed
40
60
80
DOC



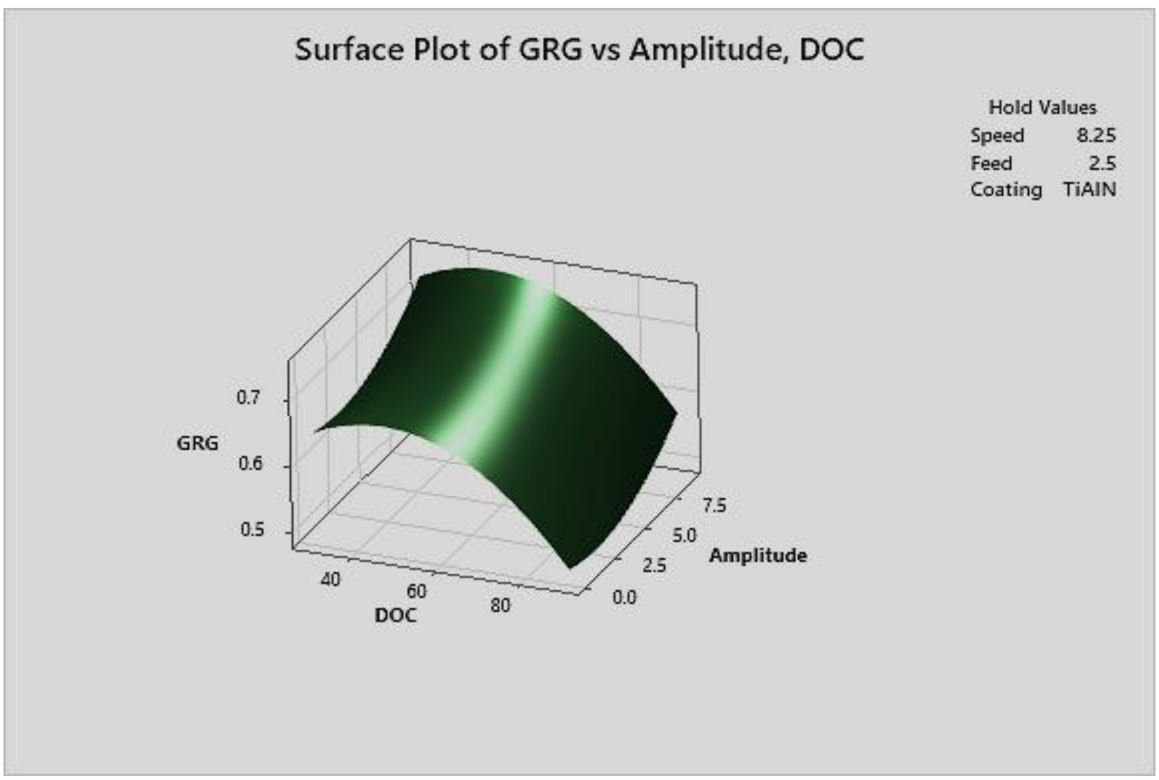


Figure 20 Surface Effect plots of GRG

5.07 Regression Model Optimization

Response surface optimization was used to identify the ideal set of machining parameters in order to produce the best output response.[50] Result visualization is shown in Fig. 10. They were also experimentally validated in addition. The ideal parameter combination for maximal GRG, which results in the lowest value of surface roughness, tool wear, and burr formation, is obtained from the response surface optimizer with a confidence level of 95%. Table 11 displays the ideal parameter combination.[20]

Response Optimization: GRG

Parameters

Response	Goal	Lower	Target	Upper	Weight	Importance
GRG	Maximum	0.420866	0.743625		1	1

Solution

Solution	Speed	Feed	DOC	Amplitude	Coating	GRG Fit	Composite Desirability
1	1	4	1.78788	4	TIAlN	0.889073	1

Multiple Response Prediction

Variable	Setting
Speed	1
Feed	4
DOC	1.78788
Amplitude	4
Coating	TIAlN

Response	Fit	SE Fit	95% CI	95% PI
GRG	0.8891	0.0471	(0.6864, 1.0917)	(0.6759, 1.1023)

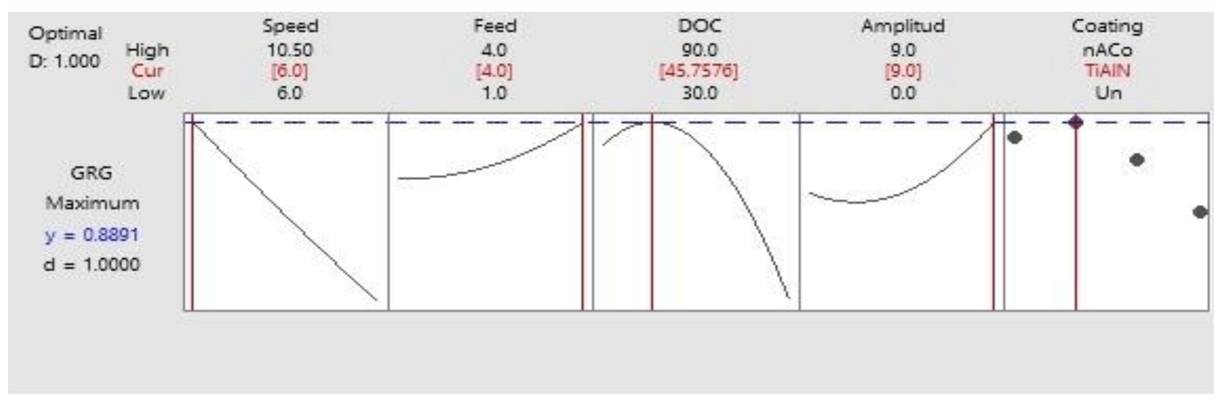


Figure 21 Optimized Solution

5.08 Validation Experiments

Table 10 provides the initial trials' (experiment #2's) best run condition along with the machining parameters that were RSM-optimized. The validation's findings revealed a considerable improvement. Improvements in Tool Wear (12.227%), Surface Roughness (15.942%), and Burr Height Down Milling (9.973%) were made. Burr Height Up Milling Decreased by 25.717%, and Burr Width Up Milling Decreased by 16.116%, according to the results. Burr Width Down Milling Decreased by 8.988%.[36], [47], [48], [55]

Figure 22 Machined Slots of confirmatory Runs

Table 12 Optimized run-in comparison with the best experimental run

	Machining Condition					Responses					
Experiment	**Speed**	**Feed**	**DOC**	**Coating**	**Amplitude**	**Surface Roughness**	**Tool Wear**	**Burr Height Down Milling**	**Burr Width Down Milling**	**Burr Height Up Milling**	**Burr Width Up Milling**
	(m/min)	**(µm/tooth)**	**(µm)**		**(µm)**	**(µm)**	**(µm)**	**(µm)**	**(µm)**	**(µm)**	**(µm)**
Best Run	**6**	**2**	**50**	**TiAlN**	**3**	**0.069**	**37.335**	**166.276**	**167.292**	**16.239**	**57.334**
Optimum Run	**6**	**4**	**50**	**TiAlN**	**9**	**0.058**	**32.77**	**149.693**	**152.256**	**21.861**	**68.349**

Chapter 6

Conclusion and Future Recommendations

6.01 Conclusion

In this study, Inconel 718 was machined using both traditional micro milling and ultrasonic aided micro milling, and the effects of ultrasonic vibration on tool wear, burr development, and surface roughness were investigated. The main conclusions are summarized as follows:

- Surface roughness, tool wear, and burr formation can all be significantly improved with ultrasonic aided micro milling, however burr development during up-milling is unaffected.
- Better machining responses with low speed, high feed, and large amplitude were obtained through ultrasonic assisted micro milling.
- TiAlN is the best tool coating in ultrasonic aided Micro milling for low-speed machining of Inconel-718, and the most effective parameters are Speed with 37.86%, Depth of cut 26.09%, Coating 10.92%, and amplitude 6.97%, while feed has the least impact on overall machining reactions.
- Our study also demonstrates the viability of using advanced technology, such as ultrasonic aided micro milling, for the low-speed machining of materials that are difficult to cut, such as Inconel-718.
- When compared to conventional micro milling, which frequently necessitates extra processes like deburring, which might compromise desired tolerances, using ultrasonic assisted micro milling produces better results for surface roughness, tool wear, and burr development.

6.02 Future Recommendations

- This work can be used for explaining the machining forces in ultrasonic assisted micro machining.
- The parameters obtained using multi objective optimization can be tested for other super alloys.

- Ultrasonic assisted machining can be tested for up milling burr formation reduction.
- This work can be used to study machining timing for super alloys specially Nickle alloys Inconel-718.
- Material removal rate for ultrasonic assisted micromachining can be studied using the defined machining parameters.

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