Statistical analysis of Process Parameters during Micro milling of Inconel-718 using cryogenic fluid as cutting coolant

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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

1 Abstract

Modern technological devices demand high accuracy miniaturized components. The utilization of such components manufactured by micromachining of super alloys has significantly increased its application in aerospace and automotive industries owing to their exceptional mechanical properties. Such desirable properties make these super alloys extremely challenging to machine and their quality metrics depends upon surface roughness and formation of burr. This research work is related to analyze the impact of several controllable input factors i.e. Feed rate (µm/tooth), Cutting speed (m/min), cutting depth (µm) and tool coating (TIALN, nACo, uncoated) on surface finish and burr width in micro-milling of Nickel based super alloy Inconel-718 using cryogenic fluid as cutting coolant. Scanning electron microscope (SEM) and Stylus profilometer were utilized to investigate machining samples while Anova statistical analysis for the effect and significance of controllable input parameters in order to find the optimum parameters for desired results. An experimental result confirms that cryogenic cooling offers a clean and effective route to improve sustainability in contrast to conventional machining procedures.

Experimental results show that core factors effecting the burr formation is Depth of cut (DOC) and surface roughness is the cutting velocity. Natures of burr formed during the micro milling of nickel-based alloy Inconel-718 was affected by the depth of cut, chip load and wasn't affected much by cutting velocity. Among the tool coatings nAco Shows promising results for minimum burr formation and TAILN for reduced surface roughness.

Keywords: Micro-milling, Nickel based alloy, Inconel-718, Surface finish, Burr Formation, Feed rate, cutting speed, Depth of cut, Scanning Electron Microscope (SEM), Cryogenic Machining. TIALN, nACo

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2 Nomenclature

DOC = Depth of Cut

CR = Contribution Ratio

SEM = Scanning Electron Microscope

Fz = Feed Rate

HB = Brinell Hardness

HV = Vickers Hardness

n = RPM

Ra = Surface Roughness

Rpm = Revolutions Per Minute

µm = Micrometer

nm = Nanometer

UTS = Ultimate tensile strength

MRR = Material Removal Rate

Vc = Cutting Velocity

Lc = length of slot

Z = No Of Teeth (Milling tool)

AlTIN = Aluminum Titanium Nitrate

nACo Aluminum Titanium Nitrate + Silicon Nitrate

Cr Chromium

HB Brinell Hardness

Cu Copper

M/Min Meter Per Min

Mm Millimeter

Gpa Gigapascal

K = Kelvin (Temperature)

3 Chapter 1: “Introduction”

Mechanical micro-milling defined by its low dimensions is an efficient machining process for precise and dynamic feature generation in numerous materials including metals, polymers, composites and ceramics at high removal rate [1]. The utilization of super alloys miniaturized components have significantly increased its application in industries such Aerospace, Marine, Automotive parts production owing to their exceptional properties that combine hardness, toughness and higher strength at high temperature along with high erosion, oxidation and corrosion resistance [2] [3]. Such desirable properties make these super alloys extremely challenging to machine, inducing a rapid tool wear and increased time that must be overcome. Micromachining of the components is one of the most imperative aspects in the advancement of conventional machining procedures and selection of optimum parameters is necessary to acquire the desired results.

Recent research in micro machining tends towards improvement of Product and Process performance by understanding the influence of numerous lubrication techniques and lubricant types on machinability and surface integrity features [4]. Investigation on using cryogenic machining helps to ameliorate the machinability of super alloys that are difficult to machine under conventional conditions.

3.1 Research Motivation

Micro machining is the substantial manufacturing technique used to create miniaturized components for various defense production industries. Demand for high accuracy and light weight components in automotive and aerospace industry foster the need for improvement in the micro machining of such components. As Inconel 718 is a major material for most of the applications in aerospace and automotive related industries due to its remarkable strength and oxidation resistive properties and cost effectiveness, but also it is one of most difficult to machine material [5]. Inconel 718 accounts for about 70 % of the weight in aerospace applications and almost 50 % of the weight in aero-engine components. [6]

Despite of noteworthy progress in cutting tool and lubrication methods, machining of aforesaid alloy is still a challenge [4]. Therefore, in-depth research and knowledge of the machining behavior of such super alloys using different lubricants and lubricating conditions would be required in order to contribute in this filed from practical point of view as most of the antiquated manufacturing processes are unable to generate the micro-features with desired accuracy required in these industries.

Over the last decade, usage of cryogenic machining for aforesaid alloys has emerged in order to ameliorate the machinability features as remarkable improvements in tool life along with better surface finish can be achieved [7].

3.2 Objectives

I. To examine the impact of input parameters on burr formation

II. To examine the impact of Input parameters on surface roughness

III. To observe the significance of each input factor using ANOVA

IV. Finding the optimum cutting conditions for minimum burr width and reduced surface roughness

V. Comparison of each coating influence on results.

3.3 Scope of Experimentation

This research work is limited to the Micro end milling of Inconel 718 using cryogenic coolant during machining to analyze the effect on the machinability by focusing burr formation and surface finish. Four controllable input parameters are used with 3 levels each, so L-9 array of Taguchi design of experimentation is used to analyze the impact of parameters on output responses of burr formation and surface roughness at lower cutting speeds. Cutting speed ranges from 8000 RPM to 12000 rpm. As lower speed machining setups are readily available and are less expensive than high speed machining system so our experimentation is limited to low speed.

4 Chapter 2: "Literature Review"

4.1 Micromachining

Micromachining of the components is one of the most imperative aspects in advancements of conventional machining processes and assortment of the optimum parameters is necessary to acquire the desired results.

Numerous definitions exist for micromachining terminology. It can be categorized on the basis of sizes as a machining procedure able to develop miniaturized and complicated 3D attributes ranged from (1µm- 999µm) or if the material removal is in microns. If thee tool diameter of milling process is less than 1 mm, it can be categorized as micro milling process [2].

Table 1 (Definition of Micromachining by several researchers)

Researchers	Year	Description of Micromachining
Masuzawa and Tonshoff **[8]**	1997	1. According to researcher definition of micromachining vary from time to time depending upon cutting tool, material, stakeholders. 2. During micromachining unreformed chip thickness should ranges from 0.1 to 200µm.
Liu et **[9]**	2004	In micromachining Cutting edge of tool should be analogous to chip Load.
Chae et **[10]**	2005	It is a process of developing miniaturized components with intricate features ranges from 10 microns to few millimeters in dimensions.
Simoneau et **[11]**	2006	For micromachining grain size of the work piece material should be greater than Chip load/depth of cut.
Aramcharoenet **[12]**	2008	1. In micromachining diameter of tool diameter should be in range of 1 to 999µm. 2. Tool cutting edge radius and material grain size shouldbe comparable to unreformed chip thickness

Salient features of micro-milling are comparable to the conventional sized milling process except for some key differences which includes: (i) cutting tool size ranges from (Ɵ of 25 µm or 50 µm), [13] (ii) high length-to-diameter ratio. The critical tool size and vibrations during machining process often leads to tool damage results in poor surface finish [14].

When compared to traditional macro milling, Material Removal Rate (MRR) is quite low in micro milling. Most challenging problem during such machining is the Material Removal Rate (MMR) [15]. This problem occurs due to difference in cutting mechanisms and work piece size in comparison to macro machining [16].

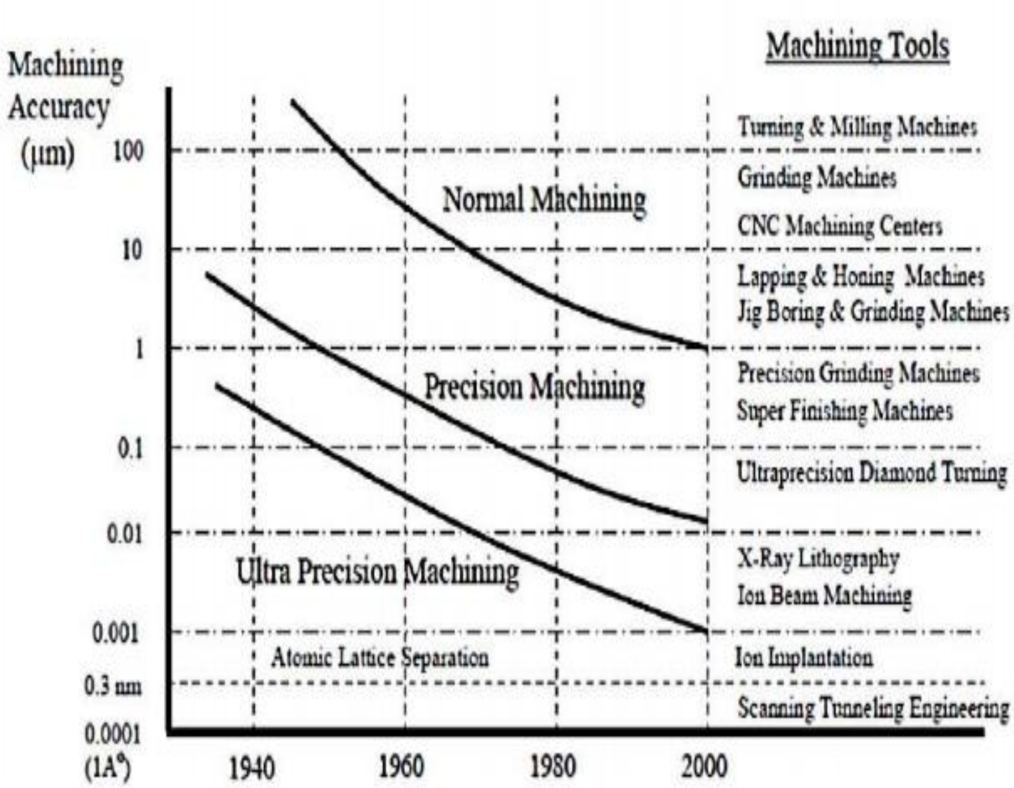

Figure 1 (Recent development in micro machining process) [17]

4.2 Super Alloys

Alloys with brilliant characteristics like increased strength at higher temperature and resistance to oxidation and corrosion can be categorized as "superalloys." Nickel, Chromium, iron cobalt, aluminum, titanium, and other elements are prudently mixed alloying additions for super alloys based on nickel. Material of workpiece used in our experimentation is Inconel 718 which is one of the nickel super alloys with above mentioned properties. Inconel-718 is a key material for most of the applications in aero and automotive industries due to its extraordinary hardness and oxidation resistive properties and cost effectiveness, but also it is one of most difficult to machine material [18].

According to literature review classification of super alloys can be categorized as shown in figure below.

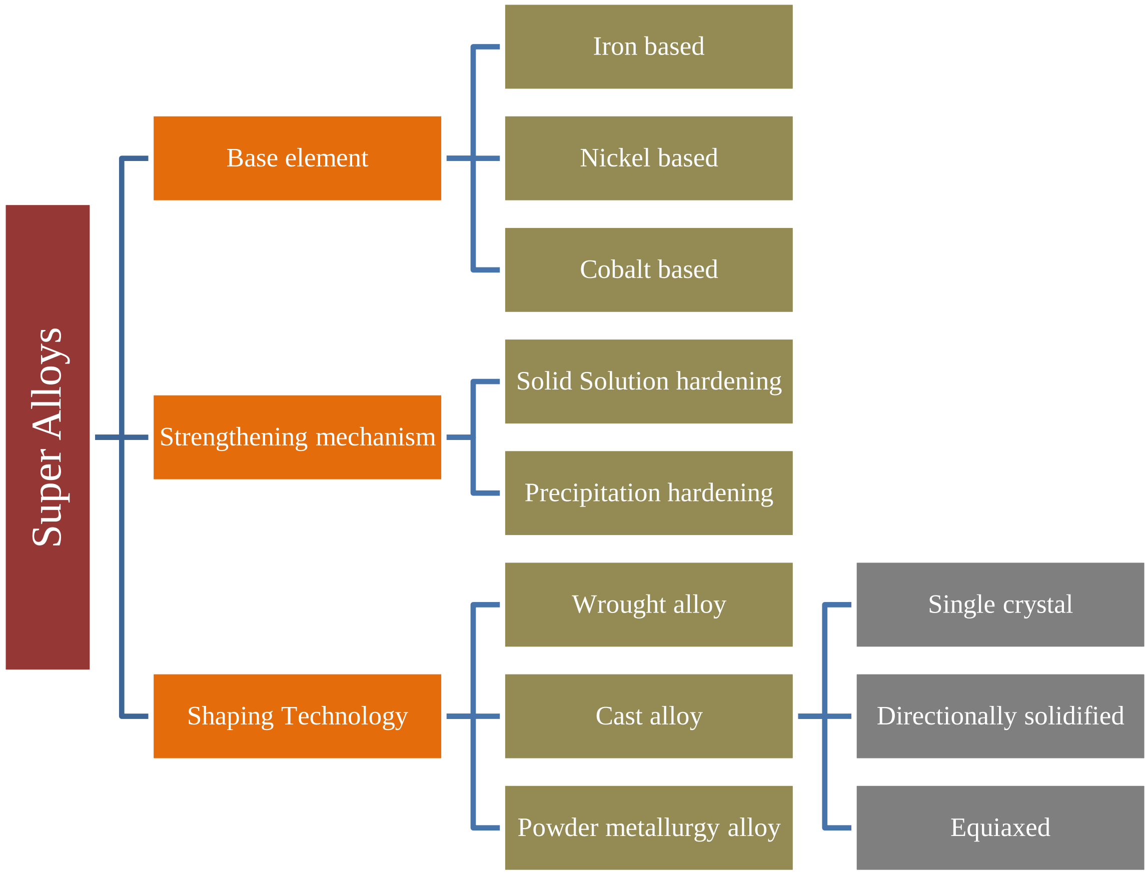

Figure 2 (Classification of Super Alloys) [18]

According to literature review, due to thermal and mechanical qualities, like strain-hardening features and abysmal heat conduction, Inconel 718 does not have high machinability in comparison to other conventional aluminum alloys, mild steel, or stainless steels. Some of the major issues while machining of Inconel-718 are; (i) Reduced tool life owing to abrasion and hardening characteristics. (ii) High temperature and pressure at tool-work piece interface leads to surface roughness and work piece hardening [19].

While machining of alloys based on nickel like Inconel-718 with poor thermal conductivity and higher shear strength, conventional coolants used over the years for other materials were not enough to lower the temperature at tool chip interface. Main reason of failure to reduce the temperature at interface of tool and chip was due to hindrance in diffusion at higher temperature on cutting zone [20] [7].

4.3 Burr Formation

Whenever a machining operation is performed on the workpiece, undesired slanted material will remain on the surface along the edges of the cutting tool commonly known as burr. A lot of research work was performed to acquire optimum cutting conditions and cutting environment to minimize the formation of burr during machining process. In contrast to macro machining, post processing is difficult in case of micro machining so these undesired sharp edges must be minimized or avoided from the workpiece to perform more efficiently in its application. Reduction of burr formation results in improvement of the tool life.

Dornfeld et al. in his research on micro milling concluded that tool wear and feed during machining process directly relates to burr height. As the tool cutting edge radius increases larger burr will be produced. He also concluded that tool entrance and exit burr for micro milling is more than macro milling process keeping in view its ratio of burr size to chip load. [21]

Formation of burr and uncut chips during the micro-milling process directly affects the life of tool by increasing tool wear and surface quality as possibility of post processing is not feasible because of limitation in part geometry and accuracy requirement in contrast to macro milling process, where post processing is done to achieve the desired results [10].

The application of a coating to the micro milling tool assisted in resolving existing tool life and burr formation issues. TiAlN and DLC coatings were found to be predominantly favored for micro-milling operations owing their exceptional corrosion resistance and higher strength during machining process [22].

Lekkala et al. performed micro milling of Steel and Aluminum alloys to analyze the burr formation using theoretical approach and experimentation. After experimentation it was concluded that burr width increases as cutting tool diameter and no of flutes are reduced, irrespective of up or down milling conditions [23].

Filiz et al. performed the micro machining for copper based alloy 101 using carbide tools to analyze the impact of process parameters on formation of burr It was observed that as cutting speed increases burr formation will also increase in contrast to feed rate as machining process at higher feed rates is subjected to shearing leads to less burr formation in comparison to ploughing. [24]

4.4 Surface finish

Xiao Hong Lu et al observed that cutting parameters influencing the surface roughness during micro milling includes tool condition, cutting parameters and experimental setup vibrations. As the cutting length increases, surface roughness first decreases but tends to increase as the cutting length increases further [25].

Alexander Meijer performed the simulations of machining procedure with the intention to reduce the surface roughness of material under consideration by considering the feed rate and cutting-edge radius as controllable input factors. It was observed that micro machined surfaces were greatly impacted by these input parameter [26].

Abd Raman et. al concluded that input parameters affecting the tool life are feed rate and axial cutting depth while for surface roughness cutting velocity is crucial factor to optimize. Minimum Quantity Lubrication (MQL) shows significant improvement in stability during the micro machining process of Inconel 718 alloy in contrast to dry milling process [27].

Irfan Ucen et. al performed the micro milling of Inconel 718 under MQL and Cryogenic precooling technique and concluded that surface finish of the sample will be increased by 25-60% in comparison to the dry milling condition. [28]

4.5 Cryogenic Machining

Machinability of difficult to cut materials like alloys based on titanium and nickel is a great challenge and researchers are using different techniques to improve the machining performance of such materials. Different cutting fluids were used to reduce the heat generation at tool-chip interface but environmental hazards of such lubricants led to their replacement and development of ecofriendly machining techniques and cutting fluids during machining. Research on cryogenic machining these days is on peak. It is proposed that machining under cryogenic environment helps to upgrade the sustainability of machining process. Also, its safe and eco-friendly in contrast to conventional lubrication machining. [29]

Evolution of cryogenic machining to replace conventional machining results in 44.7% reduction in running cost and substantial increase in tool life which is 169% higher in contrast to conventional flooded lubrication [30].

Keeping in view the environmental concerns related to orthodox cutting fluids mostly used in the industries, MQL is considered as an effective substitute of the flood cooling but recent research emphasized the basic understanding of the cryogenic cooling methods with the intention of finding an ecological and economical alternative due to their superior performance in machining processes; where liquid Nitrogen and CO_2 are used as cryogenic media [4]. Experimental results in the research proved that flooded cryogenic machining approach using LN2 generated improved results in contrast to the conventional dry machining of the Ti-6Al-4V [31].

Cryogenic cooling at the interface of tool and chip guides to reduction in heat, improved distribution of temperature so contributes towards economical and efficient machining of hard to cut materials. Cryogenic cooling ameliorates temperature generation issues but correspondingly contributes towards better cutting speed and hence productivity by saving time to machine [7] [32].

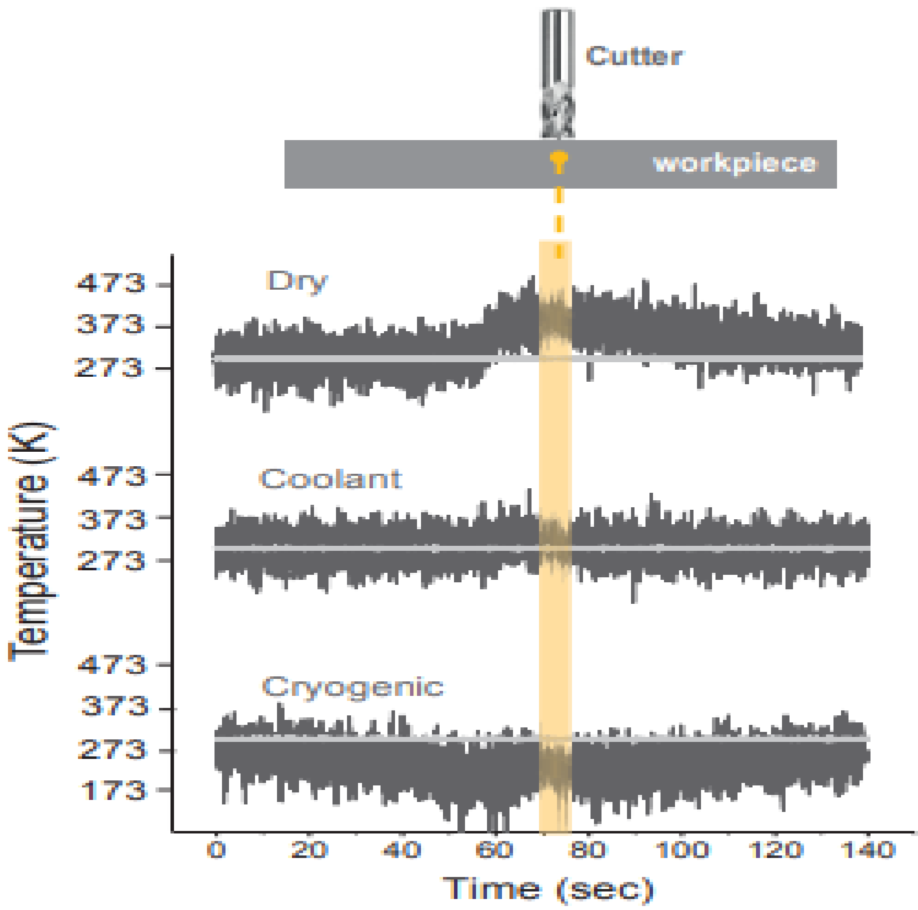

Figure 3 (comparison of temperature variation at tool-chip interface at different cutting conditions) [4]

Zhang made comparison of different cutting fluid conditions with two different materials Al6061 and steel 1018 while machining. Slots were formed on workpiece under Full immersion conditions and results showed that better finish in terms of reduced roughness can be obtained by the oil water mixture because of its exceptional properties in comparison to others [33].

Kumar et al calculated the impact of cryogenic cutting while machining stainless steel work piece. Cutting forces were significantly reduced while cryogenic fluid is used in comparison to dry because of reduced frictional coefficient at tool-chip interface [34].

Hong et al investigated the cryogenic lubrication while machining the titanium alloy (Ti-6Al-4V).

Frictional coefficient at chip-tool interface and forces generated were significantly reduced as at lower temperatures materials are less sticky [35].

In contrast to lubrication based on oil and water, cryogenic fluid disperses back into the atmosphere due to their lower temperatures. As a result, such machining processes can be categorized as dry process and environment along with workpiece are considered to be oil and contaminated free [36].

Ampara Aramcharoen et al concluded that maximum cutting temperature in micro- milling of Inconel- 718 was recorded to be 843 K while in case of cryogenic cooling it was reduced to almost half. Results illustrates that cryogenic cooling media can pierce more effectively into machining zone and leads to reduction in cutting temperature and conduction of heat through surroundings [12].

4.6 Survey of previous research on Micromachining of Inconel-718

Table 2 (Summary of Previous experimentation by different researchers on micro-machining of Inconel-718 alloy)

SR #	Work piece Dimensions	Tool Specifications	Cutting Parameters	Conclusions	Reference #
1	40mmx30mmx10 mm	Carbide tool Ø =0.768 mm Coatings = TIALN, ALCrN, DLC, , AlTiN+WC/C, AlCrN + TIALN .	Feed rate (mm/Tooth) = 1.25, 2.5, 3.75, 5 DOC (mm) = 0.1, 0.15, 0.2	1. High tool wear at lower feed rates with less DOC. 2. Optimal parameters for better surface finish, feed rate= 2.5 µm/Tooth,DOC= 0.15mm and Coating= DLC	[22]
2	500mm x 50mm x102mm	Cemented Carbide tool Ø =0.3 mm Flutes=2	RPM= 50000, 60000, 70000, 80000, 90000 Feed rate (um/Tooth) = 0.4, 0.5, 0.6, 0.7, 0.8, DOC (µm) = 10, 15, 20, 25, 30	Optimal parameters for better surface finish, feed/tooth 0.4µm, RPM=80000 , DOC= 10µm	[25]
3	50mm x 40mm x7mm	Cemented Carbide tool Ø =0.5 mm Flutes=2	RPM= 15000, 30000 Feed rate (mm/min) = 2,4 DOC (mm) 0.1, 0.15	1. MQL showed promising result for surface finish. 2. Optimal parameters for better surface finish and less tool vibrations are feed rate = 2mm/min, RPM=15000, DOC= 0.1mm	[27]
4	500mm x 50mm x102mm	Cemented Carbide tool Ø =0.6 mm Flutes=2	RPM= 39680, 49600, 59520, 69440, 79370, Feed/tooth(µm/tooth) = 0.3, 0.5, 0.7,	1. Minimum forces at DOC=15µm and 0.3µm feed per tooth. 2. Ratio of the minimum chip	[37]

			0.9,1.1 DOC(µm) = 10, 15, 20, 25, 30, 35.	thickness to the radius of cutting tool is around 3.5.	
5	30mm x 35mm x22mm	Carbide tool Ø =0.5 mm,2 flutes Coatings =uncoated, TIALN	Cutting speeds 10/,25, 20 feed per revolution 0.4, 0.6, 0.8 DOC (µm) =30, 60, 80.	1. The optimum parameters found for the surface roughness are Cutting speed=25, fz/re=0.6 DOC=30 and coated tool. 2. Optimal parameters for reduced burr formation Vc=40, fz/re=0.6 ,DOC=60 and uncoated tool.	[38]
6	Length of slot = 8 mm	TIALN coated Carbide tool , 2 flutes	Feed per tooth (µm/z)= 0.1,0.3,0.5. DOC (µm) = 20,30 40. RPM = 40,000, 60,000, 80,000.	Depth of cut significantly effecting the response of surface roughness. MRR is affected by feed per tooth.	[39]
7	Dimensions= 30 mm × 10 mm × 3 mm slot length = 10 mm	TIALN coated carbide tool Ø = 0.5 mm	Feed /tooth = 0.1- 6 DOC =0.1mm Speed=5000 Coolant: vegetable Oil (Sunflower based) flow= 50 mL/h	1.On Average 37% reduction in burr width and 32 % surface roughness reduction obtained by using aforesaid coolant in comparison to dry machining.	[40]
8	Dimensions= 15 mm × 10 mm × 15 mm Length of cut = 15 mm	carbide tool Ø = 0.4 mm Coating = ALTIN	Feed per tooth= 3 DOC= 40mm RPM = 20,000, Coolant flow rate= 40.7 mL/hr	1. At higher flow rate surface finish improved by 60%. 2. optimal condition for improved quality slots are: Pulses/min = 200 Flow = 270 ml/h	[6]

Detailed literature review shows that most of the researchers used different coatings, machining parameters, and cutting fluids in order to develop the optimum input controllable parameters effecting machining process. Previously most of the research was focused on high cutting speed owing to its advantage of less burr formation and tool vibration characteristics. As low speed machining setups are readily accessible and less expensive in comparison to higher speed machining setup so this experimentation is limited to low speed.

4.7 Techniques used for Micro machining

Different techniques used for micromachining are categorized into following.

1. Mechanical Micromachining (Micro cutting, Micro Milling)
2. Photolithography
3. Laser Technology
4. Micro-EDM

This research is related to the Mechanical micromachining (Micro-milling) of the alloy based on nickel known by Inconel-718. Machining of such super alloys is a great challenge due to their incomparable mechanical and resistive properties. Most of the research these days focused on micromachining of these alloys because of their increased demand in the automobile and aerospace industries.

Mechanical Micromachining process is capable of producing miniaturized and intricate components made up of difficult to machine materials which make it superior to other micromachining technologies. As in case of the mechanical micromachining, cutting tool touches the workpiece, therefore results in higher material removal rate in comparison to other categories which make it more suitable for mass production of the miniaturized components [17].

5 Chapter 3: "Work-piece material and controllable input parameters selection"

5.1 Selection of Work Piece Material

Selection of workpiece material is very significant in research field as each material exhibits different mechanical, thermal and physical properties which leads to pros and cons of each type. Material selection for the experimentation solely depends upon the desired properties in the final product and available materials. Material of workpiece used in the following experimentation is nickel based Super alloy Inconel-718. The dimensions of each work piece material are 20mm x 10mm x 7mm.

Nickel based super alloy Inconel-718 is one of the experimentally proven high-performance material commonly known for its ability to endure rigorous operating conditions in different industries i.e. Aerospace, Automobile and Defense components [41]. In contrast to high strength, such materials exhibit poor thermal conductivity which makes them difficult to machine. Increased wear of tool and increased surface roughness during machining are the major problems related to such super alloys [3].

The solid bar of Inconel-718 was procured from one of the authentic suppliers and the material composition was confirmed by mass spectrometry. Comparison for chemical composition for typical Inconel 718 and workpiece used in the experimentation are shown below.

Table 3 (Comparison for chemical composition of typical Inconel 718 and workpiece used in the experimentation)

Element	Reported Percentage	Measured percentage
Carbon	Max 0.08	0.033
Sulphur	Max 0.015	0.0004
Silicon	Max 0.3	0.26
Manganese	Max 0.35	0.32
Chromium	Max 17-20	19.24
Nickel	50-55	52.75
Molybdenum	2.80-3.15	2.95
Titanium	0.75-1.15	1.06
Aluminum	0.20-0.60	0.36
Cobalt	Max 1.00	0.04
Copper	Max 0.30	0.04

Niobium	5.45 max	4.49
Iron	17-20	18.61

The physical and mechanical properties of Nickel based alloy Inconel-718 are compared with other alloys of similar kind.

Table 4 (Inconel-718 mechanical properties comparison with other AerospaceAlloys) [2]

Properties	**Material**					
	Inconel 718	Ti6Al4V	Ti-6Al-6V-2Sn	Ti-10V- 2Fe-3Al	Al 7075- T6	Al6061- T6
Density (g/cm^3)	8.22	4.43	4.54	4.65	2.81	2.7
Hardness (HV)	361–438	285–342	361	303	~ 175	104
UTS (MPa)	1350	950	1060	960	572	310
Yield Strength (MPa)	1170	850	970	900	503	275
Modulus of Elasticity (GPa)	200	113	110	115	71.7	69
Ductility (%)	16	14	14	9	11	12-14
Fracture Toughness ($MPa\ m^{1/2}$)	96.4	75	60	-	20–29	-
Thermal Conductivity (W/mK)	11.4	6.7	6.6	7.8	130	167
Max. Operating Temperature (°C)	650	315	315	315	-	-

5.2 Cutting Parameters Selection

To perform any machining operation selection of optimum input process parameters is very critical. For each machining operation to be performed several process parameters must be selected during the planning phase of the operation.

In our case controllable input parameters includes.

1. Depth of cut (DOC).
2. Feed Rate.
3. Cutting velocity.
4. Tool Coating.

Cryogenic machining conditions using liquid nitrogen as a cutting coolant were used in the micro end milling slots formation by varying the input parameters and tool coatings.

5.2.1 Depth of cut (DOC)

Normally depth of cut is selected on the basis of geometry of workpiece or final shape of the Productor tool limitation. From literature optimal depth of cut for minimum burr formation during micromachining of Inconel-718 is 60 µm [38].

Final selection of the depth of cut in our experimentation is on the basis of literature by Niagara cutters according to which if cutting tool diameter is ≤ 3.175mm, then depth of cut should be calculated by

$$\text{Depth of cut} = \text{Diameter of cutting tool (D)} \times (0.05 \text{ to } 0.25)$$

Equation 1 [42]

As tool diameter used in this research is 0.5mm, therefore optimum depth of cut range is

- ✓ Minimum depth of cut = 0.5mm x 0.05 = 0.025mm
- ✓ Maximum depth of cut = 0.5 x 0.25 = 0.125mm

AS maximum allowable depth of cut is 0.125mm and minimum is 0.025 mm, therefore selected depth of cut is 30 µm, 60 µm, 90 µm.

All the machining operations will be performed under cryogenic conditions to investigate the outcome on surface finish and burr formation during machining. These input parameters are selected on the basis of recommendations by manufacturer for the equipment used during the experimentation.

5.2.2 Feed per tooth

According to the J.Chae workpiece elastic recovery is responsible for cutting forces at chip tool interface at minimum chip thickness [10]. AJ Mian suggested that minimum chip thickness in case of Inconel-60 was 18.5-25.5 percent of tool cutting-edge radius. Ratio between tool’s cutting-edge radius and feed per flute is dominating factor in reduction of burr formation. [38]

In our experimentation feed per tooth are following

- ✓ Above cutting-edge radius experimentation: 5,6,7 µm/tooth.

5.2.3 Cutting Speed

As discussed earlier, low speed machining range will be used during the experimentation. Cutting speed for micromachining of Inconel 718 are planned between 8000 RPM to 12000 RPM.

5.2.4 Tool coating

Solid carbide end mill used for the experimentation purpose were imported from the reliable supplier from china (Changzhou North Carbide Tool Co., Ltd.) Total of 30 tools were purchased for micro milling of the Inconel-718. Two different coatings (TIALN, nACo) along with uncoated tool of same quantity were comprised in the order to analyze the outcome of tool coating. Selection of the tool coating is on the basis of literature review [43]. Separate tool is used for each slot in order to avoid the tool wear contribution during the machining process.

Technical specifications of End mill carbide tools areas as following.

Table 5 (Technical specifications of tools used)

Description	Specifications
Brand Name	BFL Tools
Material	Tungsten Carbide steel
Diameter	0.5mm
Type	Square End Mill
Overall Length	50mm
Flutes	Two flutes
Shank Diameter	4mm
Cutting length of flute	1mm
Hardness	60 HRC
Helix angle	50-60◦
Precision	High Processing
Type:	High Hardness Metals
Usage:	High Speed Cutting
Grain Size:	0.5µm
Flexural Strength	43000 N/mm
Co	12%

Figure 4 (Coated carbide tools used in experimentation)

Table 6 (Properties of various tool coatings used in experimentation) [44]

Tool Properties	Tool Coatings	
	TIALN	nACO
Hardness (HV)	3200	42 (GPA)
Thickness (um)	2.5-3	3
Oxidation temperature	900	1200
Friction coefficient	0.3	0.4
Colour	Black	Blue

Cutting-edge radius of tools are determined by means of Scanning Electron microscope. The average edge radius for respective tools are given below.

Table 7 (Cutting edge radius of tools)

Tool	Average Edge Radius
Uncoated Carbide End Mill	4.04 µm
TIALN Carbide End Mill	3.367 µm
nACo Coated End Mill	2.78 µm

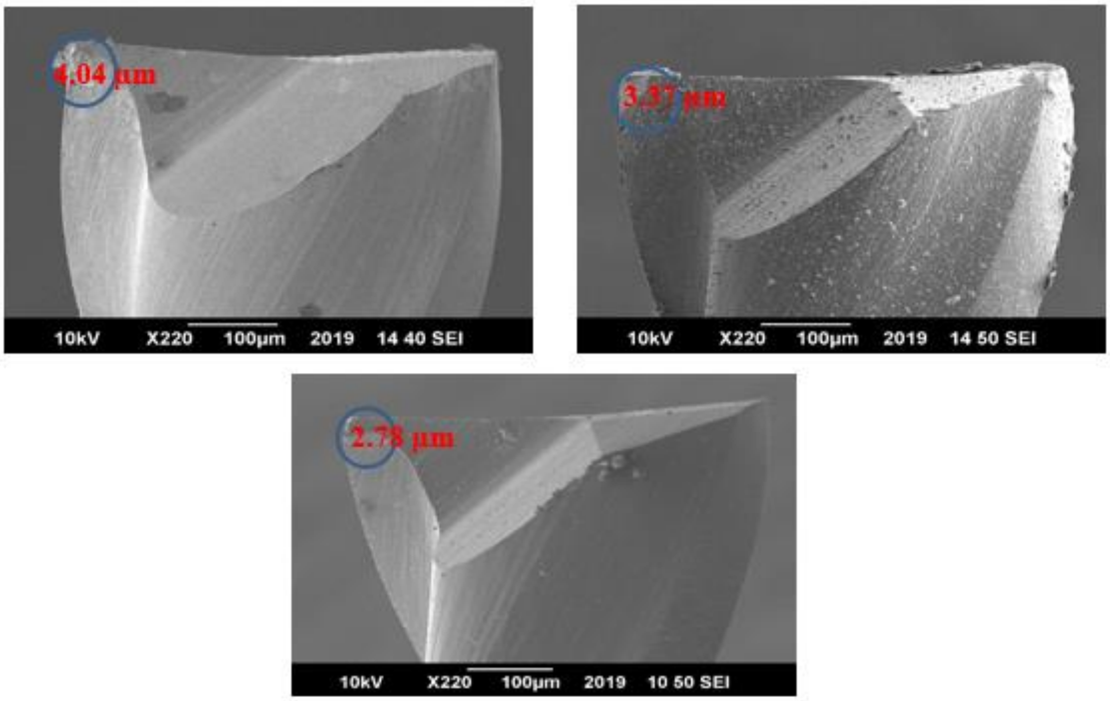

Figure 5 (Tool Cutting edge radius microscopic results)

6 Chapter 4: Taguchi Design of Experiments (DOE)

Taguchi's design of experiments is very popular in recent research due to its ability of reducing the no of experiments without compromising the efficiency. It is an important tool for robust design. It utilizes pair of combinations instead of factorial design which make experimentation lengthier and less cost effective. It allows you to collect all the necessary data to analyze the effect of each input parameter on product quality with less no of experiments. In following experimentation, we have four independent input parameters with 3 levels each.

Table 8 (Input parameters and their levels)

Parameter	Units	Level 1	Level 2	Level 3
Cutting velocity (Vc)	m/min	12.56	15.386	18.212
Feed rate (f)	µm/tooth	5	6	7
Depth of cut (d)	µm	30	60	90
Coating		TIALN	nACo	Uncoated

All the experiments will be performed under cryogenic cooling conditions to decrease the temperature effects at tool and chip interface. We had option for L9 array with selected input parameters. Combination of experiments by Taguchi are shown below.

Table 9 (Taguchi Design of Experiment)

SR #	Depth of cut (µm)	Table feed (Vf) (mm/min)	Feed/ tooth (fz) (mm/tooth)	Spindle Speed (RPM)	Cutting velocity (m/min)	Coating
1	30	80	0.005	8000	12.56	TIALN
2	30	117.6	0.006	9800	15.386	nACo
3	30	162.4	0.007	11600	18.212	Uncoated
4	60	98	0.005	9800	15.386	Uncoated
5	60	139.2	0.006	11600	18.212	TIALN
6	60	112	0.007	8000	12.56	nACo
7	90	116	0.005	11600	18.212	nACo
8	90	96	0.006	8000	12.56	Uncoated
9	90	137.2	0.007	9800	15.386	TIALN

Each experiment should be performed twice to reduce the chance of error. Fresh cutter was used for each slot to rule out the effect of tool wear on surface roughness and burr width.

7 Chapter 5: Experimental Setup and Methodology

7.1 List of Equipment

Equipment used or the experimentation purpose can be categorized into following types.

1. Machining Equipment
2. Data Collection Equipment

List of the equipment used in experimentation are as follows.

1. EDM Wire Cut CNC Machine
2. Surface Grinder Machine
3. CNC Milling Machine
4. Scanning Electron Microscope (SEM)
5. Stylus Profilometer
6. Micro Hardener Tester

7.1.1 EDM Wire cut Machine

EDM Wire cut Model # (DK7750H), make (TOPSCNC) was used to cut the Inconel-718 sample into the required workpiece dimensions.

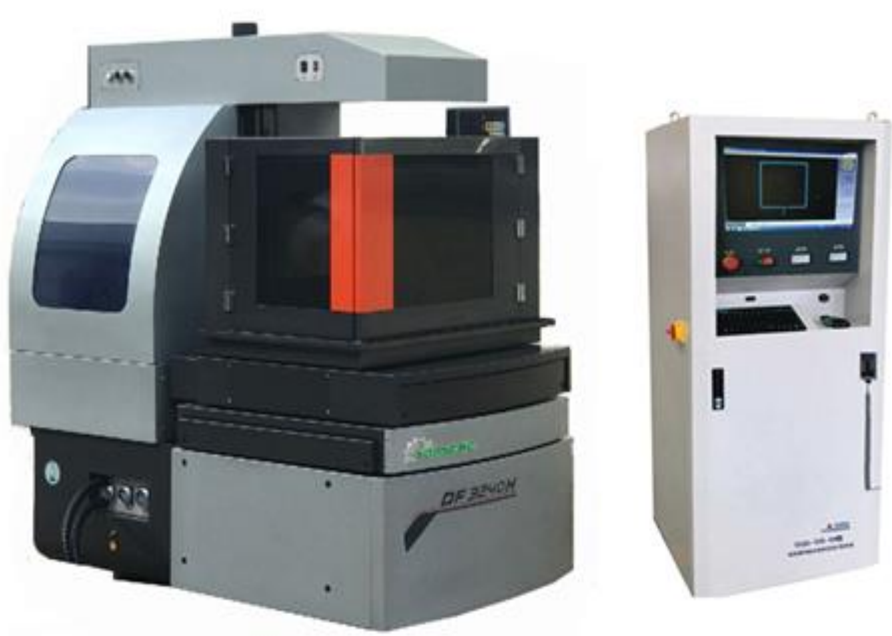

Figure 6 (EDM Wire cut Machine) [45]

7.1.2 Grinding Machine

Grinding machine Model # (1400x), make (Jones & Shipman) with Magnetic Bed, Opti dress and microprocessor-controlled unit was used to grind the surfaces of the workpiece to make them ready for the machining process in milling.

Figure 7 (Surface Grinder) [46]

7.1.3 CNC Milling Machine

CNC milling machine of make (Sky MASTER), Model # (VF-108) was used to make multiple slots in the workpiece at different selected input parameters defined by Taguchi design of experiment. Length of each slot was fixed at 10mm.

During machining process coolant used as cutting fluid was Cryogenic coolant (liquid Nitrogen). All the slots were machined under cryogenic environment.

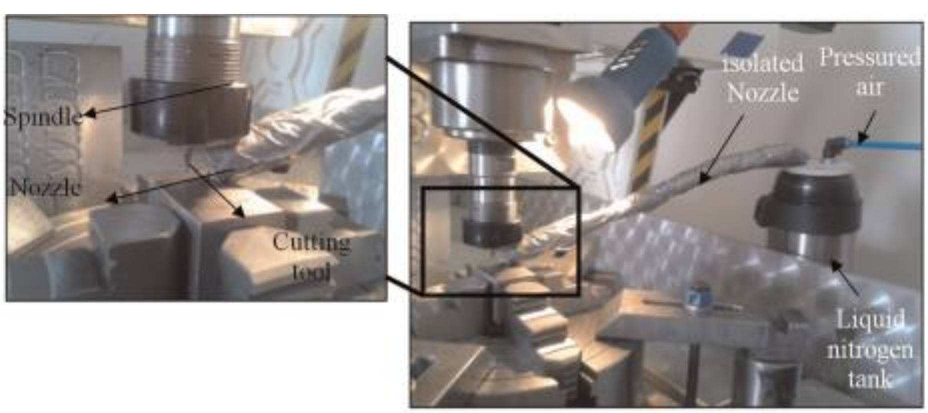

Figure 8 (Experimental setup using cryogenic cooling) [22]

Figure 9 (CNC Milling machine) [47]

The specification for the CNC milling machine used in the experimentation are as follows.

Table 10 (Specifications of CNC Milling machine used in experimentation)

Company = Sky master High speed Vertical Milling Center
Model = VF-108
Control = Fanuc Series oi-MF
Company = Sky Master- Kraft Co., Ltd, Germany
Spindle Speed = 15,000 RPM (Direct driven)
Working Area of Machine (X, Y, Z) axis = 1080,600,620 mm
Rapid traverse in (X, Y, Z) axis = 36000, 36000, 24000 mm/min
Max feed rate = 10,000 mm/min
Tool Capacity = 24 PCS
Max tool diameter = 130mm
Max length of tool = 300mm
Max weight of tool = 8 Kg
Max loading capacity = 1000kg

7.1.4 Stylus Profilometer

Stylus Profilometer was used to analyze surface roughness of the machined slots under different input parameters. It helps to extract the topographical data from the surface of machined part. Patterns developed by the profilometer helps to decide the surface roughness of machined part.

Specification and pictures to be inserted

7.1.5 Scanning Electron Microscope

Scanning Electron Microscope of make (JOEl), Model # (JSM-5910LV) was used to examine the burr formation pattern in slots during the micro machining of Inconel 718 at different input parameters and under cryogenic cooling conditions.

Figure 10 (Scanning electron microscope (SEM))

7.1.6 Micro Hardener Tester

Micro hardness tester is utilized to calculate the Vickers's hardness value of Inconel 718 alloy. Four tests were steered on different areas to be more accurate. Dwell timing value was set to be 15sec with the 4900mN force was used during the test.

Figure 11 (Vickers Hardness Tester, Vexus-hv 1000z) [48]

The formula to calculate the Vickers hardness is given below

$$HV = 1.854(F/D^2)$$

Equation 2 [49]

F is applied force and D is mean diameter of d1 and d2 [50]

Table 11 (Results of the Vickers Hardness test)

Experiment #	1	2	3	4
D1(mm)	0.0047023	0.0047065	0.006928	0.0046
D2(mm)	0.0047351	0.0047193	0.0047214	0.0046449
Mean	0.0047187	0.0047129	0.0047071	0.0046288
HV	408	409	410	424

Average value of the Vickers hardness value is 412.75

7.2 Methodology

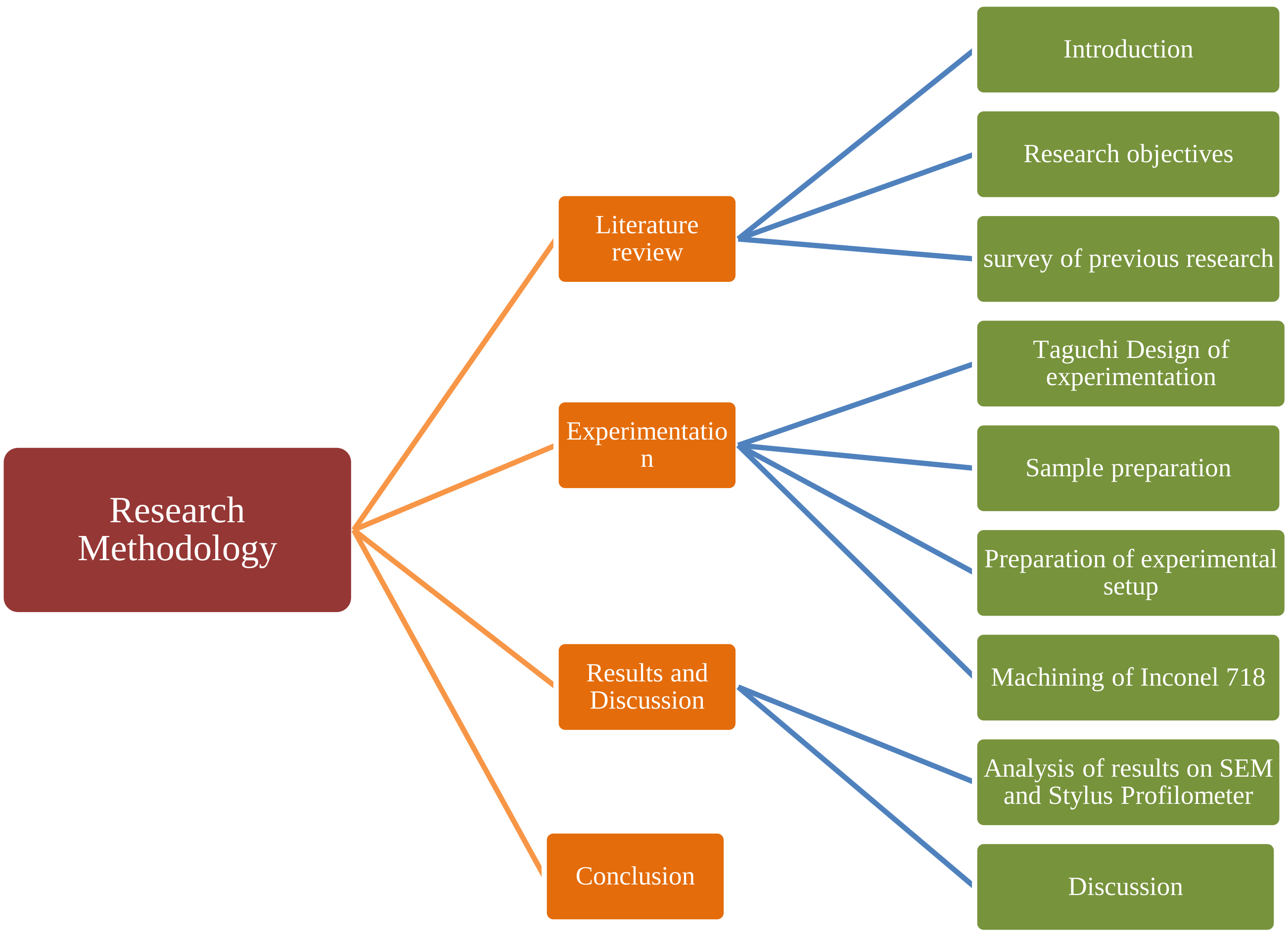

Figure 12 (Research Methodology Manifestation)

After the detailed literature review preparation of the required workpiece from raw samples was executed and later on micro milling experiments according to Taguchi design of experiments were performed on the super alloy Inconel-718 based on nickel considered as one of the hardest materials to machine. For each slot separate carbide tool was used to rule out the possibility of tool wear and its outcomes on the surface roughness and burr formation. The tools used are flat end mill with cutting dia of 0.5mm with helix angle of 50-60 degree. The dimension of the work piece is 20x10x7mm. The length of the slot for all the experimentation was 10 mm to avoid the effect of damage to tool.

Schematic illustration of the experimental setup is shown below.

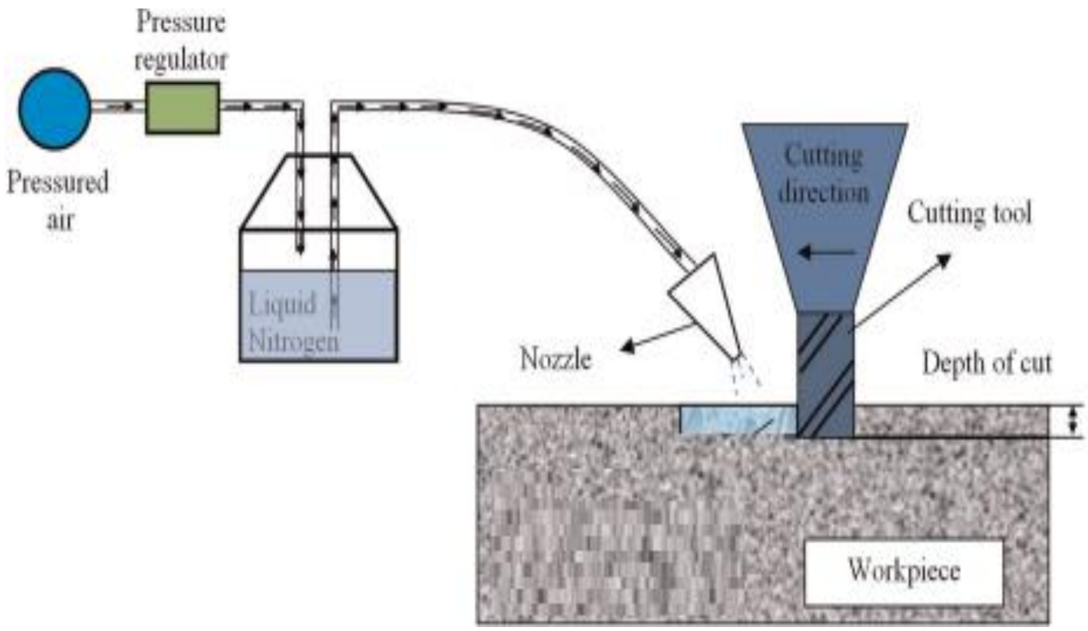

Figure 13 (Schematic of experimental setup) [22]

Brief summary of experimental conditions are as follows.

Table 12 (Brief summary of experimental conditions)

Workpiece	**Inconel-718**
Dimensions of workpiece	20mm*10mm*7mm
Tool Diameter	0.5mm
Flukes	2
Cutting Length	10mm
Cutting Fluid	Cryogenic (Liquid Nitrogen)
Tool Coatings	TIALN, nACo, Uncoated

8 Chapter 6: Results and Discussion

8.1 Results

Surface roughness and maximum burr width values are the major outcomes of the results obtained from the micro machining of the Inconel 718 under cryogenic environment. In case of micro milling, it is tough to quantify the curled burr shape, therefore formation of burr can be measured as max burr width or max burr height in micro domain experiments [51].

Burr width of the down milled micro slots was calculated by means of Scanning Electron Microscope (SEM). Top burr was the point of focus during SEM analysis. Roughness value (Ra) of the surface was measured using the Stylus-type Talysurf ® profilometer.

Table 13 (Results for Max burr width(μm) & surface roughness (nm))

Input Parameters					Burr Width (μm)			Surface Roughness (nm)		
Trial #	**Depth of cut (μm)**	**Cutting Speed (RPM)**	**Feed per tooth (mm/tooth)**	**Coating**	**Trial 1**	**Trial 2**	**Average**	**Trial 1**	**Trial 2**	**Average**
1	30	8000	0.005	TIALN	163.2	130.8	147	280	304	292
2	30	9800	0.006	nACo	121.5	135.6	128.55	261	295	278
3	30	11600	0.007	Uncoated	139.5	186.8	163.15	297	269	283
4	60	9800	0.005	Uncoated	108	128.2	118.1	275	317	296
5	60	11600	0.006	TIALN	118.6	105.8	112.2	263	301	282
6	60	8000	0.007	nACo	106	126.8	116.4	323	335	329
7	90	11600	0.005	nACo	74.53	67.2	70.865	284	294	289
8	90	8000	0.006	Uncoated	97.5	118.5	108	349	327	338
9	90	9800	0.007	TIALN	114.5	95.2	104.85	315	299	307

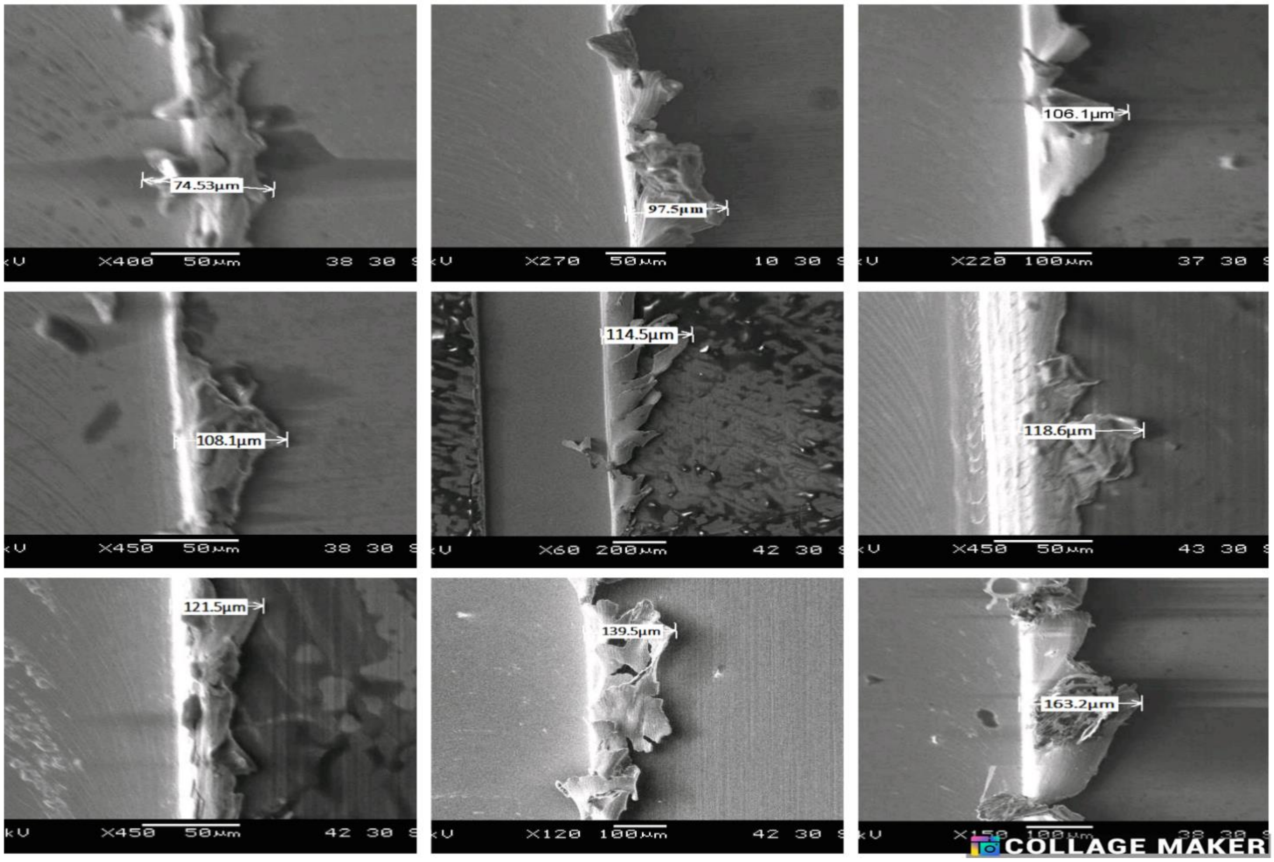

Figure 14 (SEM Images for trial 1 of burr width)

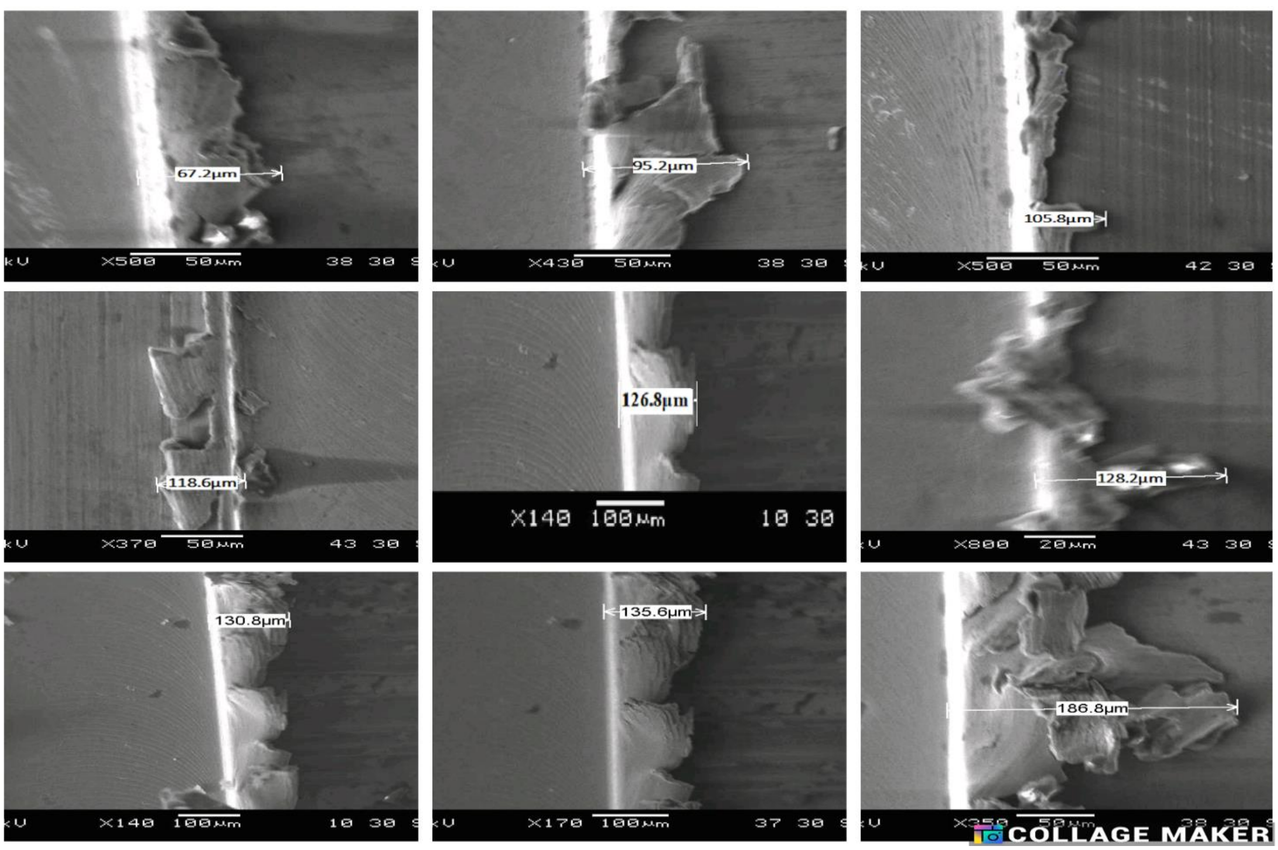

Figure 15 (SEM images for trial 2 of burr with)

8.2 Discussion

After compilation of the results from experimentation, statistical analysis obtained were analyzed using Variance analysis software ANOVA. It divides the observed cumulative inconsistencies obtained from results into two major categories commonly known as systematic and random factors. Systematic factors significantly affect the data set while random factor can be neglected to simplify the analysis [52].

As all the trials were repeated twice for confirmation so their average value was used in the analysis. Variance analysis was done by calculation of the sum of squares for each measured factor by applying the standard equation as shown below.

Equation 3 (Sum of squares formulae)

$$SS = \sum_{i=1}^{n} (Yi - Y')^2$$

n is the number of observations performed. [52]

Higher value of variance indicates the higher influence of the factor on the outcomes of the results. To calculate the percentage of contribution by each factor on results following equation is used.

Equation 4 (Percentage of Contribution)

$$\% \text{ Contribution (CR)} = {MSS - SS_{res}}/{SS_{total}} \text{ x } 100$$

If p-value falls lower than 5% than it depicts that input process variable under consideration has noteworthy impact on the results. [52]

Factor Information

Table 14 (Factors details for ANOVA General linear model)

Factor	Type	Levels	Level values
Depth of cut (µm)	Fixed.	3	30, 60, 90
Feed/ tooth (fz) (mm/tooth)	Fixed.	3	0.005, 0.006, 0.007
cutting velocity (m/min)	Fixed.	3	12.560, 15.386, 18.212
Coating	Fixed.	3	nACo, TIALN, Uncoated

Table 15 (Variance analysis (ANOVA) for Max burr width formation on down side)

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Depth of cut (µm)	2	4215.0	58.43%	4215.0	2107.5	15.79	0.004
Feed/ tooth (fz) (mm/tooth)	2	404.3	5.60%	404.3	202.1	1.513	0.126
cutting velocity (m/min)	2	470.0	6.52%	470.0	235.0	1.754	0.153
Coating	2	2124.7	29.45%	2124.7	1062.3	7.959	0.012
Error	0	*	*	*	*		
Total	8	7213.9	100.00%				

Equation 5 ((Regression Equation for Max burr width formation on down side)

Regression Equation

burr avg = 117.9 + 28.31 Depth of cut (µm)_30 - 4.077 Depth of cut (µm)_60
- 24.23 Depth of cut (µm)_90 - 6.697 Feed/ tooth (fz) (mm/tooth)_0.005
- 2.460 Feed/ tooth (fz) (mm/tooth)_0.006
+ 9.157 Feed/ tooth (fz) (mm/tooth)_0.007 + 10.07 cutting velocity (m/min)_12.560
- 3.544 cutting velocity (m/min)_15.386 - 6.530 cutting velocity (m/min)_18.212
- 19.43 coating_nACo + 1.290 coating_TIALN + 18.14 coating_Uncoated

Table 16 (Variance analysis (ANOVA) of surface roughness.)

Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Depth of cut (µm)	2	1134.0	31.26%	1134.0	567.0	8.42	0.019
Feed/ tooth (fz) (mm/tooth)	2	294.0	8.10%	294.0	147.0	2.183	0.652
cutting velocity (m/min)	2	1982.0	54.63%	1982.0	991.0	14.73	0.001
Coating	2	218.0	6.01%	218.0	109.0	1.62	0.582
Error	0	*	*	*	*		
Total	8	3628.0	100.00%				

Equation 6 (Regression Equation of surface finish)

Regression Equation

surface avg = 299.3 - 15.00 Depth of cut (µm)_30 + 3.000 Depth of cut (µm)_60
+ 12.00 Depth of cut (µm)_90 - 7.000 Feed/ tooth (fz) (mm/tooth)_0.005
+ 0.000000 Feed/ tooth (fz) (mm/tooth)_0.006
+ 7.000 Feed/ tooth (fz) (mm/tooth)_0.007
+ 20.33 cutting velocity (m/min)_12.560 - 5.667 cutting velocity (m/min)_15.386
- 14.67 cutting velocity (m/min)_18.212 - 0.6667 coating_nACo
- 5.667 coating_TIALN + 6.333 coating_Uncoated

8.2.1 Burr Formation Analysis

As per literature review during micro milling process, burr formation can be categorized into following.

1. Roll over burr
2. Feathery burr
3. Poisson burr

Overview of all the categories of burr is shown below.

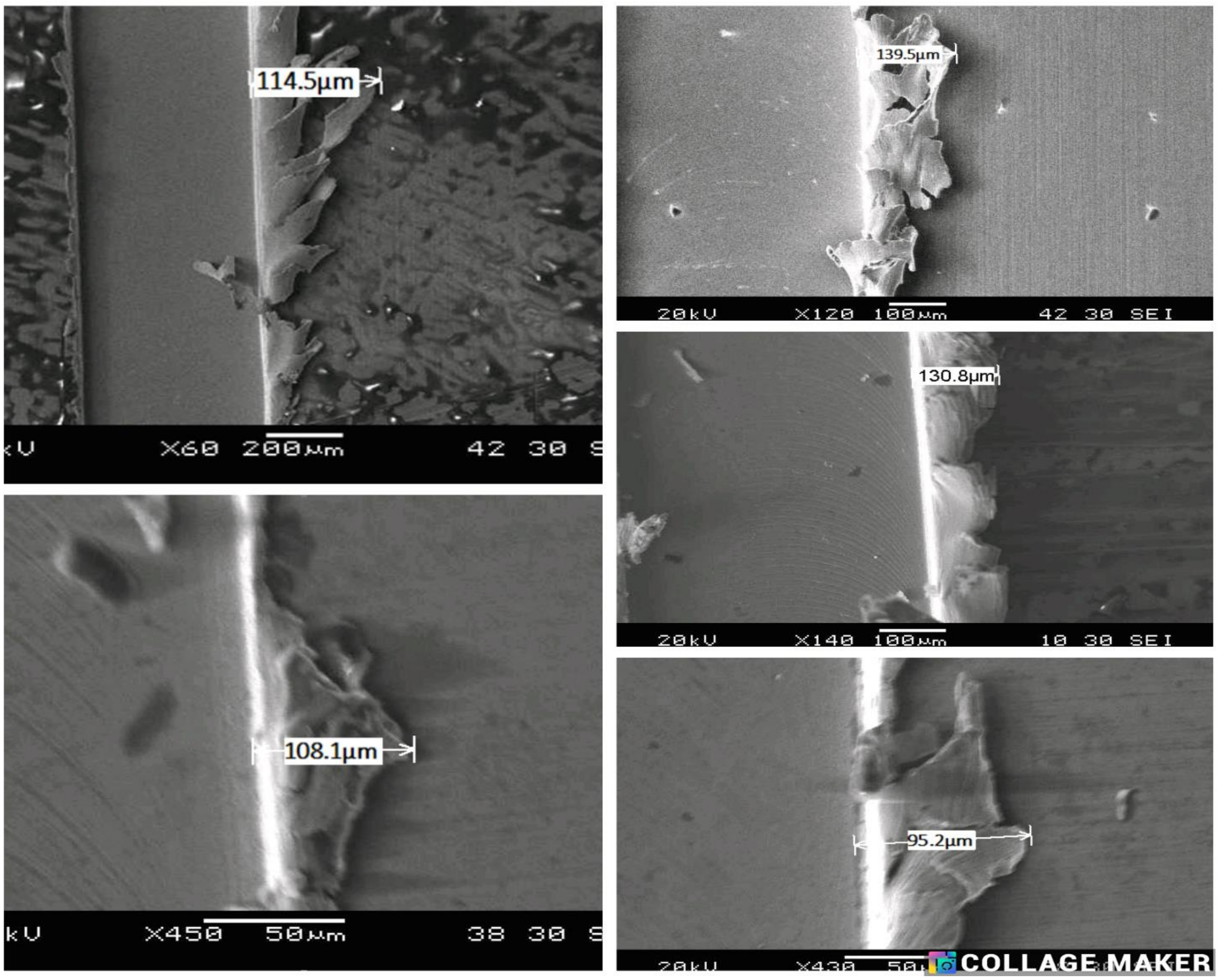

Figure 16 (Different categories of burrs formed in micro milling of super alloy Inconel-718)

8.2.1.1 Roll over burr

This type of burr is formed whenever the chip is produced as a result of pushing the material away from the cutting tool track instead of material shearing during machining process. Mostly this category of burr was produced at lower cutting depth and lesser ratio of feeds (µm/tooth) to tool cutting edge radius [53].

8.2.1.2 Poisson burr

This type of burr is formed by the material's bulging property to one way on compressing the material under machining to the point where permanent deformation of workpiece starts. Cutting conditions for which this type of burrs developed are quite similar to that of roll over burr, lower cutting depth and feed rates. [53]

8.2.1.3 Feathery burr

This type of burr is formed as a result of tearing rather than sharing for material removal during machining. Mostly this category of burr was produced at lower cutting depth and higher ratio of feed rates (µm/tooth) to tool cutting edge radius. [53]

During the micro machining of Inconel718 several burrs types were produced. According to the literature major portion of the burr formed was in case of down-milling in comparison to up milling process. [2] Same trend was observed during the experimentation process. Main focus for analysis of burr formation is on top burr as it is easy to analyze in case of the micro milling. The maximum burr of each machined slot was calculated by (SEM) Scanning Electron Microscope.

ANOVA variance analysis for burr formation was performed using the Minitab statistical software. Maximum Burr width was the output response factor during the analysis.

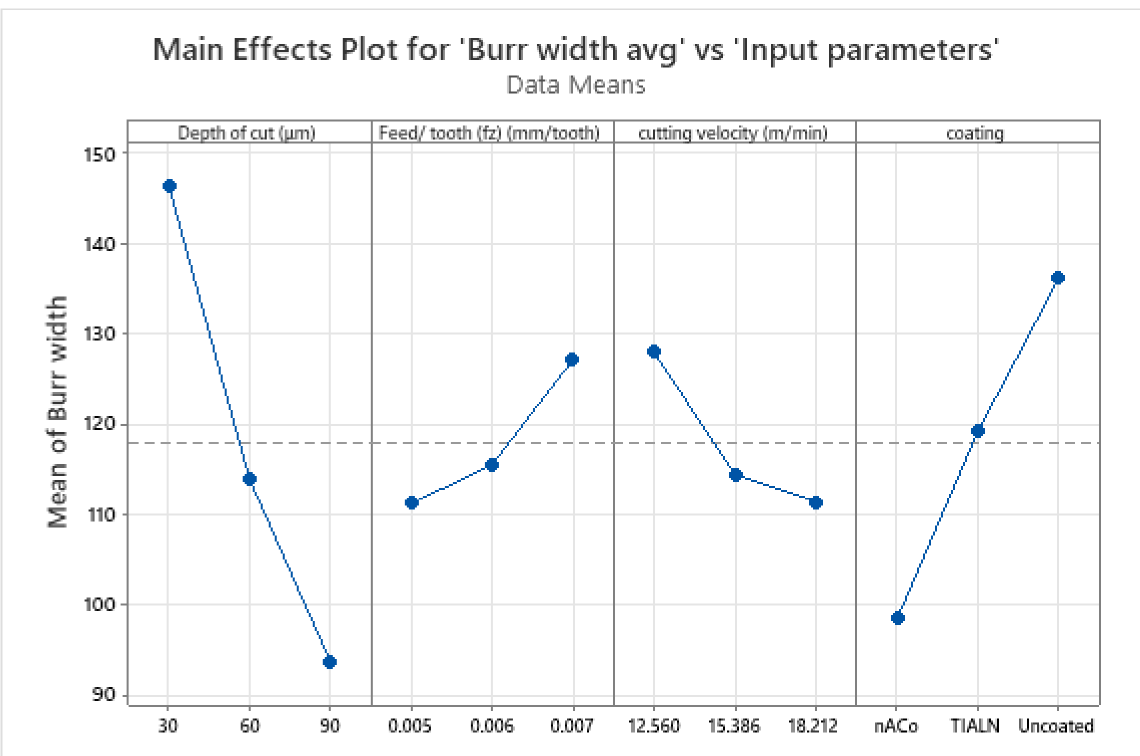

Figure 17 (Effect of input process parameters on burr width using ANOVA)

ANOVA results for General Linear Modelling shows that contribution of noteworthy parameters affecting the burr formation and its nature are following

1. Depth of cut (DOC) 73.43%

2. Coating 16.83%

Contribution of remaining two factors i.e. cutting velocity and feed/tooth is less than 10% for each which shows that are not significantly affecting the response outputs which is burr width in our case. Hence cutting velocity and feed rate are considered to be insignificant factors for burr formation analysis.

Main effect of Plot for burr formation analysis proved that as the DOC value for each slot increases there is a significant decrease in the burr width. This decremental trend was due to the reason that as the value of depth of cut increases, there is a significant increase in chip thickness of material increases. As burr is the form of uncut chip during machining, more depth of cut results in better chipping of burrs from workpiece. Therefore, larger the depth of cut value lesser the burr will be produced.

Cutting speed and formation of burr are inversely proportional to each other. As the cutting speed increases burr formation decreased [54] owing to the reduction in cutting forces and a variation of cutting temperature at various cutting velocities [55]. The cutting temperature at workpiece and tool's interface is higher in case of higher speed but frictional effect at aforesaid interface is reduced which is the basis of a reduction of welding process between workpiece and chips developed during machining and heat generation too that contributes towards minimization of burrs produced [56].

Feed rate and burr width directly relates with each other. As the feed rate increases material removal rate (MRR) increases and at higher values more material is cuddled at the machining area in comparison to removal [57] and cutting forces also increases therefore contributing in formation of larger burr width. [58]

In case of tool coating, results show that nACo coated tools shows promising results in comparison to other tools due to lesser cutting-edge radius and TIALN coated tools shows 2nd best results. As per literature review [49] reason of higher values for burr formation in case of non-coated tools in comparison to the coated one's is the higher value of cutting-edge radius. This results in most of the cutting under minimum chip thickness value and contributes towards the increased cutting forces at tool chip interface and more deformation during machining of Inconel-718 and results in larger burr width. Higher friction of coefficient for tool coating is the major contributor in larger burr width [59]. Same was confirmed during experimentation.

Similar trends for results were observed during experimentation by Jaffery et al. [2], Shukri et al. [60], Atif et al. [61], Gulfam et al. [62], Irfan Ucen et al. [28]. This similarity in trends for input factor on response output validates the results obtained during the experimentation.

8.3 Surface finish analysis

As per literature review surface roughness of micro machined component is based on selection of depth of cut, cutting speed, feed rate to tool cutting-edge radius and difference in tool coating [27] [63] [64]. Separate tool was used to rule out the tool wear effect on surface finish during machining process.

ANOVA analysis for surface finishing during machining of Inconel-718 is shown below.

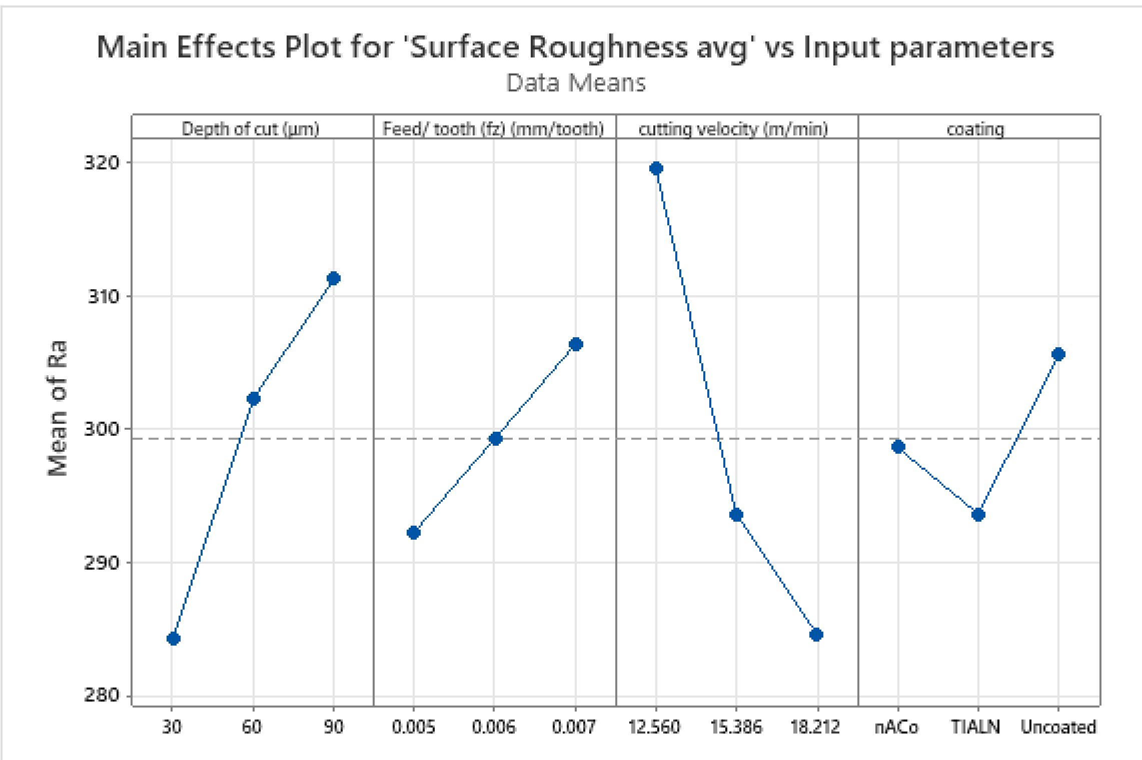

Figure 18 (Effect of input process parameters on value of surface roughness)

From above plots for different input parameters, it was observed that depth of cut, (Vc) cutting velocity, feed rate and tool coating significantly alters the surface finish of the machined slots in Inconel-718.

ANOVA results for General Linear Modelling shows that contribution of noteworthy parameters affecting the burr formation and its nature are following

1. Cutting Velocity (Vc) 54.63%
1. Depth of cut (DOC) 31.26%

Contribution of feed/tooth and tool coating is less than 10%. p value is greater than 5% (0.05) which shows that it’s not significantly affecting the response outputs which is surface Roughness in our case.

Surface roughness mean effect plot analysis illustrates that as the depth of cut value increases, surface roughness value (Ra) increases due to increase in temperature at tool chip interface caused by increases in friction and tool vibration. At higher depth of cut, heat affected zone along with the shear angle increases and results in increased friction and tool wear that ultimately contributes towards the poor surface finish [5]. Machining above minimum chip thickness produces better results and as per literature, minimum chip thickness for micro milling of Inconel 718 is in range of 22-25 % of tools cutting edge radius. [65]. Beneath minimum chip thickness, deformation in workpiece begins and chips are not produced and results in built up edges which are main source of roughness on surface.

From above figure it was clear that in case of surface roughness, cutting speed plays an important role in determination of quality surface. Definite cause is the difference in temperature caused by the variation in cutting speed. Surface roughness relates indirectly with the cutting speed. At lower values of cutting speeds, larger built-up edges are formed that contributes towards larger burr formation with higher values of surface roughness. At higher speeds, lower values of built up edges are formed and as a result surface finish quality increase. At higher cutting speed, cutting forces are reduced and results in less vibration that helps to improve surface finish. [5] [27]

Increasing trend for surface roughness with increase in value of feed rate was observed in our experimentation. In contrast to lower feed rates at lower values of feed rate, larger built-up edges are formed along with the feed marks and results in poor surface finish. [40]

Among the two coatings TIALN coated tools showed promising results for better surface finish because of their higher coefficient of friction that leads to higher cutting temperatures [66]. Higher temperature at tool chip interface helps material to deform easily. This leads to increased burr formation as discussed earlier but improves surface finish quality because of better chips formation. Results for nACo coatings are better while uncoated tools give maximum roughness in comparison to nACo and TIALN coating.

Machining under cryogenic environment had the tendency to increase the hardness of the material.

Application of liquid nitrogen hardens the workpiece due to dropping temperature at interaction point of tool and chip interface and results in reduction of surface roughness in contrast to soft materials with high elasticity [35]. Value of surface roughness decreased by almost 50% with the help of cryogenic pre-cooling technique. [28]

Similar trends were observed by the researcher during micro milling of similar alloys under dry machining and approximately similar input cutting factors. [61] [5] [28] [40] [25]

9 Reponses Optimization

In our experimentation process formation of burr and roughness of surface are of critical importance and main aim of research is to minimize the value of both the responses. As both of the responses ae subjected to similar input parameters with same levels, so minimization of one response may cause an increase in other. Therefore, optimization of both the responses is the resolution to get both of them in optimal range. Minitab response optimizer feature is used to get optimistic levels of input parameters by giving equal weightage to both responses.

Parameters

Table 17 (Input Parameters to Response Optimization)

Response	Goal	Lower	Target	Upper	Weight	Importance
surface avg	Minimum		278.000	338.00	1	1
burr avg	Minimum		70.865	163.15	1	1

Solution

Table 18 (Optimized Parameters for Minimum Values of Reponses)

Solution	Depth of cut (µm)	Feed/ tooth (fz) (mm/tooth)	cutting velocity (m/min)	coating	surface avg Fit	burr avg Fit	Composite Desirability
1	90	0.005	18.212	nACo	289	70.865	0.903696

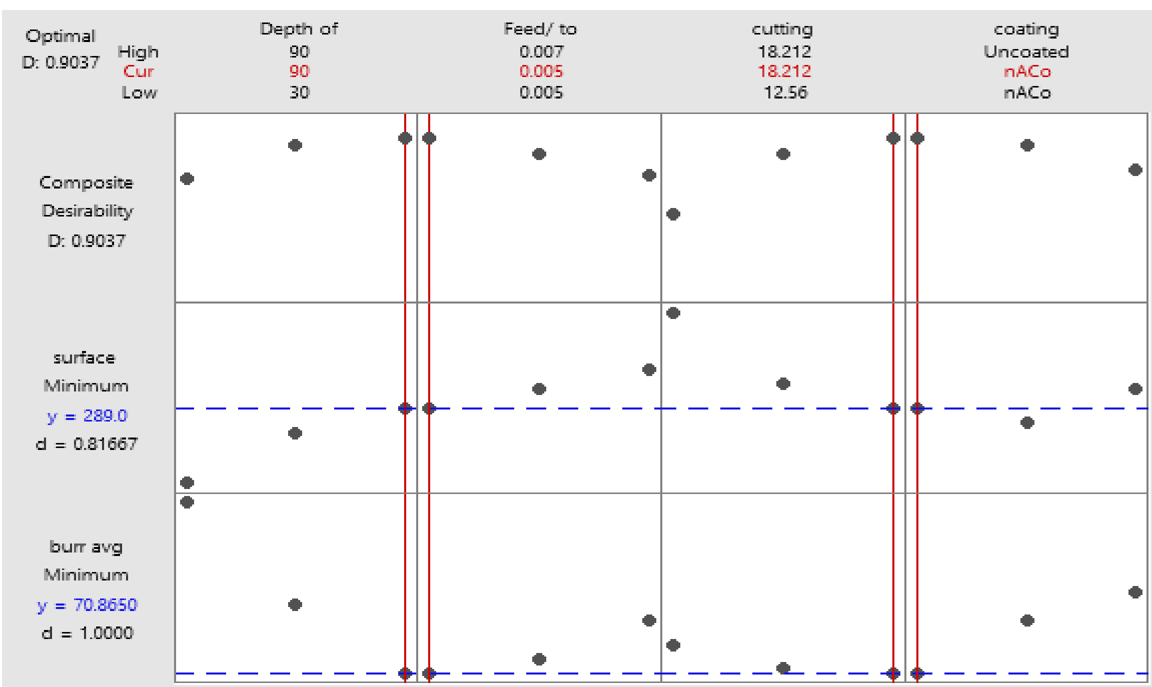

Figure 19 (Response optimization using Anova)

10 Conclusions

Main aim of the dissertation is to analyze the effect of different controllable input factors and the tool coatings on burr formation and surface finish in micro milling of nickel-based alloy commonly known as Inconel-718. Micro end mill solid carbide tool of diameter 0.5mm were used to make slots on workpiece during the experimentation. Experiments were performed under Cryogenic cutting coolant under lower speeds and feed rate values above cutting-edge radius of tool.

After experimentation ANOVA analysis was performed using Minitab analysis software in order to understand the importance of the input factors on desired outputs.

Conclusions from the obtained results after experimentation and ANOVA analysis can be summarized as following.

- Statistical Analysis of the results shows that aim of minimizing surface roughness can be achieved by optimizing the most dominant factor of cutting velocity while in case of reducing burr formation, cutting depth is most dominating factor for more than 50% of total value.

- From variance statistical analysis of burr formation, it was concluded that depth of cut (DOC) along with tool coating were noteworthy factors with a combined level of confidence higher than 85%, however feed rate was less momentous factor for reduction of burr width. Different Sorts of burr produced in experimentation were primarily influenced by the combination of depth of cut and tool coating and least affected by feed rate and cutting velocity. Hence different natures of burrs formed were mostly affected by DOC and cutting speed.

- ANOVA analysis of the surface roughness results shows that input parameters such as depth of cut (DOC), cutting velocity and feed were the noteworthy factors with a combined level of confidence higher than 95%. Results for surface finish and burr formation at low-speed machining are promising and almost equivalent in comparison to transition as well as high-speed machining.

- Two different coated tools along with uncoated tool were used for the experimentation. From the ANOVA analysis on effect of tool coating it was concluded that the coated tools frictional coefficient along with cutting edge radius contributes towards the determination of quality metrics for surface finish and burr formation. Higher the tools frictional coefficient is higher will be the machining temperature that leads to easy deformation of material results in better surface finish due to formation of better-quality chips but cause an increase in burr formation.

- Machining under cryogenic environment had the tendency to increase the hardness of the material. Application of liquid nitrogen hardens the workpiece by dropping the temperature at interaction of tool and chip therefore results in reduction of surface roughness in contrast to soft materials with high elasticity. Increase in hardness under cryogenic environment also leads to decrease in toughness of workpiece and results in reduction of burr formation in comparison to dry machining.

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