Statistical Analysis of Inconel-600 Micro-Milling

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Declaration

I certify that this research work titled "*statistical Analysis of Inconel-600 Micro-Milling"* 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 acknowledged / referred.

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2016-NUST-MS-DME-172476

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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

Abstract

Increasing demand of micro scale components in the industry of electronics, aerospace, automotive and biomedical has opened up a door where there is strong research potential in the field of micro machining Micro machining is one the best process for the mass production of 3D micro product with a micron level accuracy. Micro milling is one of the most efficient process is the micro machining technology.

Inconel based alloys are suitable to be used as work piece material for different applications in these industries. Most of the previous research has been done on Inconel-718 and comparatively very less research is found on Inconel-600. Inconel 600 has high-strength, corrosion-resistant nickel chromium which is mostly used at high temperature (-423° to 1300°F). Due to its high strength and work-hardening characteristics proper tool materials, tool coating and operating parameters should be selected.

So Inconel-600 has been selected to check the effect of input parameters on quality of work pieces. In this research, feed per tooth, cutting velocity, depth of cut and tool coating are considered as input parameters and their effect on surface roughness and burr formation are analyzed through statistical technique of analysis of variance (ANOVA) to determine key process variables.

Keywords: Micro-machining, Inconel Alloy, statistical analysis, burr formation, surface roughness, tool wear, micro-milling, Tool coating, ANOVA

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CHAPTER 1: INTRODUCTION

Over the time, the demand in modern materials expanded because of their properties at high temperature such as Super alloys, Ceramics, Composites etc. These properties are used to fulfill the requirement in different areas such as aviation, car and biomedical businesses etc. These materials are hard to machine. Micromachining is one of the most important aspects in the advanced of machining process.

There are variety of materials being used for making products through micro milling process. Every material has different properties which lead to advantages and disadvantages of each type. Selection of material is mainly dependent on desired properties of product and available materials.

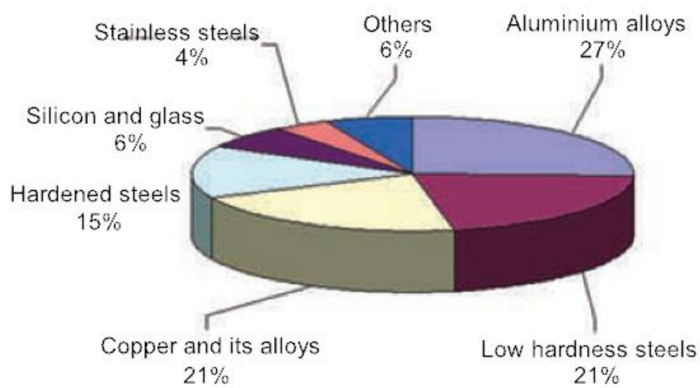


Figure 1: Usual work materials used in micro milling

Previously research has been done mainly on materials like aluminum, copper, Brass, Stainless steel, Mild steel, Titanium, Inconel-718, silicon and glass. Still there is a lot of research opportunity in the field because of addition of new alloys.

Among different types of hard to machine materials, super alloy is resistant to creep at high temperature; it has high mechanical strength, favorable surface stability and corrosion & oxidation resistance. Super alloys are usually based on nickel chromium, cobalt, or nickel-iron. The use of these materials is in industrial gas turbine, aerospace, marine turbine industries etc. Inconel 600 is nickel chromium alloy which has high strength and resistance to corrosion at high temperature. Due to its high strength and work-hardening characteristics proper tool materials, tool coating and operating parameters must be carefully selected.

The high temperature resistance makes Inconel-600 feasible for different applications involving temperatures from cryogenic to above 1095°C. This alloy is widely is used in the chemical industry i.e. bubble towers, heaters, stills, evaporator tubes, tube sheets, flaking trays and condensers because of its corrosion resistance. Its high strength and oxidation resistance at elevated temperatures make it suitable for various applications in the heat treatment industry. It is used in manufacturing of muffles, retorts, roller hearths and for heat-treating trays and baskets and other furnace components. This alloy is being used in aeronautical field for making different engine and airframe components i.e. exhaust liners, lock wire and turbine seals.in the electronic field it is being used in making of cathode-ray tube spiders, thyratrongrids, tube support members and springs. Inconel 600 is a standard material for manufacturing of nuclear reactors.

Inconel 600 (UNS N06600/W.Nr. 2.4816) has chemical composition as following

Nickel (plus Cobalt)...	72.0 % min.
Chromium..	14.0-17.0 %
Iron	6.00-10.00 %
Carbon	0.15 % max.
Manganese	1.00 % max
Sulfur...	0.015 %max.
Silicon	0.50% max.
Copper..	0.50% max.

Table 1: composition of Inconel 600

As far as mechanical properties of Inconel 600 are concerned a broad range of strength and hardness is obtainable with INCONEL alloy 600, depending on form and condition. It shows moderate yield strengths of 172 to 345 MPa While annealed. Yield strengths in that range, combined with elongations of 55 to 35%, makes alloy to be fabricated with minute difficulty. However this alloy can have tensile strengths as high 1517 MPa after Heavy cold working. Some physical properties are given in below table.

property	Range	Unit
Density	8.47	8.47
Melting Range	1354-1413	°C
Specific Heat	444	J/kg-°C
Electrical Resistivity	1.03	µΩ-m
Curie Temperature	-124	°C

Table 2: Physical properties of Inconel 600

1.1 Research Motivation

Burr formation is on the biggest problem is mechanical machining process. It occurs is both macro machining process and micro machining process. In macro machining process the removal of burr is easy and have different procedure for removal of burr due its large size and in micro machining the removal of burr is hard due to its size and accuracy required the part may be damaged during deburring process.[1, 2]extra measures are taken for less burr formation during micro milling process.

Surface roughness of components is one of the vital quality characteristics. Mostly surface roughness is measured in (Ra) which is the arithmetic average deviations of the roughness profile from the center line. Controlling the surface roughness within specification limits is sometimes found to be difficult because of multiple machining parameters effect. So proper selection of input parameters is necessary to control surface roughness value.

AJ Mian studied the burr formation in micro machining of Inconel, the optimum parameter was at minimum chip thickness and transition cutting speed for uncoated and AlTiN Coating tool of 0.5mm diameter.[3] As he studied the micro machining process for the wide range of cutting speed little date in obtained how burr formation is effected by the cutting speed. So, to check the influence of cutting speed on burr formation we are going to take closer cutting speeds with different tool coating. From the literature review it was found that high cutting speed is more effective during micro machining processesso, mostly work is done at high cutting speed and less data is present on low cutting speed.[4-9][10]

As low speed machining setup is easily available and more economical as compared to high speed machining setup. So, we are going to work on low cutting speed (conventional machining range). And see the effect of input parameters on surface roughness and burr formation at low cutting speed.

1.2 Research Objectives

1. Examine the effect of input parameters on burr formation
2. Examine the influence of Input parameters on surface roughness
3. To analyze the effect of each cutting parameter using ANOVA
4. Finding the optimum cutting parameters for minimum burr formation and surface roughness
5. Comparing the results of each coating with each other

1.3 Research Scope

This research is limited to the micro end milling of Inconel 600 using Carbide end mill tools of 0.5mm diameter with different coatings cutting speed in range of 6m/min to 23 m/min below 15000rpm.As low speed machining setup is easily available and more economical as compared to high speed machining setup. So, we are going to work on low cutting speed (conventional machining range). And see the effect of feed, speed, depth of cutand tool coating on burr formation and surface roughness at low cutting speed.

1.4 Why Research on Burr formation

Reductions of burr formation in milling and drilling increase the tool life. Burr formation is a big problem is micro milling because unlike macro machining the post processing to remove burr is not possible in micro machining due to the accuracy requirement in micro parts.[2]

There are different problems that occurs in conventional machining (macro machining) such as poor edge finish, surface defects and burrs which is been avoided by post processing for some time. In micro machining these problems are more significant needs much more consideration because due to limitations in part geometry and material characteristics some of the solutions cannot be applied that is used in conventional machining (macro machining).[11]

1.5 Why Research on Surface Roughness

Controlling surface roughness is major challenge in micro milling process as it is effected different parameters and burr width and other factors are also influenced by same parameters so optimizing surface roughness may cause increase in burr size. So we need optimal level of each parameter to control all required factors.

Too rough surface doesn’t fulfill assembly demands while too smooth surface lead to additional tooling cost and higher machining time. So we need to control surface roughness with in specification limit.

Chapter 2: LITERATURE REVIEW

Micro machining process is capable of producing small mechanical components ranging from 1μm to 999μm or if the material removal is in micro level. There is an increase in demand for the industrial product that has number of functions and also reduced dimensions. Micro machining is a process of producing small parts and components in mass production. In recent time demand in micro parts and component has increased in industrial sector such as medical, telecommunication, aerospace, automobile, electronics etc. applications include connectors, diagnostic devices, micro-reactors, medical implants, micro-engines, switches, micro pumps drug delivery systems, and printing heads.[12-14]

Fabrication of small parts requires more reliable, precise and repeatable methods, with precise tooling system. Most common methods used for the fabrication of micro parts is based on semi-conductor processing techniques. Many scholars have investigated other manufacturing method for the manufacturing of micro component, such as laser manufacturing, photo-lithography method, ultrasonic, and ion beam.[15, 16]. Definitions of micro machining by different authors/researchers. Micro machining definitions are given below in Table 2.1

Table 3: Micromachining definition by different researchers

Researchers	**Year**	**Definition**
Aramcharoen et [17]	2008	Tool diameter should be in range of 1 to 999μm or if tool cutting edge radius and grain size of material should be comparable to unreformed chip thickness
Simoneau et [18]	2006	Chip load and depth of cut ratio should be less than the work piece material's grain size
Dornfeld et [19]	2006	Chip load and depth of cut ratio should be then 1mm with a define tool cutting edge radius
Chae et [2]	2005	Process of creating small mechanical parts which feature varies from 10 of microns to few millimeter
Liu et [20]	2004	Tool cutting edge should be comparable to chip load/unreformed chip thickness

T. Masuzawa[16]	2000	Definition of micro machining from time to time depending on person, era, process, cutting tool, material etc
Masuzawa and Tonshoff[21]	1997	Unreformed chip thickness ranges from 0.1 to 200µm

2.1 Micro Machining

Following are different types of micro machining.

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

Mechanical micromachining is superior to other micromachining technologies because it can produce parts of different size and shape with a variety of material that is not possible by other micromachining technologies. In this process the tool contacts with work piece and have high material removal rate which is suitable for the mass production. It also has a good surface finish and more accuracy.[13, 19]

Development in micro machining processes over the year given in Figure 2.1 [22]

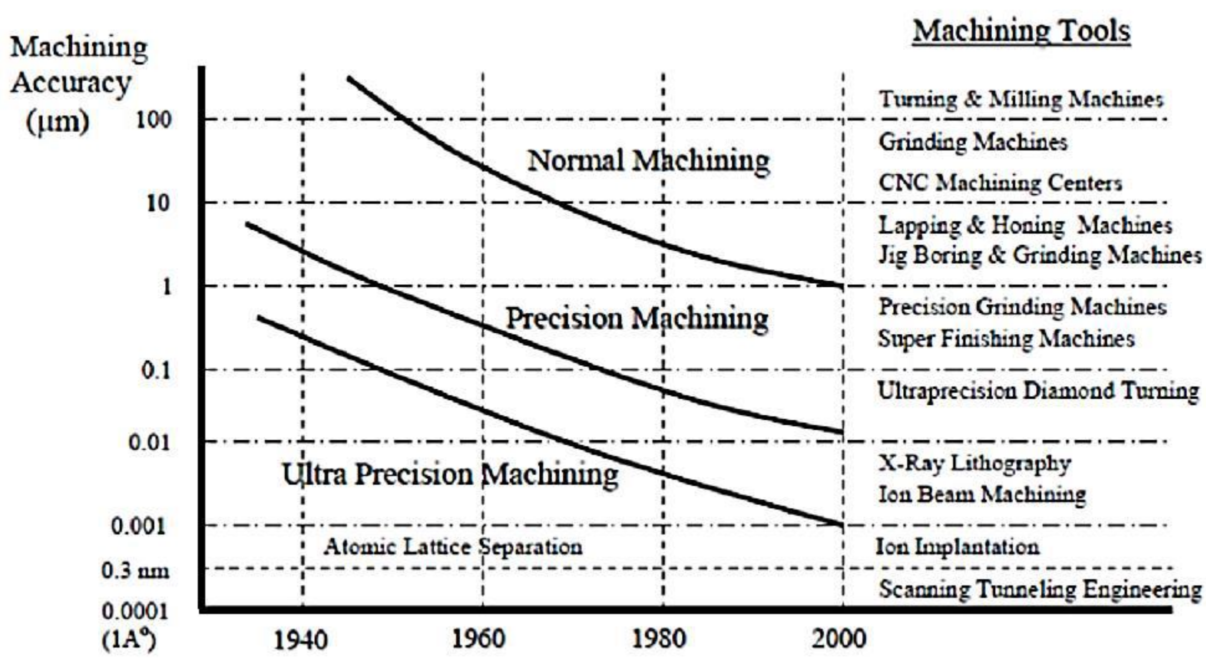


Figure 2: Development in micro machining processes over the year

2.2 Micro milling

Micro mechanical machining is a method of fabrication of small component by removing the material in form of chips which range is form tens of microns to few millimeters the component produced by micro mechanical machining are more accurate and fast manufacturing time.[20]micro mechanical process is more economical the other manufacturing systems in micro domain.[13]It is a process capable of producing small parts/devices from variety of materials i.e. composites, ceramic, polymers and metallic alloys materials. Some of the bio-MEMs labs are presently researching on different ways based on the micromechanical processes to produce bio-MEMs devices.[23]

A lot of serious issues are connected with micro-mechanical manufacturing system that needs a standard change from macro manufacturing-processes. These problems are mostly because of small size of tools, parts and processes. The quality micro end mills are greatly affected by minor vibrations and extreme forces, which is not good for tools life and for the tolerances of components. It is hard to notice the loss of cutting edges of micro end mill.[15, 24, 25]

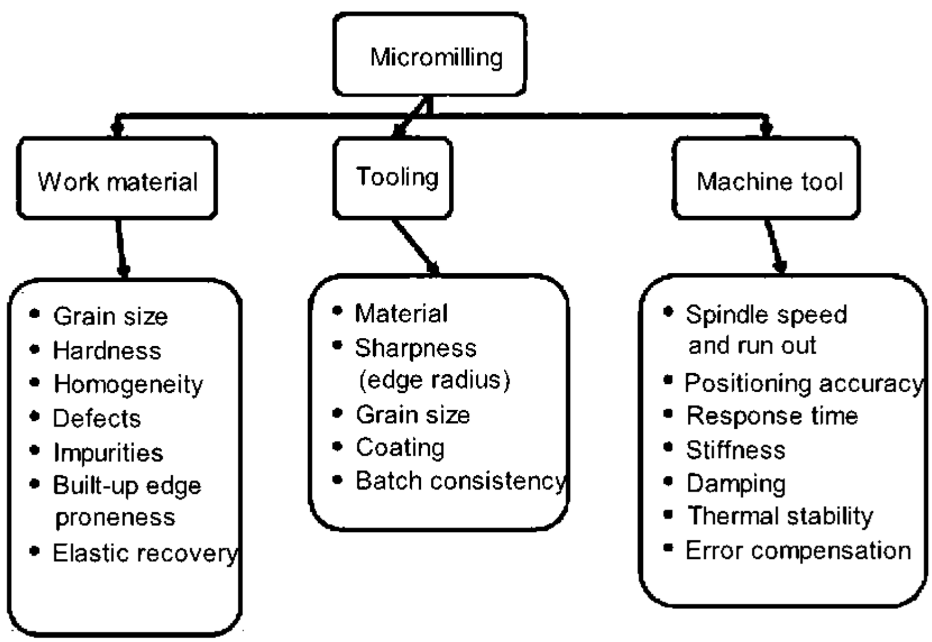


Figure 3: micro milling input variables

In micro milling the material properties, the tooling specifications and machining parameters play an important role in controlling quality of products. The quality can be enhanced by controlling these input factors.[12]

Table 3: Micro milling capabilities [26]

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

Due to the size of micro machnical fabricated part testing, handling and assembling are hard compared to macro fabricated parts. Little work has been done on testing of micro machanical fabricated parts.[2]

Micro milling procces mostly depends on the following three parameters cutting speed, feed and depth of cut. It also depends on different factors such as tool material, tool coating work piece.

2.3 Super Alloys

Super alloys are usually based on nickel chromium, cobalt, or nickel-iron. The use of these materials is in industrial gas turbine, aerospace, marine turbine industries etc. Classification of super alloys in the given Figure 4 .[27]

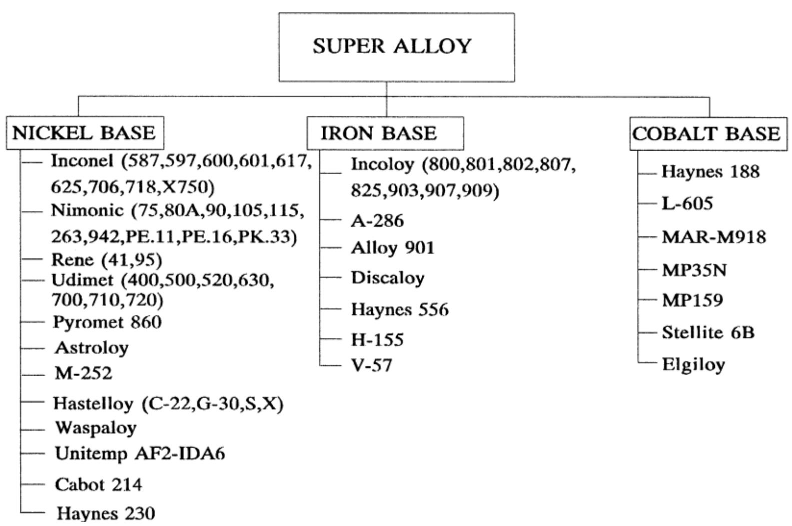


Figure 4: Classification of super alloys

These super alloys are divided into three broad categories. Iron base, nickel base and cobalt base alloys. Inconel 600 is an alloy of nickel and chromium which has high strength and corrosion resistance to at very high temperatures and also have excellent mechanical properties at high temperature (-423° to 1300°F). Inconel 600 is austenitic solid-solution and stable alloy.[12]

Most of the wrought nickel-base super alloys have at least 50% for nickel and other material such as 10– 20% Cr, 5–15% Co, up to 8% Ti and Al combined, and small proportion of tungsten zirconium, boron, carbon niobium, molybdenum and magnesium. Aluminum and chromium are required to improve surface stability.[27]

Thermal stresses are generated in work pieces due to high temperature between the work piece and tool cutting edge which is higher from the temperature generated during conventional machining but with smaller temperature gradient. During the machining process of Inconel the hottest spot was the tool cutting edge and for steel it was rake face.[28, 29]

2.4 Cutting Tools

The following parameters influence the cutting tool's performance during the machining of super alloys [30].

I. Fracture toughness
II. wear resistance
III. high hardness
IV. Chemical inertness

Regarding the first three properties Ceramic tools are most suitable for high cutting speeds. carbide tools and high speed steel tools have higher fracture toughness than ceramic[31].For high feed rate cutting tungsten-based carbides is used but they are not effective on high speed due of their lower thermochemical instability. On the other hand, coated carbides tools are used for its strength and high wear resistance.[32]

During the machining of nickel-based super alloys. Notch wear is produced in ceramic tools because of the contact between tool and work piece while Sialon and silicon carbide whisker reinforced alumina ceramics have resistance towards it. For whisker-reinforced alumina and sialon tools it was flank wear which is mainly due the chemical reaction. Ceramic tools of alumina–TiC are suitable for higher feed rates or high cutting speed over 400m/min. For low feed rate and medium cutting speed (100–400m/min) whisker-reinforced alumina is preferred. [34]

2.5 Minimum Chip Thickness

Chip formation is mostly nonlinear in nature. To accurately predict the cutting forces understanding of micro-chip formation is necessary. For the formation of chip the chip load must be equal or greater then minimum chips thickness.[35]

The variation in chip thickness h(Ø) for milling processes, can be estimated asØ is for angle of immersion, whereh(Ø)=c sin(Ø)and c is for chip load.[36]But this method cannot be applied to estimate the deviation in chip thickness in micro milling processes. This is because of small cutting edge of the tool, lower feed rate and also the cut depth is very small which causes a very large negative rake angle. Ploughing phenomena occurs which causes higher surface roughness and also elastic recovery of material.[20, 37]

The min chip thickness is when chip is formed by sharing deformation at minimum cutting depth and elastic deformation recovery of work piece does not occur and below that depth of cut elastic recovery of work piece occurs and proper chips are not formed. Chips are formed by both shearing and elastic deformation of the work piece as minimum chip thickness is approached by the uncut chip thickness. Effects of minimum chips thickness are given the Figure 5.

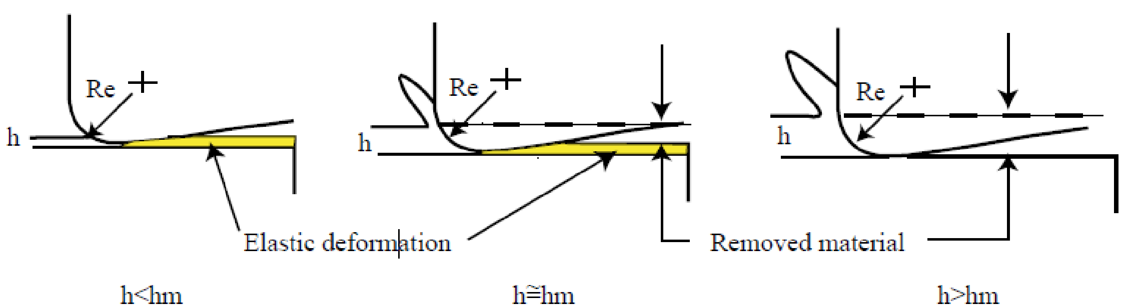


Figure 5: Effects of minimum chips thickness

This is also undesired uncut chip thickness due to the elastic deformation in the material. However, elastic deformation decreases significantly when the thickness of uncut chips is increased from the minimum chip thickness then the material removal starts in the form chip from the work piece.

Liu et al examined the cutting forces and chip formation during micro machining operation. They concluded that minimum chip thickness can be determined using the sudden change in thrust forces. The abrupt change in thrust forces was due to sudden shifting of plowing sliding forces to shearing forces as shown in the Figure 6.[38]

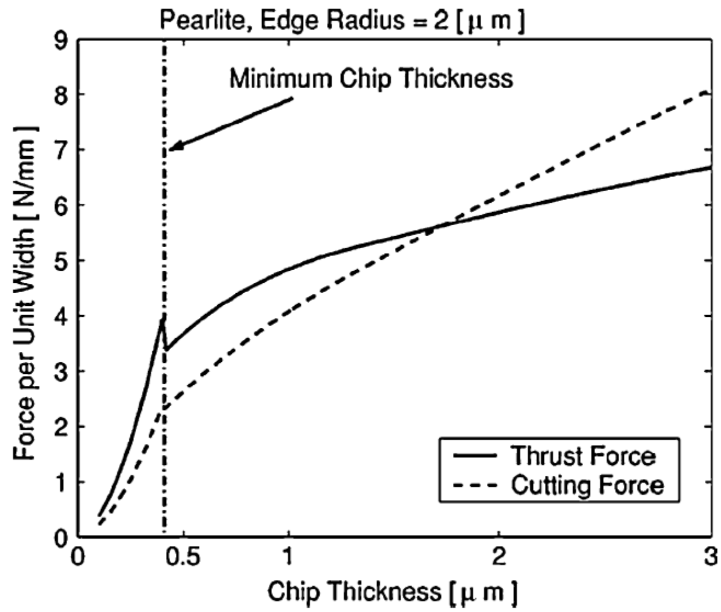


Figure 6: Chip thickness VS cutting force (Pearlite)[20]

The minimum chip thickness found are different for different material e.g. 11.2–18% for Cu (OFHC), 18.5–25.5% for Inconel 718, 19–27.5% for Ti-6Al-4V, 19.7–35.5% for AISI 1045 steel, 31.3–42% for AISI 1005 steel and 33–38.9% for Al 6082 of the tool edge radius.[39]

2.6 Build-up-edge Formation

Built-up-edge is formed when the chip material welds or sticks to the material surface and tool rake surface. This extra layer of welded chip on tool surface protects the original rake surface from wear and also the layer on welded chip on the work material changes it surface properties and also decrease the surface finish.

This new layer of material on a tool act as a coating which enhances their properties. This BUE appears more commonly while machining ductile materials such as stainless steel and mostly effects tool life, cutting forces, surface finish and vibrations. The BUE formation on tool increases in size and breaks off from the rake surface of the tool and forms again. Investigation on BUE formation has always been a subject of main interest in the realm of manufacturing.

In micro machining the grain size effect the machining surface. As the tool moves from one grain to another grain its causes the chip to break and deformation starts in other grain which caused the build-up-edge formation. It is also found when the feed /tooth is lower than the cutting-edge radius which increases plowing forces [18]

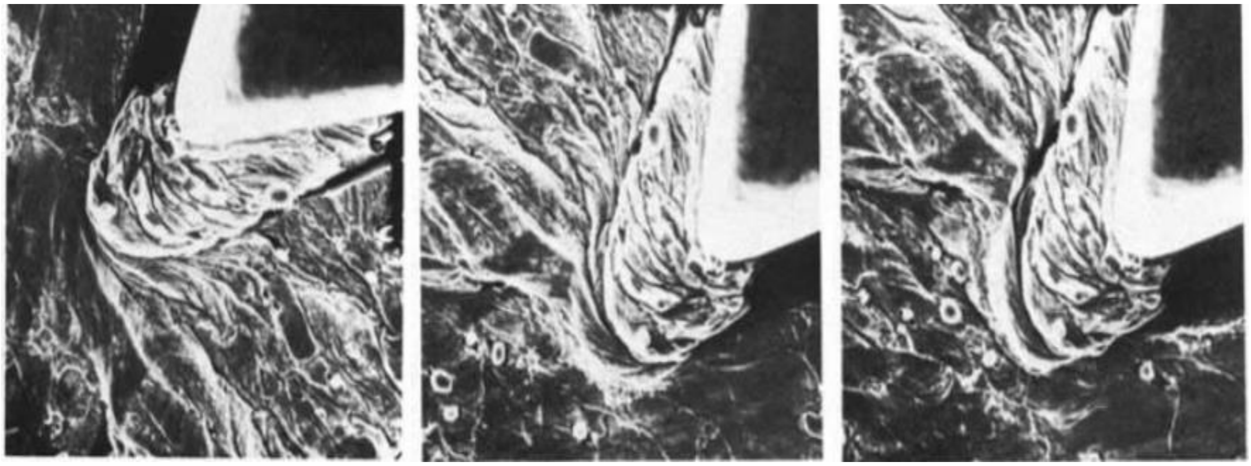


Figure 7: SEM show the growth of BUE formation.

2.7 Tool Wear

In micro-machining due to small depth of cut there is significantly increase in friction between material and the tool which results in temperature rise and tool wear. Because of which, there is an increase in tool cutting edge radius which lowers the quality of the component and increase tool wear rate.[40, 41]

Tansel[42]developed a way to estimate tool wear using wear data and cutting force. This method was used to estimate tool wear for the micro-machining of steel and aluminum, steel was found with faster tool wear rates than for aluminum. This was also observed by Weule that tool wear is low for soft work piece and high for the hard work piece.[43]

Laser assisted machining is used to increase the tool life by decreasing the specific up to 35%. And also used to improve surface finish up to 22%.[44]. Different typing of tool coating is also used to increase the tool life during micro machining of Inconel 718[4, 5, 45].Tool wear is decrease by decreasing the coefficient of friction of tool with Coating [5]. Cryogenic tooling process is used to decrease the cutting edge temperature during machining process to increase the tool life.[45]

Rahman[46]concluded that the tool wear of 1 mm diameter depended on the depth of cut and the tool helix angle. In their research they found that larger depth of cut (0.25 mm) has lower tool wear than smaller depth of cut (0.15 mm).

Form this phenomenon they interpreted that tool wear is the result of continuous chip which increases the force on its rake face due to the rubbing of chips on tool. Parkash[47] found in his research that during the micro machining process the cutting speed and feed rate have more effect on flank wear of cutting edge than the axial depth of cut.

2.8 Burr Formation

It is the unwanted deformed material which is remained on the surface or edges of work piece that has been machined. Burr is formed in almost all the machining processes. It is usually in the form of sharp cutting strip at the edge of work piece besides cutting operation. Burr formation is removed for the part to work more efficiently. In micro machining as the feed / tooth decrease the friction between material and tool increases as a result there is increase in cutting tool radius and tool wear rate.

The burr formation in micro machining need to be removed because post processing cannot be applied to some parts. Burr formation is produced more in hard material due to increase in tool wear rate. Poor edge and burr formation is more problematic in conventional machining for some time. Post processing is done to avoid this problem. But for some parts in micro machining is not possible due to its small size.[2]

The material properties become non-homogenous at micro level thus the variation in hardness cause the tool to vibrate. This effect is more at low cutting speed and feed rate which cause the irregular surface during the machining. Ductile material is easy to deform which cause more burr and long chips. Burr formation is also significantly influenced by the tool run out[48]

In milling process as the tool exit from the work piece bending of the work piece is done rather than sharing which cause the burr formation [49].Weule et al. [50]during the machining of hard material burr formation in increase to the increase in tool wear. Schaller et al. [51]found a new way to minimize the burrs formation in during machining of stainless steel and brass.

For this, cyanoacrylate polymeric material coating was done brass filled cavities around the work piece edges, which allows the cutting tool to constantly engage with the cyanoacrylate layer or the work piece. The cyanoacrylate is detached with the help of acetone in an ultrasonic bath after machining. Electro-chemical polishing techniques was used on stainless steel to minimize burr. It’s an expensive process but necessary to remove burrs.

2.8.1 Classification of Burr Formation

According to Gwo-Lianq Chern and Ying-Jeng[52] Burr formation is classified in four different types for micro machining processes as shown in Figure 8.

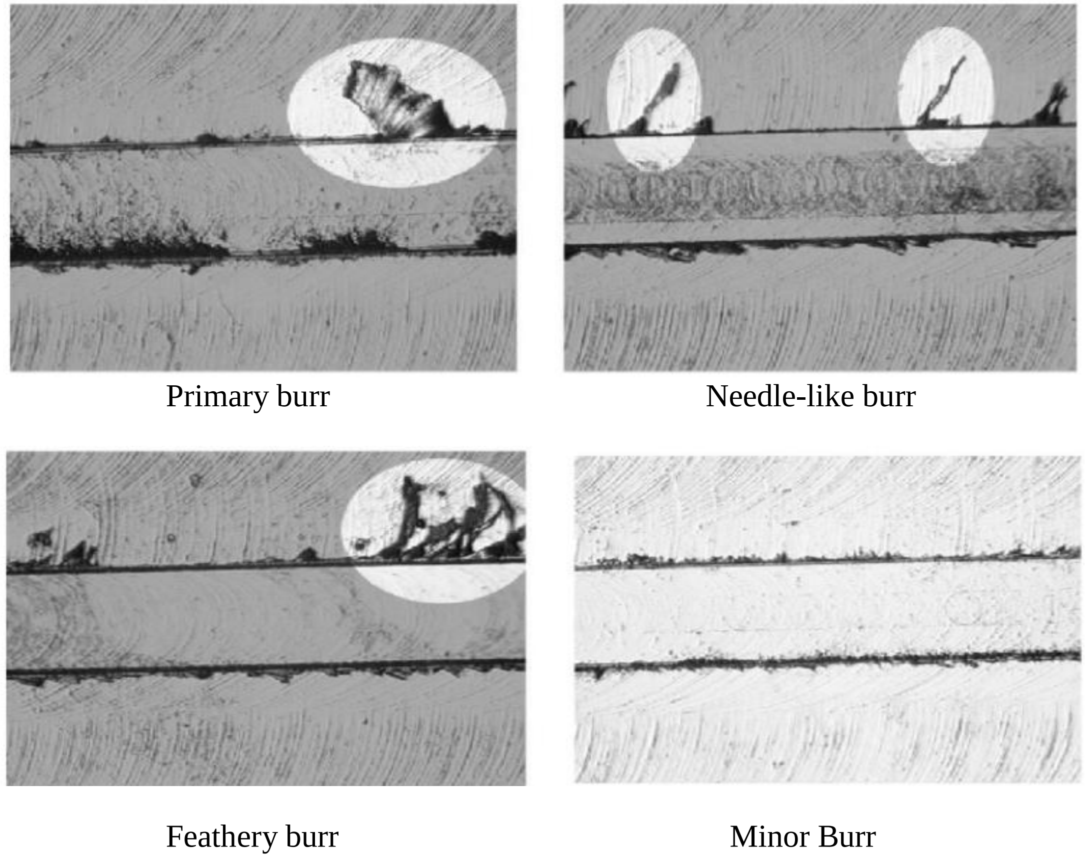


Figure 8: Classification of burr according to Gwo-LianqChern

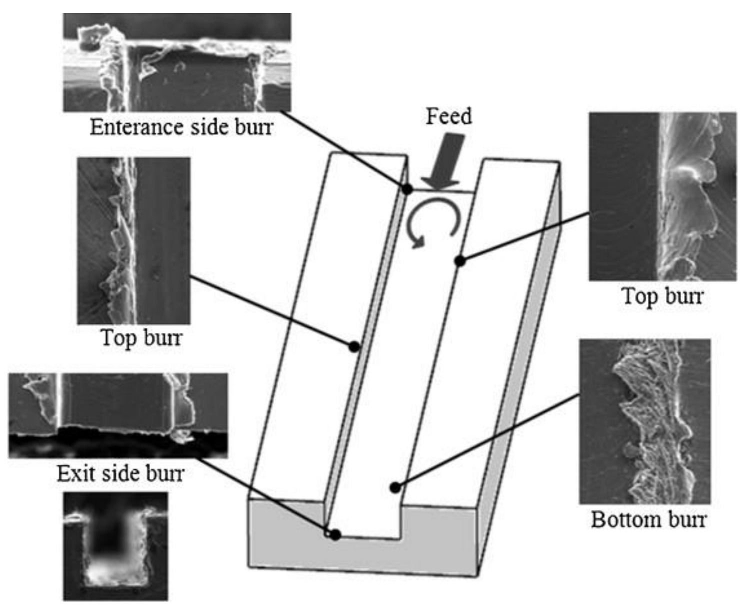


Figure 9: Different types of burr formation according to G.Kiswanto[53]

The burr formation in micro milling is difficult to remove and also the removal of burr can damage the work piece.

2.9 Micro Milling Machining Survey

IrfanUcun , KubilayAslantas , FevziBedir[10]investigated the influence of different coating on wear of tool during the micro machining of Inconel 718. Carbide tool of 0.768 mm diameter with different types of coatings (A) AlCrN (B) AlTiN (C) DLC (D)AlCrN+AlTiN(E)AlTiN+WC/C. The cutting parameters were a feed rate of 1.25, 2.5, 3.75, 5 mm/Tooth, 20,000rev/min (Vc¼ 48 m/min), and cutting depths of 0.1, 0.15, 0.2mm and a constant cutting length of 120mm.DLC and TiAlN +WC/C coatings show good performance against tool wear and BUE formation. High tool wear was witnessed at lower feed rates and with smaller cutting depths. It was concluded that the MQL process helped in increasing the life of tool and also minimized chip adherence.

Irfan Ucun , Kubilay Aslantas , Fevzi Bedir[5] investigated the performance of uncoated and DLC coated carbide tool in micro milling of Inconel-718. The cutting parameters for experimentation were spindle speed 20000, depth of cut 0.1, 0.15, 0.2(mm) and feed per flute (µm) 1.25, 2.5, 3.75, 5.DLC coating increased resistance to tool wear, the reduction of tool diameter, less Built up Edge formation were seen. Minimum wear was observed atf = 5 µm/flute for both coated and uncoated. Less cutting force is required in DLC coated tool.

Irfan Ucun , Kubilay Aslantas , Fevzi Bedir[4]investigated the influence of different types of coatings on surface roughness during the micro machining of Inconel-718. Carbide tool of 0.768 mm diameter with different types of coatings (A) AlCrN (B) AlTiN (C) DLC (D) AlCrN + AlTiN (E) AlTiN + WC/C. The cutting parameters were, feed rate 1.25, 2.5, 3.75, 5 µm/Tooth, 20,000rev/min (Vc¼ 48 m/min), and cutting depths of 0.1, 0.15, 0.2mm and a cutting length was 120mm. The minimum roughness value was obtained by DLC-coated tool, followed by the AlTiN and TiAlN + WC/C-coated cutting tools. The optimal parameters for the surface finish was found to be feed rate 2.5 µm/Tooth, cutting depth 0.15mm and DLC coated cutting tool.

Xiaohong Lu[6]investigated the influence of different cutting factors on surface roughness during the micro milling of Inconel 718. Two fluted cemented carbide end milling tools with coatings with a diameter of 0.3mm were used. The cutting parameters were spindle speed (rpm) 50000, 60000, 70000, 80000, 90000, feed / tooth (µm/tooth) 0.4, 0.5, 0.6, 0.7, 0.8, depth of cut (µm) 10, 15, 20, 25, 30 cutting time (minutes) 2, 4, 6, 8, 10. The optimum parameters for the surface roughness were found to be feed/tooth 0.4µm, spindle speed 80000rpm and cutting depth 10µm and it was also concluded that not only the cutting parameters effects the surface roughness but it is also affected by the vibration, tool wear and BUE formation.

Mohamed Abdul Rahman[8]investigated the influence of different cutting factors on vibration and surface roughness during the micro milling of Inconel-718. The cutting parameters were spindle speed (rpm) 15000, 30000, feed rate (mm/min) 2,4 and cutting depth (mm) 0.10, 0.15using two fluted tungsten carbide end mill with Ø 0.5 mm diameter. The minimum tool vibration and surface roughness ware at spindle speed 15000rpm, feet rate 2mm/min and depth of cut 0.1mm.

Mohamed Abd Rahman [9]investigated the effect of minimum quantity lubrication during the micro machining of Inconel 718. Ten slots were made in dry condition and 10 slots were made in MQL condition using Micro tools DT-110 multi-process micro machine. The process parameters were depth of cut 0.15mm, feet rate 2mm/min and spindle speed of 28000. It was concluded from the experimentation that MQL show more consistency and stability during the micromachining.

Xiaohong Lu [7]investigated the influence of various cutting factors on cutting forces during the micro machining of Inconel 718. Two fluted cemented carbide end milling tools with coatings with a diameter is 0.6mm and working edge length of 0.5mm was used. The cutting parameters were The mount of micro-milling cutter overhanging L(mm) 12, 14, 16, 18, 20, spindle speed(rpm) 39680, 49600, 59520, 69440, 79370, feed/tooth(μm/tooth) 0.3, 0.5, 0.7, 0.9,1.1 and depth of cut(μm) 10, 15, 20, 25, 30, 35. The cutting forces were found to be minimum at extended length of micro milling cutter 12mm and 16mm, depth of cut 15μm and feed per tooth0.3μm. The cutting forces in x-axis and y-axis is minimum at 40000rpm and 60000rpm and in z-axis the forces are minimum at 50000. The forces were minimum at depth of cut 15μm and 0.3μm feed per tooth. With the increase in overhanging length of micro milling cutter and depth of cut the fluctuation in the forces increases. It is also founded that the ratio of min chip thickness to the radius of cutting tool is around 3.5.

Ikawa et al.[54]investigated the machining of copper using a specially prepared diamond cutting edge of radius less than 1nm and produced chips in the range of 1 nm. They also validated their claim that chip is only produced above critical value by developing atomistic models. They also found the minimum chip thickness value which is to be 1nm below which the chip cannot be formed.

Moronuki[54]investigated the effect of cutting on cutting depth on cutting force during the machining aluminum alloy. The author observed that the specific cutting force increases as the cutting depth decrease below 3μm this is due the sliding of the tool flank on aluminum alloy due elastic recovery of aluminum alloy at small depth if cut and the specific cutting forces reaches to it standard level when the cutting depth increase.

Yuan et al.[54]examined the influence of edge radius of tool on minimum chip thickness in ultra-machining of aluminum alloys using diamond coated cutting tools. They derived mathematical equations to estimate minimum thickness of cut based on cutting forces. The author concluded that min chip thickness was a function of coefficient of friction (μ) between the tool material and work piece. They investigated the minimum chip thickness for different combinations of work piece and tool materials. They found it to be between 20-40% of tool edge radius in cutting most of the materials.

S. G. Kapoor and X. Liu, R. E. DeVor[2]studied the research work done on the micromachining founded that specific cutting force mainly depends upon ratio of uncut chip thickness to the edge radius of cutting tool. The min chip thickness is up to the 1/10 of the edge radius of cutting tool. The researcher also concluded that saw tooth like surface is the effect of min chip thickness. The ratio of min chip thickness to cutting edge radius is to be estimated 0.293 and also strongly depend on the type of material used.

In Lee and Dornfeld[11] investigated the formation of burr in micro milling. The burr was found to be bigger in conventional machining considering the ratio of burr size to the chip load which is due to the low cutting speed in the conventional machining. The material deforms more at low speed and break at speed so the burr formation is more at low cutting speed. Large tool edge radius to chip load ratio produces more burr during to rubbing and compression instead of cutting.

A.J mian[3] investigated the formation of burr and surface during the micro milling of Inconel 718 on different parameters. He used 0.5mm carbide end mill with 2 fluke (uncoated and TiAlN), cutting speeds 10/ 25/ 20, feed per revolution 0.4/ 0.6/ 0.8 and depth of cut 30/ 60/ 80. It was concluded that most effected parameter in micro machining for surface roughness and specific energy is cutting velocity and feed per revolution is dominant factor in reducing burr formation. The optimum parameters found for the surface roughness are=25, fz/r_e=0.6 ,a_p=30 and coated tool, for burr formation Vc=40, fz/r_e=0.6 ,a_p=60 and uncoated tool and for specific energy Vc=40, fz/r_e=0.4 ,a_p=30 and uncoated tool.

Chapter 3: Experimentation

3.1 List of Equipment

There is different type of equipment's used for the experimentation. This equipment can be categorized into the machining equipment, data collection equipment and analysis equipment. The details and specification of the equipment will be discussed later in the experimentation section. The list of equipment that are used for the experimentation are given bellow.

1. Band Saw machine (Behringer)
2. Turning machine (EMCOMAT-17D)
3. Grinding Machine
4. CNC Milling Machine (AS-500T)
5. Atomic Force Microscope (AFM)
6. Scanning Electron Microscope(SEM)
7. Optical Profilometer

3.2 Tool Specification

There 0.5 millimeter diameter tools were imported from china with two types of coatings. Total 75 tools were purchased for micro milling of Inconel 600.Technical specifications of tools are as following

Brand Name: SUPAL	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: 35^0
Precision: High	Processing Type: High Hardness Metals
Usage: High Speed Cutting	Grain Size: 0.5µm
Co: 12%	Flexural Strength: 43000 N/mm

Three types of tungsten carbide square end mill cutting tools were used for experimentation. Difference among them was type of coating applied on tools as first set was uncoated, second set AlTiSiN coated and last set was DLC coated. The selection of these coatings was done on basis of literature review. The hardness of all tools was HRC 60. Some properties of these coatings is as following

Fig 10: (a) Un coated (b) AlTiSiN Coated (c) DLC Coated

3.2.1 AlTiSiN Coating

AlTiSiN PVD coating has golden color. It is often used in hard, dry and high-speed machining applications. This coating exhibits extremely high resistance against oxidation in combination with high thermal hardness.

3.2.2 Diamond Like Coating (DLC)

DLC tools have black color. This coating is mostly used to minimize wear due to its outstanding tribological properties. Its high resistance to abrasive wear makes it feasible for using in applications which face intense contact pressure, both in sliding and rolling contact. Its application areas include razor blades, bearings, shafts, cams and cam followers and metal cutting tools including turning and milling inserts.

3.3 Work piece Material

Inconel 600 is used in the experimentation as work piece material during this research. The Inconel 600 was available in rod form. The rod is cut using Saw cutting machine then with the help of milling machine it was turned into shape of rectangular bar. The measurement of the work piece material is 40mm*15mm*10mm.

Physical Properties	°F	British Units	°C	Metric Units
Density	Room	0.304 lb./cubic in.	Room	8.43g/cubic cm
Electrical Resistivity	70 200 400 600 800	40.6 microhm-in. 40.9 41.5 42.2 43.0	21 93 204 316 427	1.03 microhm-m 1.04 1.05 1.07 1.09
Mean Coefficient of Thermal Expansion	70-200 70-400 70-600 70-800	7.4 microinches/in.-°F 7.7 7.9 8.1	21-93 21-204 21-316 21-427	13.3 x 10(-6)m/m·K 13.9 14.2 14.6
Thermal Conductivity	70 200 400 600 800	103 Btu-in./ft².-hr.-°F 109 121 133 145	21 93 204 316 427	14.8 W/m·K 15.7 17.4 19.2 20.9
Modulus of Elasticity	Room	30.0 x 10(6) psi	Room	207 GPa

Table 4: Avg. physical properties of Inconel-600

Form	Condition	Ultimate Tensile Strength, MPa	Yield Strength at 0.2% offset, MPa	Elongation in 2 in. or 4D, percent
Sheet	Annealed	98 (676)	42 (290)	40
Plate	Annealed	95 (655)	41 (283)	45
Bar/Billet	Annealed	95 (655)	41 (283)	45
Sheet, Plate, Strip, Bar	Annealed	80 (550)*	35 (240)*	30*

* - minimum

Table 5: Average Room Temperature Tensile Data

Micro hardness tester is used to find the Vickers's hardness of Inconel 600. Five tests were conducted on different areas to be more accurate. Dwell time was 6sec and 9800mN force was used during these test

Vickers hardness test is divided into two types.

1. Micro hardness Test (10 gm to 1 kg)
2. Macro hardness Test (1 kg to 50 kg)

The formula to calculate the Vickers hardness is given below

$$HV = \frac{2F\sin 136^o}{d^2} = 1.854\,\frac{F}{d^2}$$

F is the force applied and d is the mean diameter of d_1 and d_2 given below.[55]

Test No	**1**	**2**	**3**	**4**	**5**	**Min**	**Max**	**Mean**
D1(µm)	72.15	69.76	72.51	75.02	6.47	69.76	76.47	73.182
D2(µm)	68.41	70.73	70.31	73.35	68.96	68.41	73.35	70.352
Mean	70.28	70.04	71.41	74.185	72.72	60.09	74.91	71.767
HV	375	376	364	337	351	337	376	361

Table 6: Micro hardness test results

Figure 11: Micro Hardness Tester

Grain size has a large effect on the mechanical properties of the Inconel 600. The following figure 3.3 gives the idea about the effect of grain size on major mechanical properties namely; strength, tensile, Low Cycle fatigue (LCF), crack growth and creep.

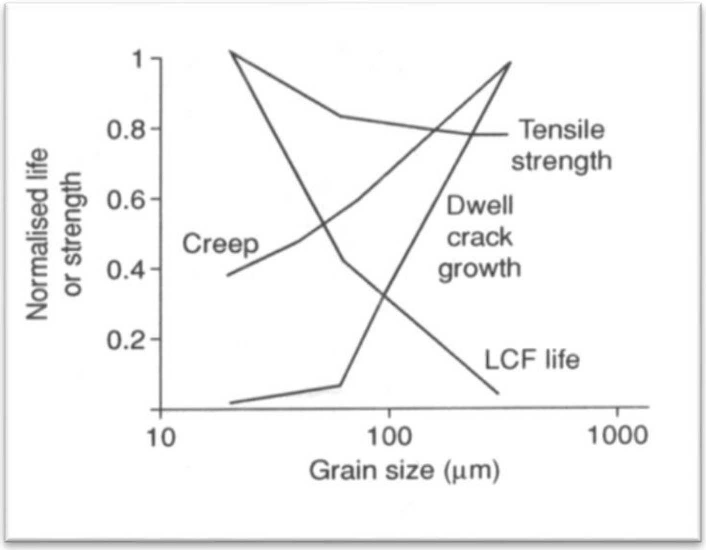


Figure 12: Effect of grain size on mechanical properties[56]

The effect of decreasing grain size on weld ability, toughness, strength and ductility are given in the following figure 13.

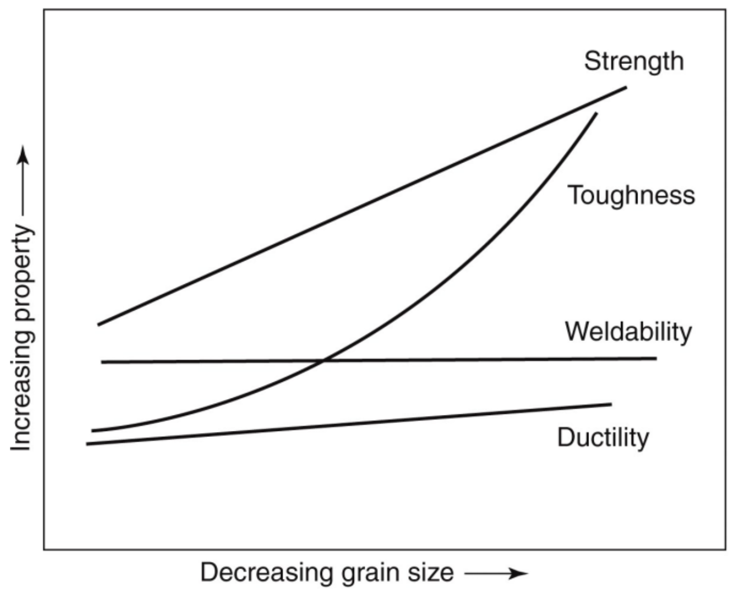


Figure 13: Effect of grain size on mechanical properties[57]

Grain size number was measured using ASTM standard method. First the work material is grinded and polished. After that waterless kalling's is used[58] for itching for almost 5sec and then cleaned with water. The micro structure was studied using optical microscope using different magnification. The micro structure found for Inconel 600 is given below in Figure 14.

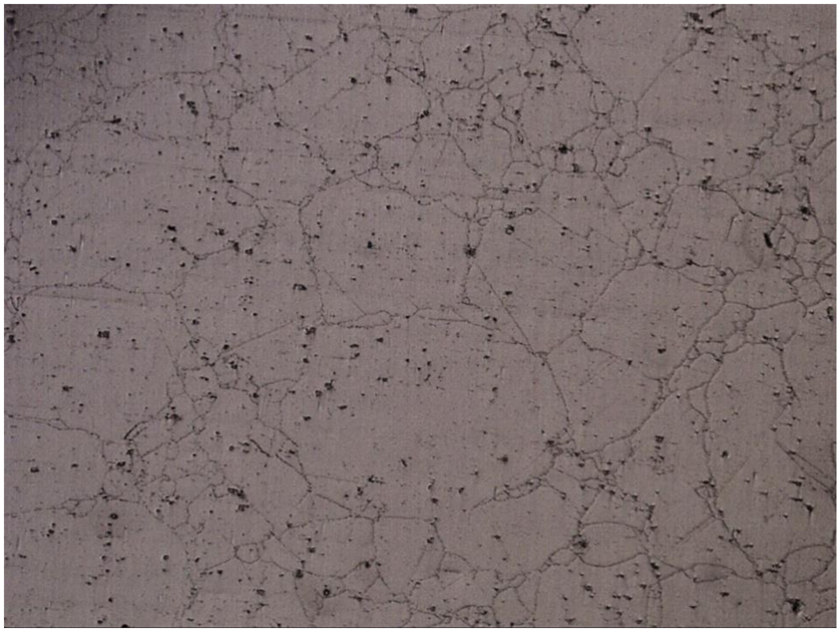


Figure 14: Micro structure of Inconel 600 at 100x

The following procedure is used to find ASTM Grain Size Number[59]

$N_A = f(n_{inside} + 0.5n_{intercepted})$

Where N_A is the number of grains per mm^2 at 1X and f is the Jeffries multiplier:

$f = 0.0002M^2$

and M is the magnification used for analysis and a is the area. If the test area is different from 5000 mm^2, then the magnification square is divided by the alternate area used.

The N_A, is the reciprocal of grain area A. Then the ASTM grain size number calculated is:

$G = 3.321928 \text{ Log } N_A – 2.954$

N_{inside}=218

$n_{intercepted}$=32

f=8 at M=200x

So, **N_A=1872**No/mm^2

This process is repeated for three different samples

Average grain diameter from table = 22.5 µm

Average grain area from table = 500 μm^2

And ASTM grain size number **G=8**

3.4 CNC Milling Machine

CNC milling machine is used to make slots by using different parameters for the experimentation. The specification for the CNC milling machine is given below

Company: AKIRA SEIKI

Vertical Milling Center (without B-axis)   Model: AS-500T

Sr # RTA080095   Manufactured: Aug 2008

Control: Fanuc Series oi-MC   Company = AKIRA SEIKI Co., Ltd, Taiwan

Spindle Speed = 15 – 15,000 RPM

3.4.1 Technical Specifications:

Rapid traverse x-axis = 96 m/min   Rapid traverse y-axis = 60 m/min

Rapid traverse z-axis = 96 m/min   Drilling capacity = Φ 12 x 0.1 mm x mm/rev

Cutting feed rate = 10,000 mm/min

3.4.2 Working Area of Machine:

X-axis travel = 500 mm   Y-axis travel = 280 mm   Z-axis travel = 280 mm

3.4.3 Tool Specifications:

Number of tools in tool ring= 24   Maximum tool = Φ 40 mm

Maximum tool length = 175 mm   Maximum tool weight = 2.5 mm

Tool change time = 0.7 sec

3.4.4 Machine Specifications:

Weight: 3,500 kg   L x W = 1.50 m x 2.24 m

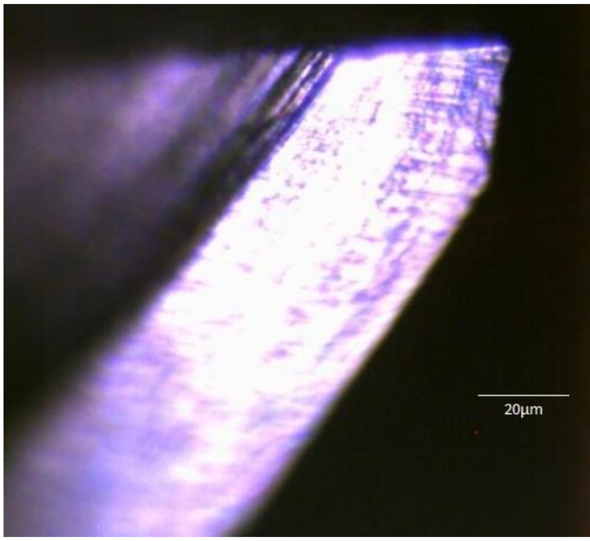
Maximum Power Consumption = 20k watt

Full load current = 28 A @ 410 V;   3-phase 50-60 Hz supply

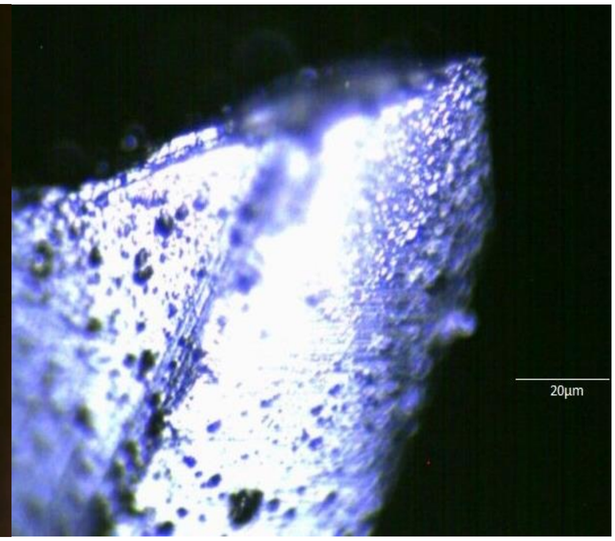
3.5 Cutting Edge Radius

The cutting-edge radius of the carbide steel tool is measured using optical microscope of 50x magnification. It was measured to set the depth of cut per tooth. First an image was taken of all tools with the linear measurement. Then these pictures were opened in Image J software. The measurements were set separately for each picture in µm. After that by using the areas of circle command the cutting- edge radius was found by converting the areas of a circle into a radius. The cutting- edge radius found was different for every tool with a little deviation.

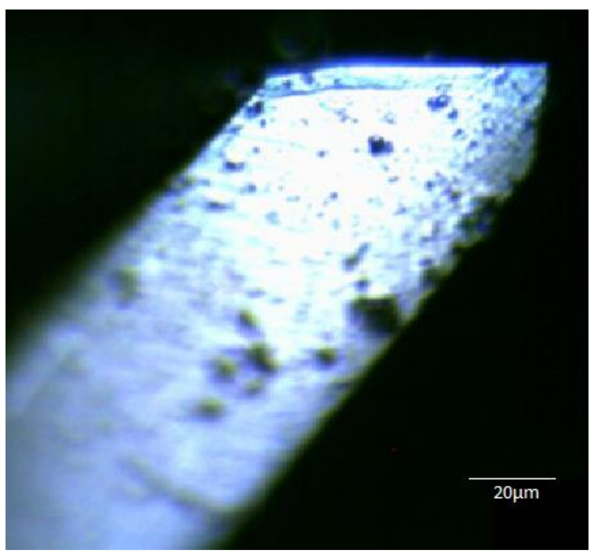
Figure 15 shows the cutting-edge radius of three tools with different coating. These pictures of the tools were taken with the optical microscope of 500x magnification. The cutting edges were found 1.3 µm (a), 1.15 µm (b) and 1.2 µm (c) respectively.



(a) Uncoated Tool



(b) TiAlSiN Coated



(c) DLC Coated

Figure 15: SEM Images of different Tool’s cutting edges at 500x resolution

3.6 Cutting Parameters

Different levels of parameters were used to find their effect on surface roughness and burr formation. Following criteria is used for the selection of different level of parameters.

3.6.1 Depth of Cut

The optimum depth of cut found for the minimum burr formation during the micro machining of Inconel 718 is 60µm[3]. And also, every tool according to it dimensions have its own recommendation for the depth of cut. The depth of cut is set using the following procedure by Niagara cutters.[61]

If the cutting tool diameter is 3.175mm or below then.

The depth of cut =DOC = Tool diameter (D) x (0.05 to 0.25)

So, the minimum depth of cut become= 0.5 x 0.05 = 0.025mm

And maximum depth of cut becomes= 0.5 x 0.25 = 0.125mm

So, the range for the depth of cut is 25µm to 125µm. And the optimum depth of cut for burr is 60µm. we take the depth of cut to be 30µm, 60µm and 90µm.

3.6.2 Feed per tooth

J.Chae[2] founded in his review that elastic recovery of the work piece contributes to the increase in cutting force below minimum chip thickness/ low feed rate. According to AJ mian[39] research the minimum chip thickness for Inconel 600 was found at 18.5–25.5 percent of the tool cutting edge radius and in other research he founded that ratio of feed per tooth to cutting edge radius was a dominant factor in reducing the burr formation as the minimum burr formation occur at minimum chip thickness. [3]

The feed per tooth was selected 0.2, 0.3 and 0.4 µm/tooth for below cutting edge experiments while 3, 4 and 5 µm/tooth for above cutting edge experiments.

3.6.3 Cutting Speed

At micro level the properties of the material become non-homogenous which causes the variation in micro hardness that leads to the cause of vibration in tool. This is low at high cutting speed and feed rate. Due to this irregular surface is formed during machining process. High speed is also used in micro machining due to formation of fewer burrs. [2, 3] High-speed machines also present new challenges for micro-machining. At higher speeds, the dynamics of machine tools change, with an unbalanced spindle producing centrifugal and gyroscopic effects.[2]

Tool run-out and unbalance is usually a minor problem in macro-machining operations; however, the problem is severely amplified when the diameter of the tool decreases and spindle speed increases significantly.[2]

$$n = \frac{Vc}{\pi D}$$

Above formula is used for converting cutting speed to revolution per minute. As low speed machining setup is easily available and more economical as compared to high speed machining setup. The maximum RPM of the available machine is 15000 so, we are going to work with two ranges of cutting speed (conventional machining range) to see the effect on surface finish and burr formation. Lower cutting velocity ranged from 6-10 m/min while higher cutting velocity set ranged from 19-23 m/min.

3.7 Design of Experiments

In few years, the Taguchi method for experimentation has become a powerful tool for improving productivity during research and development phase so that high quality research can be done in short amount of time with low cost. Taguchi method for parameter design is an important tool for robust design. It uses a special method to study the entire parameter space with a limited number of experiments using orthogonal arrays.

The Taguchi is used on for four factors, 2 with three levels while remaining 2 factors with 6 levels is to find the experimental plan for the research. We had 2 option to either choose two L18 arrays or four L9 arrays. The latter option of four L9 arrays was selected and parameters were categorized in four sets as following

Set 1: Below cutting edge radius with Lower RPM

Set 2: Below cutting edge radius with higher RPM

Set 3: Above cutting edge radius with lower RPM

Set 4: Above cutting edge radius with higher RPM

Taguchi's L9 orthogonal arrays are used to define the 9 trials for each of sets. So we got 36 number of combinations with 4 different L9 orthogonal arrays. Each trial was repeated one time to minimize error. Due to this repetition total number of trails performed were 72. Fresh tools was used for each test to minimize effect of tool wear on surface finish and burr width.

Each of the 9 trials and their parameter are given below in table. The parameters selected for the micro-milling of Inconel 600 is given in the below Table 7.

Table 7: Process parameters and their levels

Factor	Set 1 (Below Edge Radius) Lower RPM			Set 2 (Below Edge Radius) Higher RPM		
Feed/tooth, f (μm/tooth)	0.2	0.3	0.4	0.2	0.3	0.4
Cutting velocity, Vc (m/min)	6	8	10	19	21	23
Depth of cut, ap (μm)	30	60	90	30	60	90
Coating applied on tool	Un coated	TiAlSiN	DLC	Un coated	TiAlSiN	DLC

Factor	Set 3 (Above Edge Radius) Lower RPM			Set 4 (Above Edge Radius) Higher RPM		
Feed/tooth, f (μm/tooth)	3	4	5	3	4	5
Cutting velocity, Vc (m/min)	6	8	10	19	21	23
Depth of cut, ap (μm)	30	60	90	30	60	90
Coating applied on tool	Un coated	TiAlSiN	DLC	Un coated	TiAlSiN	DLC

Table 8: Experimental plan using an L9 orthogonal array

Trial	Feed μm/tooth	Cutting Velocity m/min	Depth of cut μm	Tool Coating	Tool Dia μm	Spindle speed RPM
T-1	0.2	6	30	Un coated	500	3815
T-2	0.2	8	60	TiAlSiN	500	5086
T-3	0.2	10	90	DLC	500	6358
T-4	0.3	6	60	DLC	500	3815
T-5	0.3	8	90	Un coated	500	5086
T-6	0.3	10	30	TiAlSiN	500	6358
T-7	0.4	6	90	TiAlSiN	500	3815
T-8	0.4	8	30	DLC	500	5086
T-9	0.4	10	60	Un coated	500	6358
T-10	0.2	19	30	Un coated	500	12080
T-11	0.2	21	60	TiAlSiN	500	13352
T-12	0.2	23	90	DLC	500	14623
T-13	0.3	19	60	DLC	500	12080
T-14	0.3	21	90	Un coated	500	13352
T-15	0.3	23	30	TiAlSiN	500	14623
T-16	0.4	19	90	TiAlSiN	500	12080
T-17	0.4	21	30	DLC	500	13352
T-18	0.4	23	60	Un coated	500	14623
T-19	3	6	30	Un coated	500	3814
T-20	4	8	60	TiAlSiN	500	5086
T-21	5	10	90	DLC	500	6358
T-22	3	6	60	DLC	500	3814
T-23	4	8	90	Un coated	500	5086
T-24	5	10	30	TiAlSiN	500	6358

T-25	3	6	90	TiAlSiN	500	3814
T-26	4	8	30	DLC	500	5086
T-27	5	10	60	Un coated	500	6358
T-28	3	19	30	Un coated	500	12080
T-29	4	21	60	TiAlSiN	500	13351
T-30	5	23	90	DLC	500	14623
T-31	3	19	60	DLC	500	12080
T-32	4	21	90	Un coated	500	13351
T-33	5	23	30	TiAlSiN	500	14623
T-34	3	19	90	TiAlSiN	500	12080
T-35	4	21	30	DLC	500	13351
T-36	5	23	60	Un coated	500	14623

3.8 Methodology

The micro milling experiments were done on Inconel 600 (nickel alloy). The experiments were done on conventional speed machining center AKIRA SEIKI. AKIRA SEIKI motion controller is used to control the relative motion between the work piece and milling tool during the micro machining process. The tools used during experiments of micro-milling were ultrafine tungsten carbide steel tools The tools used were flat end mills with cutting diameter of 500µm, number of flutes 2 and helix angle of 30^o.

The dimension of the work piece that is mounted on the fixture is 11x50x20mm. The length of the slot for the experimentation was fixed at 12 mm so the wear and damaged to the tool can be neglected. Experimental conditions for these tests are given in Table 9.

Table 9: Experimental conditions

Work piece	Inconel 600
Tool Diameter	0.5mm
Flukes	2
Cutting Length	12 mm
Cutting Fluid	Dry Condition
Milling Type	Full Immersion

3.9 Experiments

- Experimentation was done in dry condition for the worst-case scenario.
- Tool pre-setter is used for the accurate depth of cut (offset).
- Each slot is 2mm apart from each other.
- All the experiments for the one coated tools are done one piece which is 18 slots per work piece as shown is Figure.
- Total of five work pieces were used for the experimentation and the last and fifth one was used for the confirmation experiments.
- Experiment no. 1-18 were performed on Sample 1
- Experiment no. 19-36 were performed on Sample 2
- Experiment no. 37-54 were performed on Sample 3
- Experiment no. 55-72 were performed on Sample 4
- Confirmation experiments were performed on sample 5

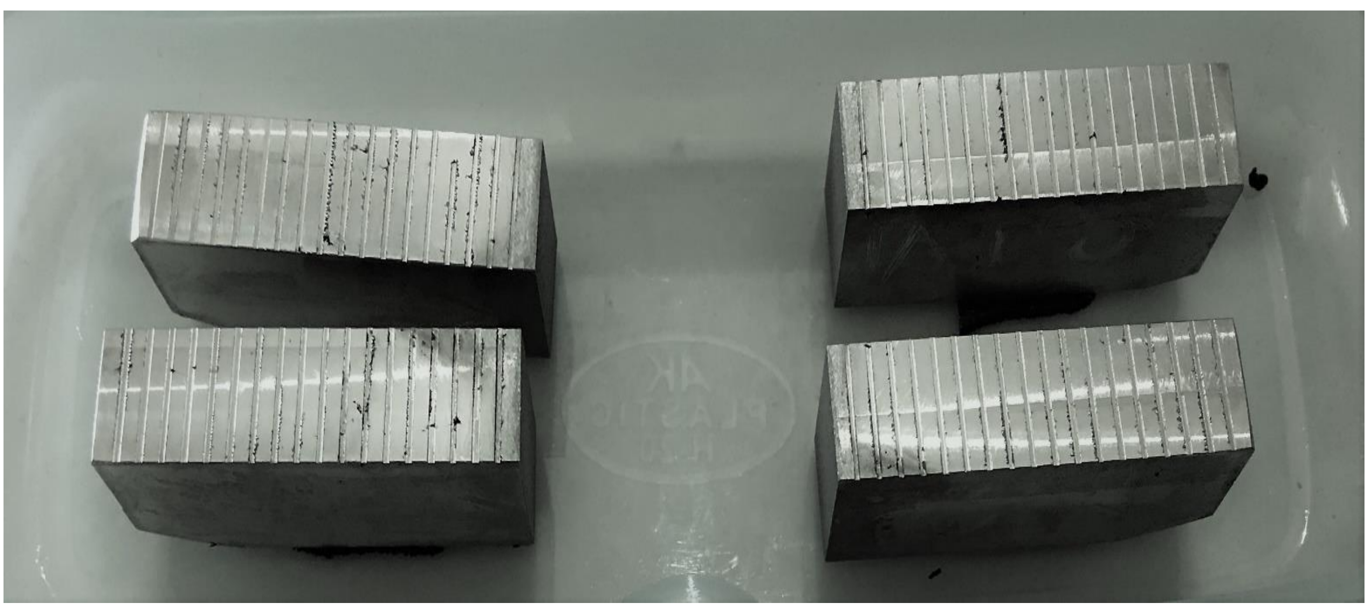


Figure 16: Micro Machined Samples

CHAPTER 4: RESULTS & DISCUSSION

4.1 Burr Formation Analysis

There are different types of burr such a top burr, exit burr, entrance burr and bottom burr. In our experimentations during the burr analysis the main focus is given to top burr and it is being calculated using scanning electron microscope. During burr formation analysis maximum burr lengths found for each slot. All of the samples are analyzed to find the effect of machining parameters and tool coating on burr formation. Taguchi method is used to find the effect of parameter on burr formation and finding the best parameter for minimum burr formation. ANOVA is used to find the percentage effect of machining parameters on burr formation. During our analyses most of the burrs were formed during the end of the end of slot. Burrs are formed on both side of the milling slots. In our case most of the burr were formed on the up-milling side.

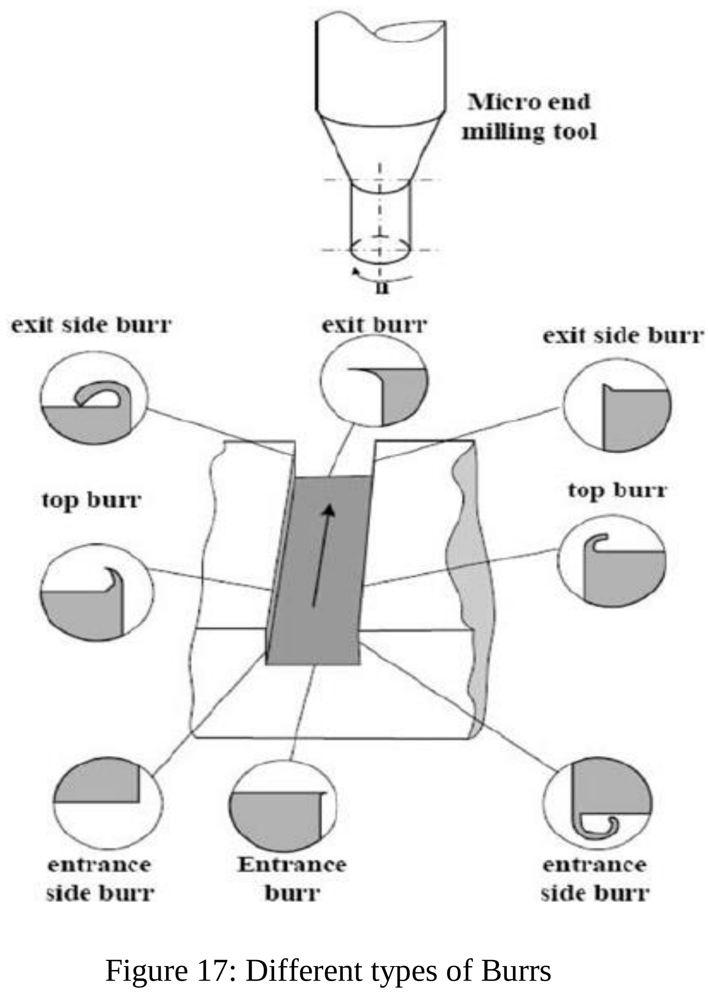


Figure 17: Different types of Burrs

4.1.1 Set 1 (Below cutting edge radius with Lower RPM)

Sr.No	Feed	Vc	DOC	Coating	Trail 1	Trail 2	Avg. width	Deviation
T-1	0.2	6	30	Un coated	218	438	328	155.6
T-2	0.2	8	60	TiAlSiN	191	312	251	85.6
T-3	0.2	10	90	DLC	263	215	239	33.6
T-4	0.3	6	60	DLC	394	167	280	160.2
T-5	0.3	8	90	Un coated	287	205	246	58.2
T-6	0.3	10	30	TiAlSiN	306	226	266	57.0
T-7	0.4	6	90	TiAlSiN	189	246	217	40.5
T-8	0.4	8	30	DLC	199	330	265	92.9
T-9	0.4	10	60	Un coated	346	279	312	47.0

Analysis of Variance

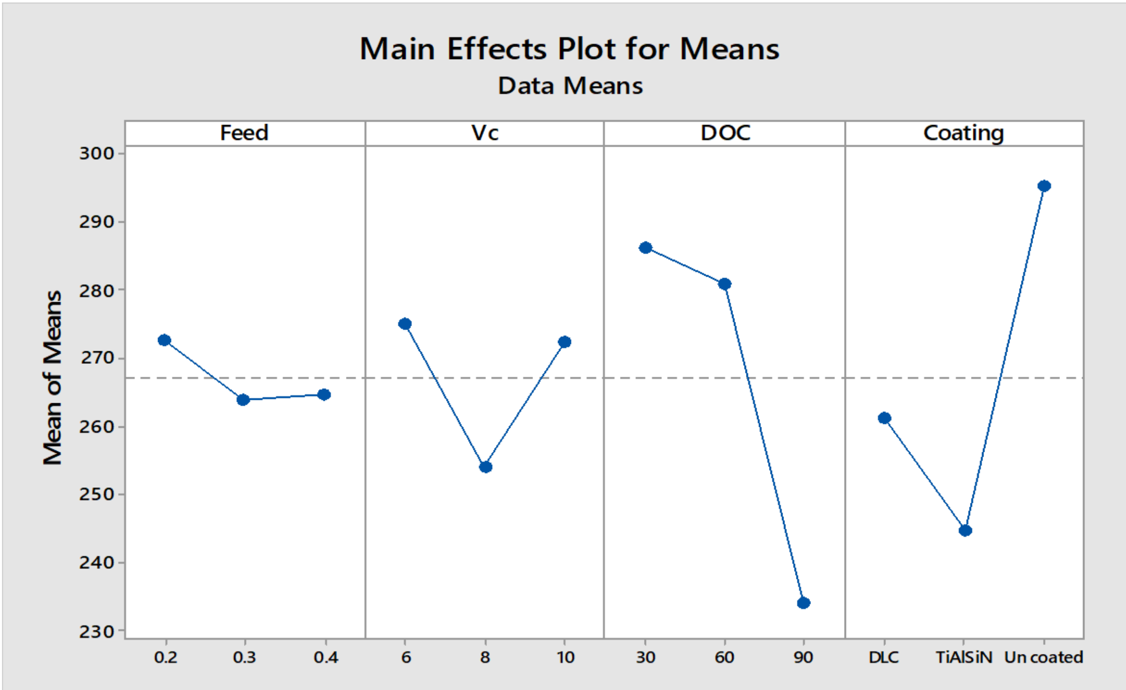
Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	CR
Feed	2	139.6	139.6	69.8	*	*	1.4%
Vc	2	784.2	784.2	392.1	*	*	7.9%
DOC	2	4976.2	4976.2	2488.1	*	*	50.3%
Coating	2	4000.9	4000.9	2000.4	*	*	40.4%
Error	0	*					
Total	8	9900.9					100%

Response Table for Signal to Noise Ratios (Smaller is better)

Level	Feed	Vc	DOC	Coating
1	-48.63	-48.66	-49.09	-48.33
2	-48.42	-48.09	-48.94	-47.74
3	-48.36	-48.65	-47.37	-49.34
Delta	0.27	0.57	1.72	1.6
Rank	4	3	1	2

Regression Equation

Burr Width = 294.0 + 0.0 Feed_0.2 - 8.667 Feed_0.3 - 8.000 Feed_0.4 + 0.0 Vc_6 - 21.00 Vc_8- 2.667 Vc_10 + 0.0 DOC_30 - 5.333 DOC_60 - 52.33 DOC_90 + 0.0 Coating_DLC- 16.67 Coating_TiAlSiN + 34.00 Coating_Un coated



In this set which has lower RPM with below cutting edge radius, depth of cut is most influencing input parameter followed by tool coating.

Burr width results are better as depth of cut is increasing so best results are found on larger depth of cut (90 micro meter).

TiAlSiN coating showed best results followed by Diamond like coated tools while non-coated tools have worst results.

Cutting velocity level 8.0 have better response than level 6.0 and level 10.0

Feed per tooth level 0.3 and 0.4 have better response than level 0.2

4.1.2 Set 2 (Below cutting edge radius with higher RPM)

Sr.No	Feed	Vc	DOC	Coating	Trail 1	Trail 2	Avg. width	Deviation
T-10	0.2	19	30	Un coated	181	147	164	23.8
T-11	0.2	21	60	TiAlSiN	370	201	285	118.9
T-12	0.2	23	90	DLC	206	443	324	167.8
T-13	0.3	19	60	DLC	215	214	214	0.4
T-14	0.3	21	90	Un coated	290	172	231	83.8
T-15	0.3	23	30	TiAlSiN	266	199	232	47.0
T-16	0.4	19	90	TiAlSiN	148	275	212	89.9
T-17	0.4	21	30	DLC	153	191	172	26.9
T-18	0.4	23	60	Un coated	172	367	269	138.1

Analysis of Variance

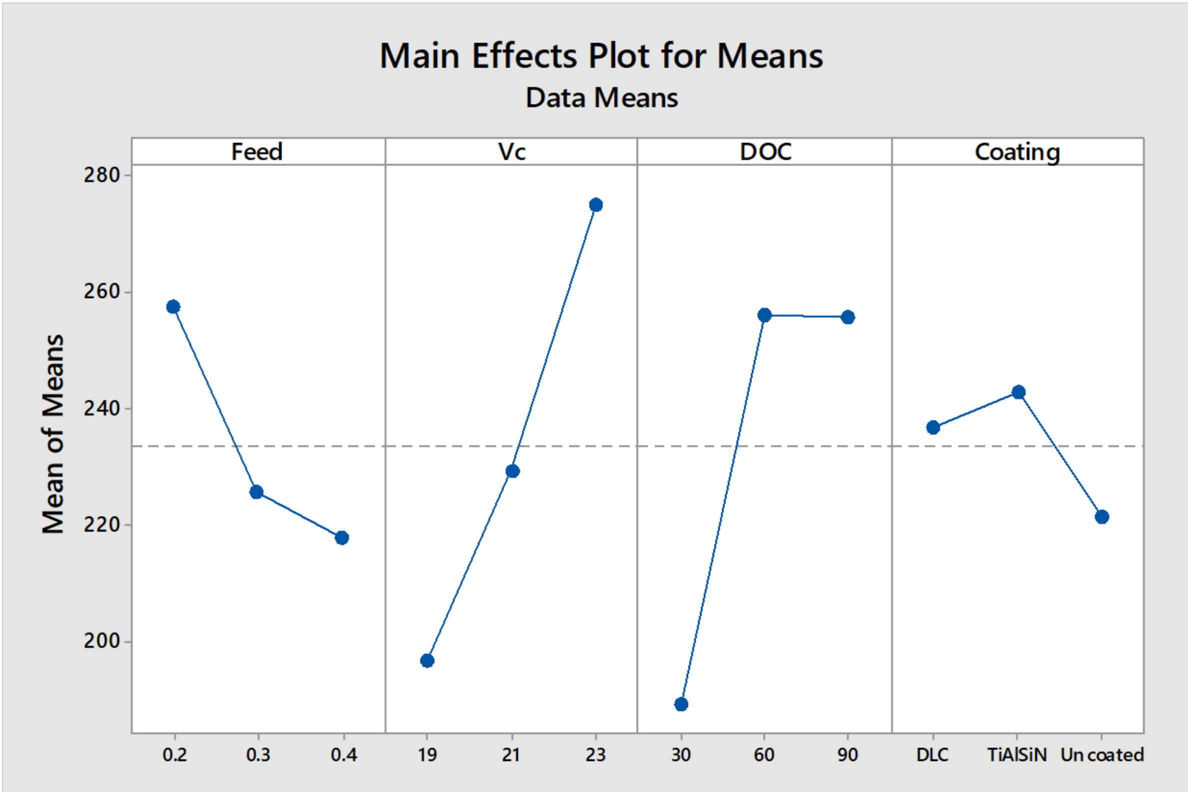
Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	CR
Feed	2	2688	2688	1344	*	*	12.5%
Vc	2	9288.7	9288.7	4644.3	*	*	43.1%
DOC	2	8844.7	8844.7	4422.3	*	*	41.0%
Coating	2	744.7	744.7	372.3	*	*	3.5%
Error	0	*	*	*	*	*	*
Total	8	21566					100%

Response Table for Signal to Noise Ratios (Smaller is better)

Level	Feed	Vc	DOC	Coating
1	-47.87	-45.81	-45.44	-47.18
2	-47.06	-47.03	-48.1	-47.64
3	-46.61	-48.71	-48	-46.72
Delta	1.26	2.89	2.66	0.92
Rank	3	1	2	4

Regression Equation

Burr Width = 179.3 + 0.0 Feed_0.2 - 32.00 Feed_0.3 - 40.00 Feed_0.4 + 0.0 Vc_19
+ 32.67 Vc_21+ 78.33 Vc_23 + 0.0 DOC_30 + 66.67 DOC_60 + 66.33 DOC_90+ 0.0 Coating_DLC
+ 6.333 Coating_TiAlSiN - 15.33 Coating_Un coated



In this set having higher RPM and below cutting edge radius feed, cutting velocity is found to be most influencing input parameter followed by depth of cut. Feed per tooth have also prominent effect on response.

Feed have inverse relation with burr width as burr value is higher on lower feed and lower on higher feed levels.

Burr width have direct relation with cutting velocity as its value is lower on lower cutting velocity and higher on higher cutting velocity levels.

In this set burr width formation is lower on lowest depth of cut level.

Non-coated tools have better response than remaining two coatings.

4.1.3 Set 3 (Above cutting edge radius with lower RPM)

Sr.No	Feed	Vc	DOC	Coating	Trail 1	Trail 2	Avg. width	Deviation
T-19	3	6	30	Un coated	189	129	159	42.8
T-20	4	8	60	TiAlSiN	172	108	140	45.7
T-21	5	10	90	DLC	166	162	164	2.8
T-22	3	6	60	DLC	119	220	169	71.1
T-23	4	8	90	Un coated	163	228	195	46.3
T-24	5	10	30	TiAlSiN	258	181	219	54.5
T-25	3	6	90	TiAlSiN	204	158	181	32.8
T-26	4	8	30	DLC	114	221	168	75.7
T-27	5	10	60	Un coated	154	173	163	13.4

Analysis of Variance

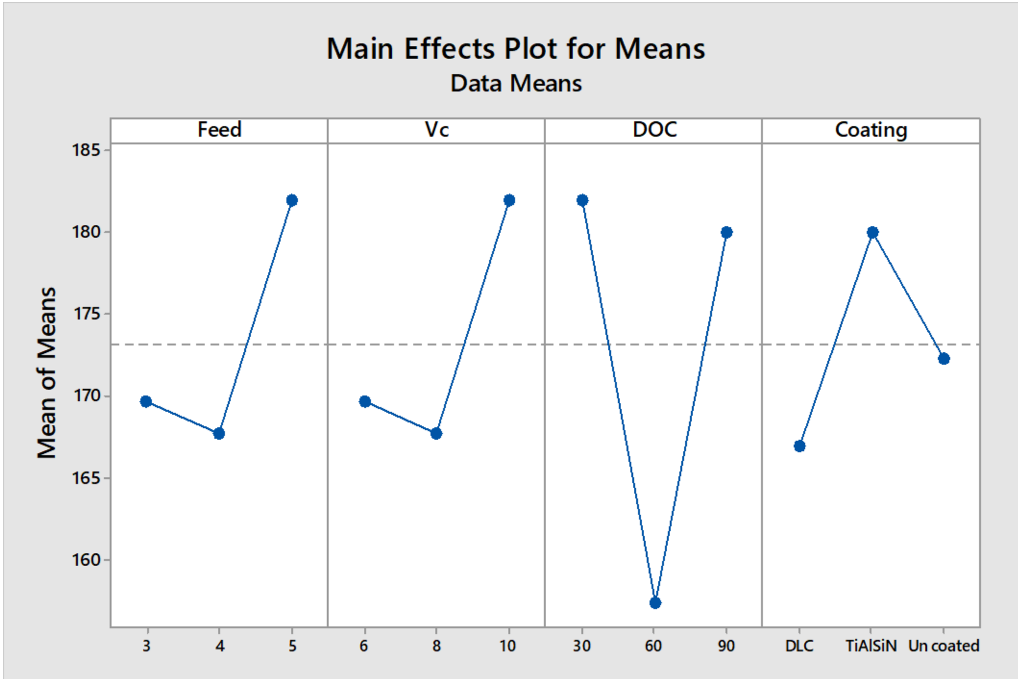
Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	CR
Feed	2	361.6	361.6	180.8	0.15	0.87	8.7%
Vc	2	1126.2	1126.2	563.1	0.46	0.683	27.0%
Coating	2	256.2	256.2	128.1	0.11	0.905	6.1%
Error	0	2426.9	2426.9	1213.4			58.19
Total	8	4170.9					100%

Response Table for Signal to Noise Ratios (Smaller is better)

Level	Feed	Vc	DOC	Coating
1	-44.58	-44.58	-45.11	-44.45
2	-44.41	-44.41	-43.91	-44.96
3	-45.12	-45.12	-45.08	-44.69
Delta	0.71	0.71	1.21	0.51
Rank	2.5	2.5	1	4

Regression Equation

Burr Width = 172.4 + 0.0 Feed_3 - 2.0 Feed_4 + 12.3 Feed_5 + 0.0 DOC_30 - 24.7 DOC_60 - 2.0 DOC_90 + 0.0 Coating_DLC + 13.0 Coating_TiAlSiN + 5.3 Coating_Un coated



In this set having lower RPM with above cutting edge radius feed, depth of cut is found to be most influencing input parameter.

Burr width measurement is lower on feed level 4.0 and cutting velocity level 8.0 and higher on highest levels of feed and cutting velocity.

Medium level depth of cut (60 micro meter) have better response.

Diamond like coating has better results rather remaining two coatings.

4.1.4 Set 4 (Above cutting edge radius with higher RPM)

Sr.No	Feed	Vc	DOC	Coating	Trail 1	Trail 2	Avg. width	Deviation
T-28	3	19	30	Un coated	161	108	134	37.7
T-29	4	21	60	TiAlSiN	180	207	193	18.7
T-30	5	23	90	DLC	207	170	188	25.6
T-31	3	19	60	DLC	228	209	219	13.3
T-32	4	21	90	Un coated	345	206	275	98.2
T-33	5	23	30	TiAlSiN	190	140	165	35.4
T-34	3	19	90	TiAlSiN	279	186	233	65.8
T-35	4	21	30	DLC	195	150	172	31.3
T-36	5	23	60	Un coated	238	407	322	119.6

Analysis of Variance

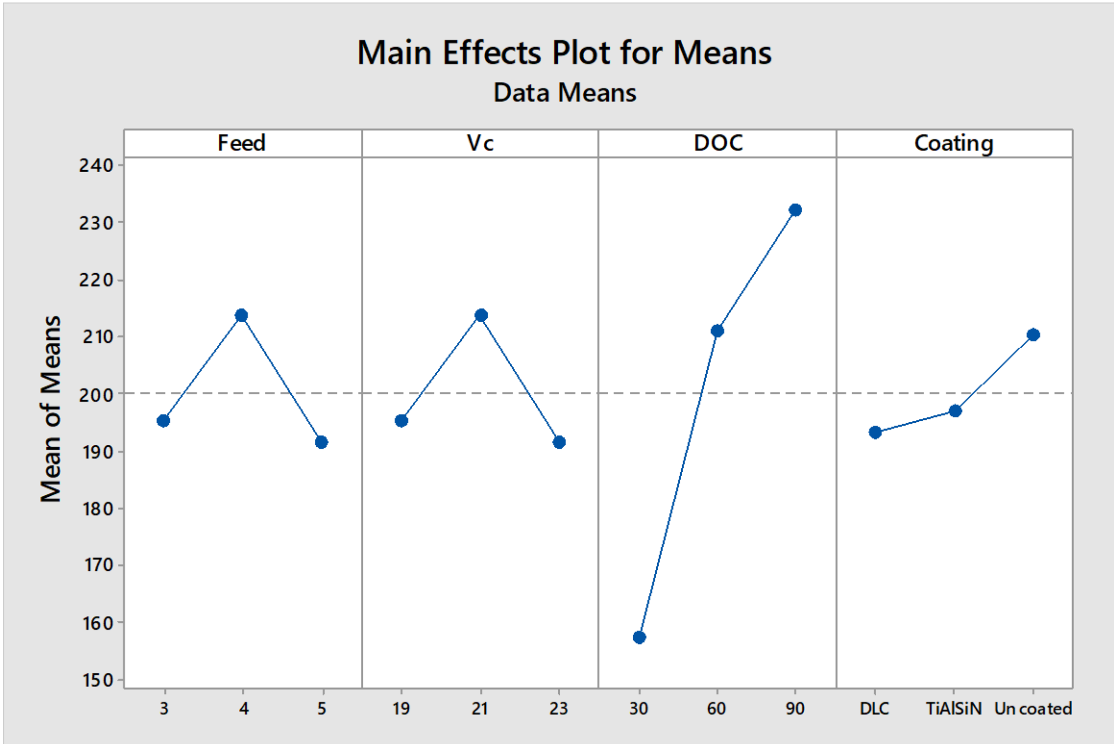
Source	DF	Seq SS	Adj SS	Adj MS	F-Value	P-Value	CR
Feed	2	841	841	420.5	0.23	0.816	6.0%
DOC	2	8918.5	8918.5	4459.2	2.39	0.295	63.1%
Coating	2	478.1	478.1	239	0.13	0.886	3.4%
Error	0	3724	3724	1862			26.67
Total	8	13961.6					100%

Response Table for Signal to Noise Ratios (Smaller is better)

Level	Feed	Vc	DOC	Coating
1	-45.56	-45.56	-43.88	-45.68
2	-46.41	-46.41	-46.47	-45.8
3	-45.58	-45.58	-47.21	-46.08
Delta	0.85	0.85	3.33	0.4
Rank	2.5	2.5	1	4

Regression Equation

Burr Width = 145.4 + 0.0 Feed_3 + 18.4 Feed_4 - 3.7 Feed_5 + 0.0 DOC_30
+ 53.7 DOC_60+ 74.8 DOC_90 + 0.0 Coating_DLC + 3.8 Coating_TiAlSiN + 17.0 Coating_Un coated



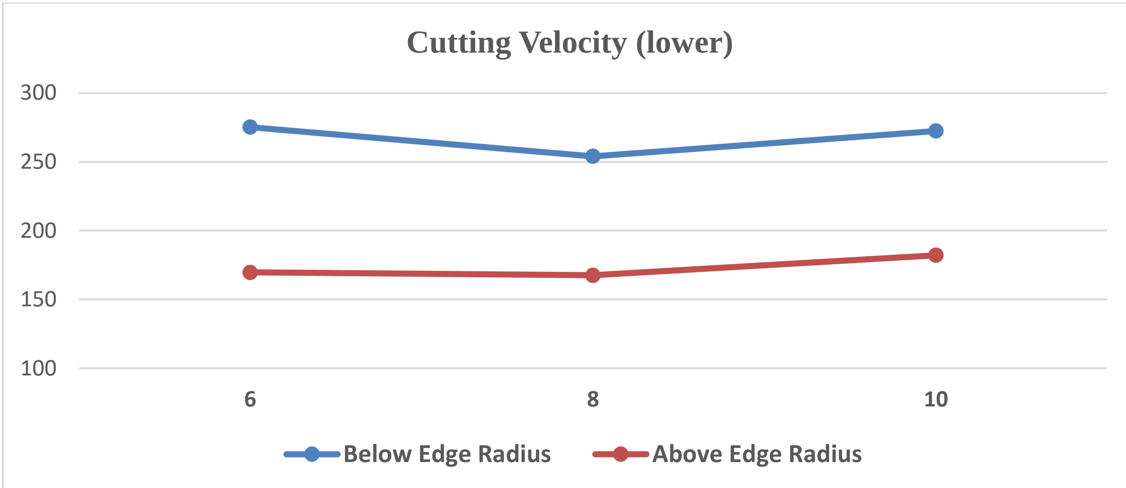
In this set having higher RPM with higher (above cutting edge radius) feed, depth of cut is again most influencing input parameter while feed and cutting velocity have same effect on response.

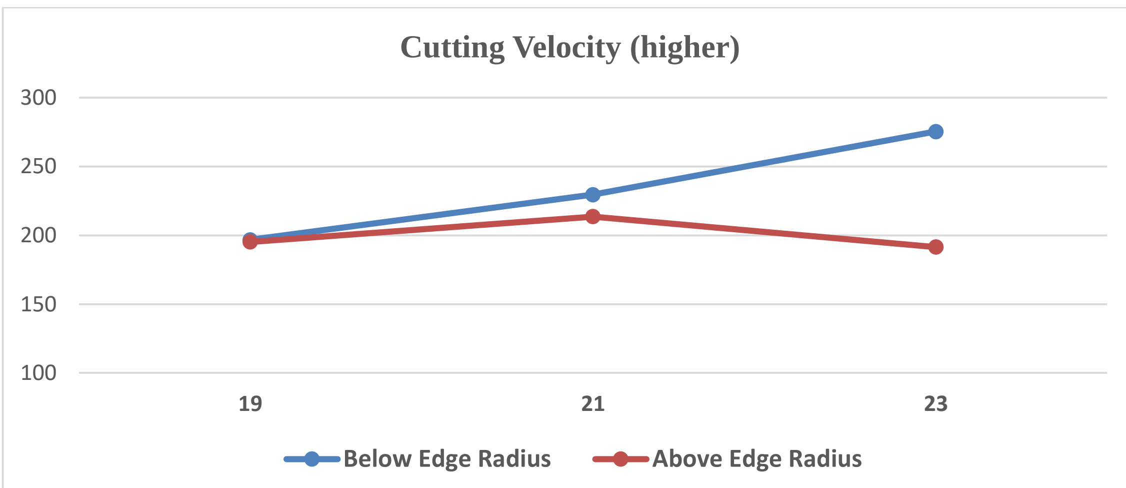
Burr width formation have direct relation with depth of cut as its value increases with increase in depth of cut.

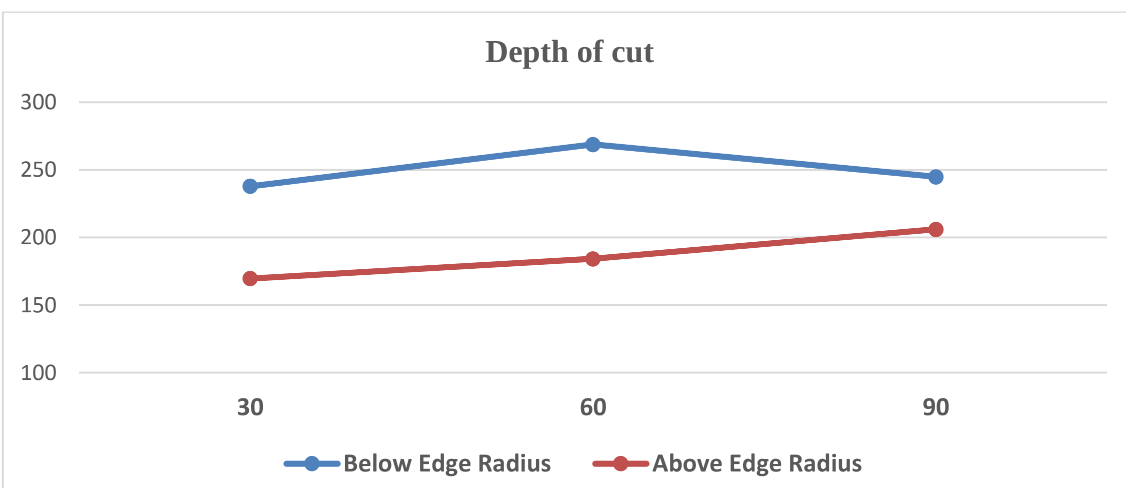
Diamond like coating have better response followed by TiAlSiN coating while non-coated have worst response.

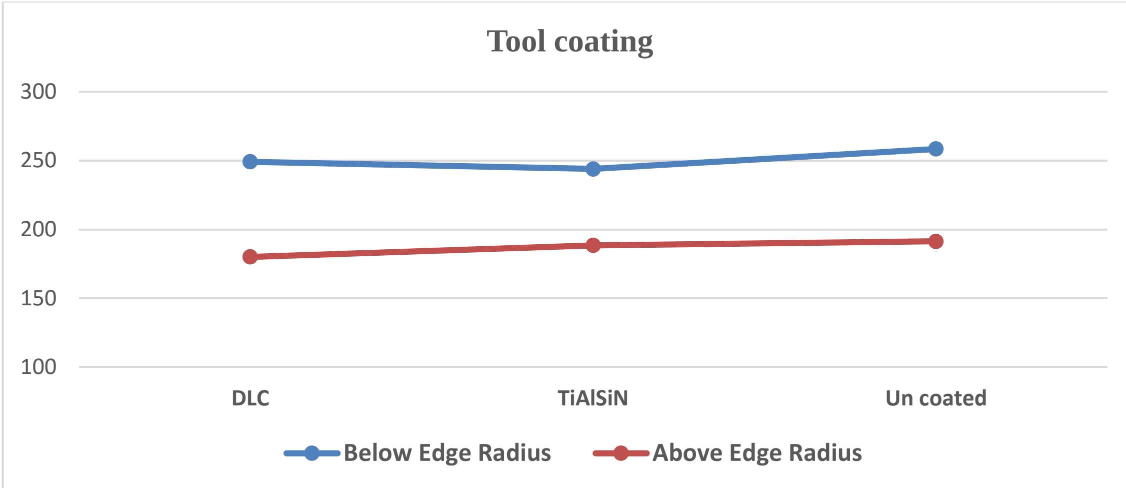
Burr formation response is lowest on highest levels of feed and cutting velocity.

4.1.5 Effect of Feed (Below vs. Above Edge Radius) on Burr Width:





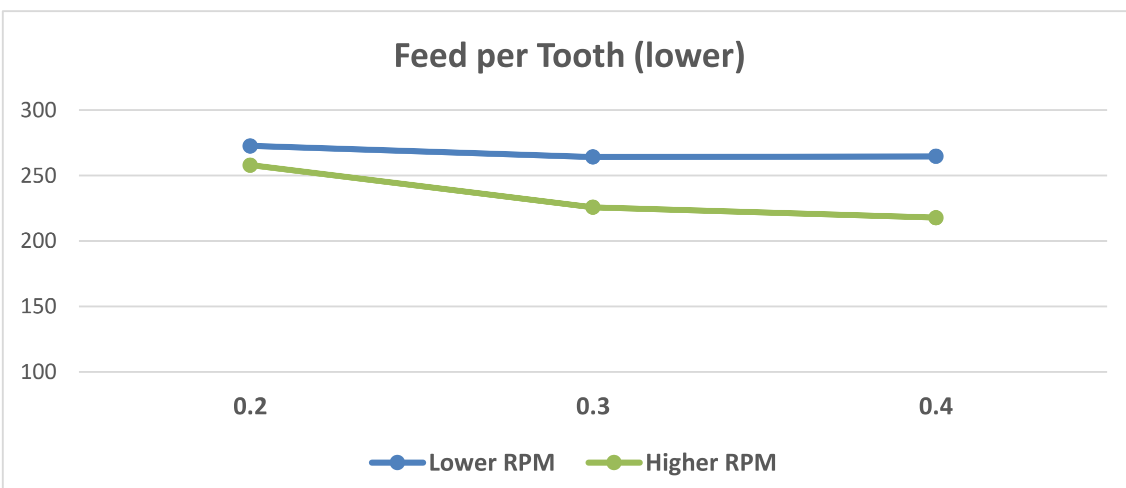


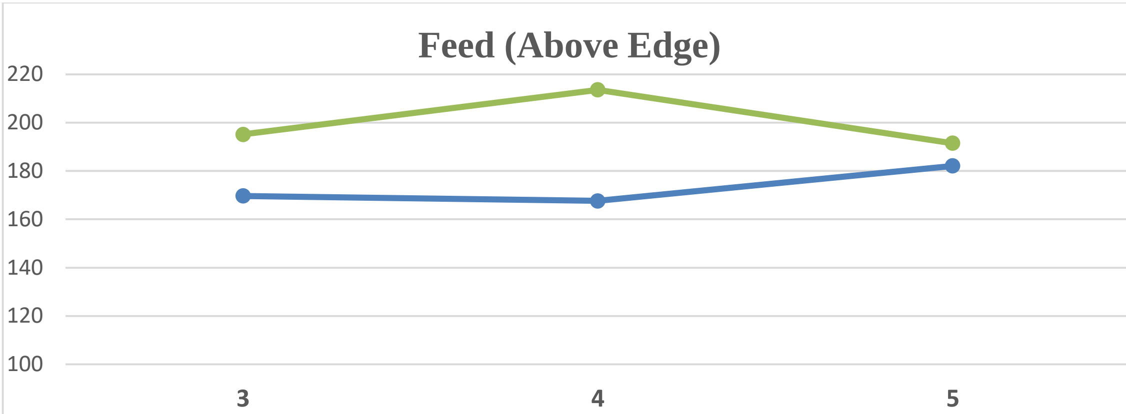


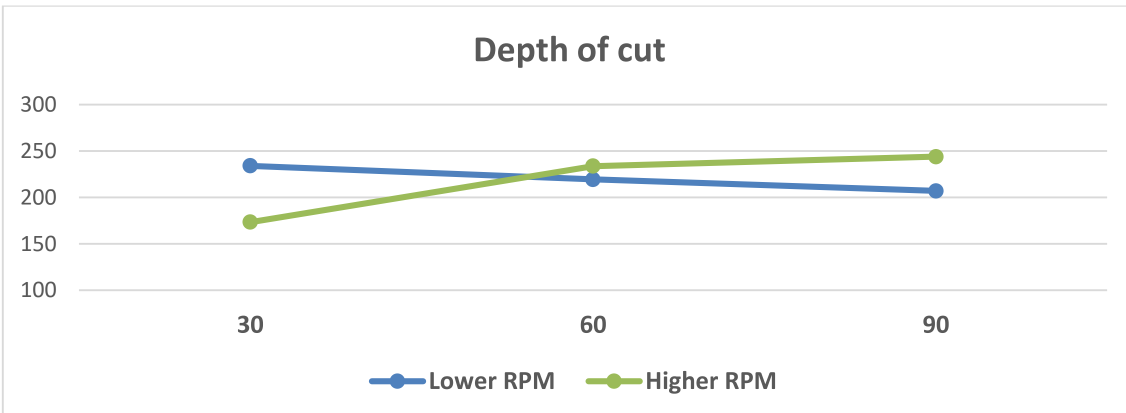
In these graphs blue lines are showing below edge radius feed while red lines are showing above edge radius feed. It shows us effect of feed on other input parameters in reference to burr width response. These graphs shows us clearly that above edge radius have better results than below edge radius feed.

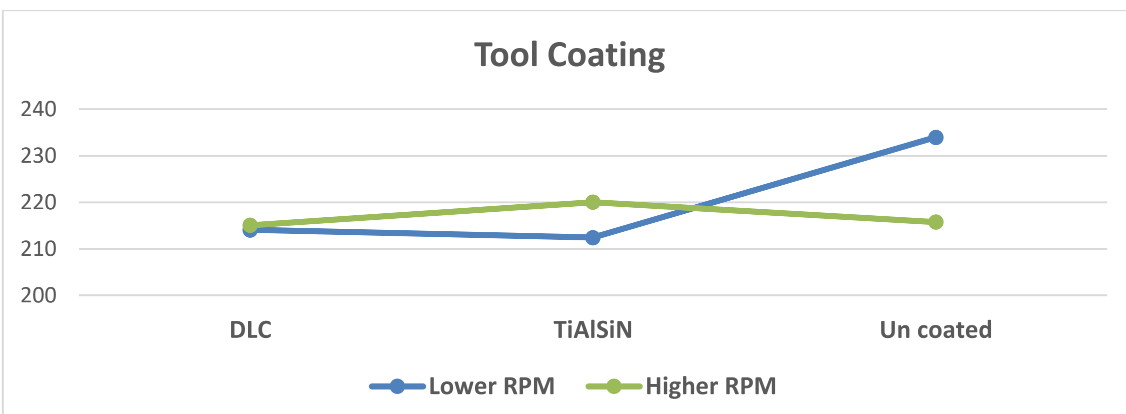
4.1.6 Effect of cutting Velocity (Higher vs. lower RPM) on Burr Width:

In these graphs blue lines are showing lower cutting velocity (RPM) while green lines are showing higher cutting velocity (RPM). It shows effect of cutting velocity on other input parameters in reference to burr width response.









Burr width result of lower cutting velocity on both lower feed and higher feed is better than higher cutting feed levels. Lower cutting velocity have better result on higher depth of cut while higher cutting speed have better response on lower depth of cut. Higher feed have better response on non-coated tools than lower feed.

4.2 Surface Roughness Analysis

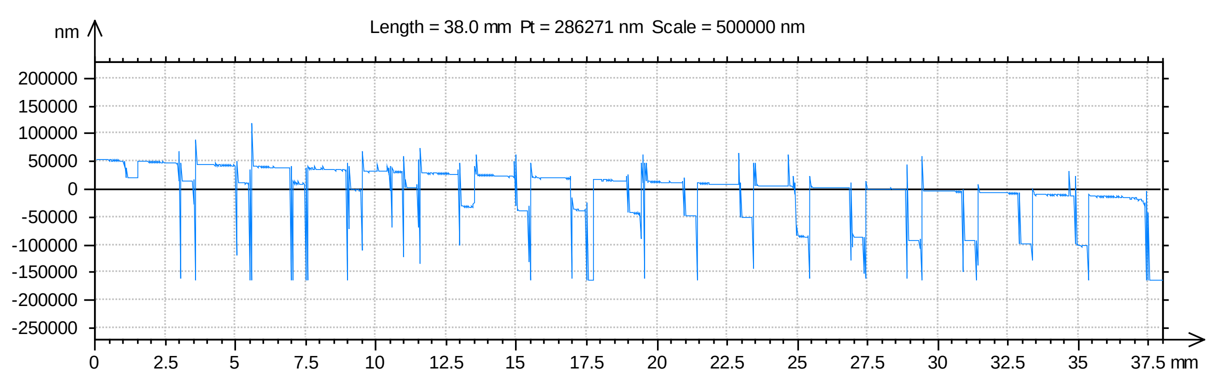
Surface roughness of all the slots were measured using optical profilometer as it is of great importance in micro milling operation. Surface roughness of the slots were measured during the starting of machined slots so there will be no effect of tool wear. Surface roughness values were measured in nanometers. The standard used to calculate surface roughness was ISO 4287. The specification of optical profilometer used is given in table 10.

Optical Profilometer Specifications	
Company	Nanovea
Model	PS 50
Test Facility	Thickness and topography of thin films
X-Y Axis Travel	50 mm
X-Y Axis Resolution	0.1 µm
Vertical Resolution	12 nm

Table 10: Optical profilometer specifications

All of the samples are analyzed to find the effect of machining parameters on surface roughness. Taguchi method is used to find the effect of parameter on surface roughness and finding the best parameter for surface roughness. AOVA is used to find the percentage effect of machining parameters on surface roughness.

All the four specimen have 18 slots each. Every specimen's slots were scanned and then every slots was analyzed separately by using software of profilometer.



4.2.1 Set 1 (Below cutting edge radius with Lower RPM)

Sr.No	Feed	Vc	DOC	Tool Coating	Trail 1	Trail 2	Avg. (nm)	Deviation
T-1	0.2	6	30	Un coated	321	249	285	51
T-2	0.2	8	60	TiAlSiN	328	271	299	41
T-3	0.2	10	90	DLC	268	262	265	4
T-4	0.3	6	60	DLC	284	294	289	7
T-5	0.3	8	90	Un coated	293	286	289	5
T-6	0.3	10	30	TiAlSiN	334	296	315	27
T-7	0.4	6	90	TiAlSiN	319	297	308	15
T-8	0.4	8	30	DLC	535	589	562	38
T-9	0.4	10	60	Un coated	298	322	310	17

Analysis of Variance

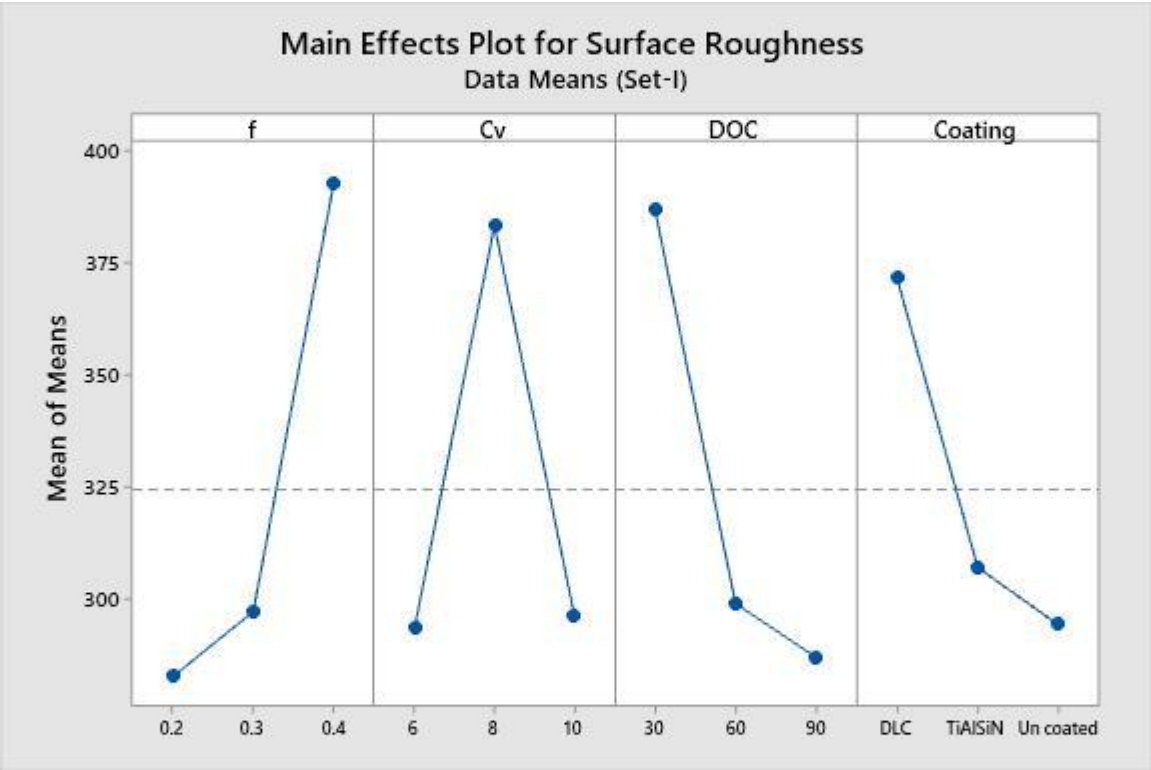
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
f	2	21554	32.98%	21554	10777	*	*
Cv	2	15647	23.94%	15647	7824	*	*
DOC	2	17857	27.32%	17857	8928	*	*
Coating	2	10305	15.77%	10305	5153	*	*
Error	0	*	*	*	*		
Total	8	65363	100.00%				

Response Table for Signal to Noise Ratios (Smaller is better)

Level	f	Cv	DOC	Coating
1	-49.02	-49.35	-51.35	-50.88
2	-49.46	-51.24	-49.51	-49.75
3	-51.53	-49.41	-49.15	-49.37
Delta	2.51	1.89	2.2	1.51
Rank	1	3	2	4

Regression Equation

Surface Roughness = 324.5 - 41.64 f_0.2 - 27.06 f_0.3 + 68.69 f_0.4 - 30.89 Cv_6 + 58.94 Cv_8- 28.06 Cv_10 + 62.61 DOC_30 - 25.31 DOC_60 - 37.31 DOC_90+ 47.28 Coating_DLC - 17.22 Coating_TiAlSiN - 30.06 Coating_Un coated



First table is showing surface roughness results gotten from both trials and their average value. Second table is showing ANOVA results for set-I while third table is showing response table for signal to noise Ratios (Smaller is better) followed by regression equation. In last effects plot is drawn to check individual effect of each input parameter.

In this set feed per tooth is most influencing input parameter followed by depth of cut and cutting velocity while tool coating have relatively less influence as compared to other parameters. Feed per tooth is directly proportional to roughness value, lower the feed lower the roughness value while higher feed results in higher surface roughness. Depth of cut have inverse relation with roughness value as its value is higher on lower depth of cut whereas lower on higher depth of cut.

Cutting velocity have mixed up effect on roughness as its value is lower on both lower level and higher level whereas higher on medium level. Non-coated tools have lower roughness results followed by TiAlSiN coated tools while DLC coated tools have higher results.

4.2.2 Set 2 (Below cutting edge radius with higher RPM)

Sr.No	Feed	Vc	DOC	Tool Coating	Trail 1	Trail 2	Avg. (nm)	Deviation
T-10	0.2	19	30	Un coated	294.5	298.5	296.5	2.8
T-11	0.2	21	60	TiAlSiN	239.5	332.5	286.0	65.8
T-12	0.2	23	90	DLC	292.5	245	268.8	33.6
T-13	0.3	19	60	DLC	366	313.5	339.8	37.1
T-14	0.3	21	90	Un coated	274	272	273.0	1.4
T-15	0.3	23	30	TiAlSiN	342.5	323.5	333.0	13.4
T-16	0.4	19	90	TiAlSiN	351	379.5	365.3	20.2
T-17	0.4	21	30	DLC	229	267.5	248.3	27.2
T-18	0.4	23	60	Un coated	290	226	258.0	45.3

Analysis of Variance

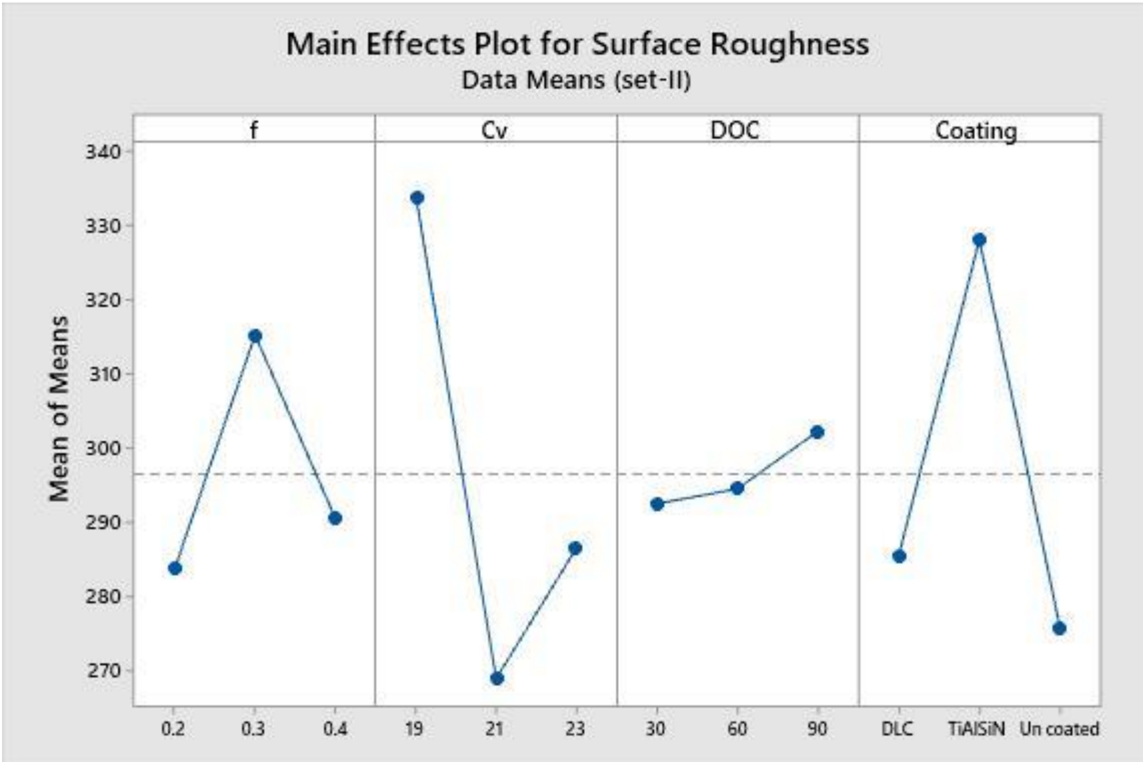
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
f	2	1650.4	12.53%	1650.4	825.19	*	*
Cv	2	6731.4	51.10%	6731.4	3365.69	*	*
DOC	2	159.1	1.21%	159.1	79.56	*	*
Coating	2	4631.4	35.16%	4631.4	2315.69	*	*
Error	0	*	*	*	*		
Total	8	13172.2	100.00%				

Response Table for Signal to Noise Ratios (Smaller is better)

Level	f	Cv	DOC	Coating
1	-49.05	-50.44	-49.26	-49.04
2	-49.93	-48.58	-49.33	-50.28
3	-49.13	-49.09	-49.52	-48.8
Delta	0.88	1.86	0.26	1.48
Rank	3	1	4	2

Regression Equation

Surface Roughness = 296.5 - 12.75 f_0.2 + 18.75 f_0.3 - 6.000 f_0.4 37.33 Cv_19- 27.42 Cv_21 - 9.917 Cv_23 - 3.917 DOC_30 - 1.917 DOC_60 + 5.833 DOC_90 - 10.92 Coating_DLC + 31.58 Coating_TiAlSiN - 20.67 Coating_Un coated



First table is showing surface roughness results for set-II gotten from both trials and their average value. Second table is showing ANOVA results while third table is showing response table for signal to noise Ratios (Smaller is better) followed by regression equation. In last effects plot is drawn to check individual effect of each input parameter.

In this set cutting velocity (51% CR) is most influencing input parameter followed by tool coating (35% CR) and feed (12.5%) while depth of cut has least influence.

Feed has mixed up response on roughness as its value is lowest on first level and highest on second level while depth of cut has direct relation with roughness. On-coated tools have again better roughness results.

4.2.3 Set 3 (Above cutting edge radius with lower RPM)

Sr.No	Feed	Vc	DOC	Tool Coating	Trail 1	Trail 2	Avg. (nm)	Deviation
T-19	3	6	30	Un coated	306.5	293	299.8	9.5
T-20	4	8	60	TiAlSiN	381.5	295	338.3	61.2
T-21	5	10	90	DLC	305.5	279.5	292.5	18.4
T-22	3	6	60	DLC	319	325.5	322.3	4.6
T-23	4	8	90	Un coated	331.5	289.5	310.5	29.7
T-24	5	10	30	TiAlSiN	378.5	333.5	356.0	31.8
T-25	3	6	90	TiAlSiN	477.5	368	422.8	77.4
T-26	4	8	30	DLC	331.5	317	324.3	10.3
T-27	5	10	60	Un coated	355	295.5	325.3	42.1

Analysis of Variance

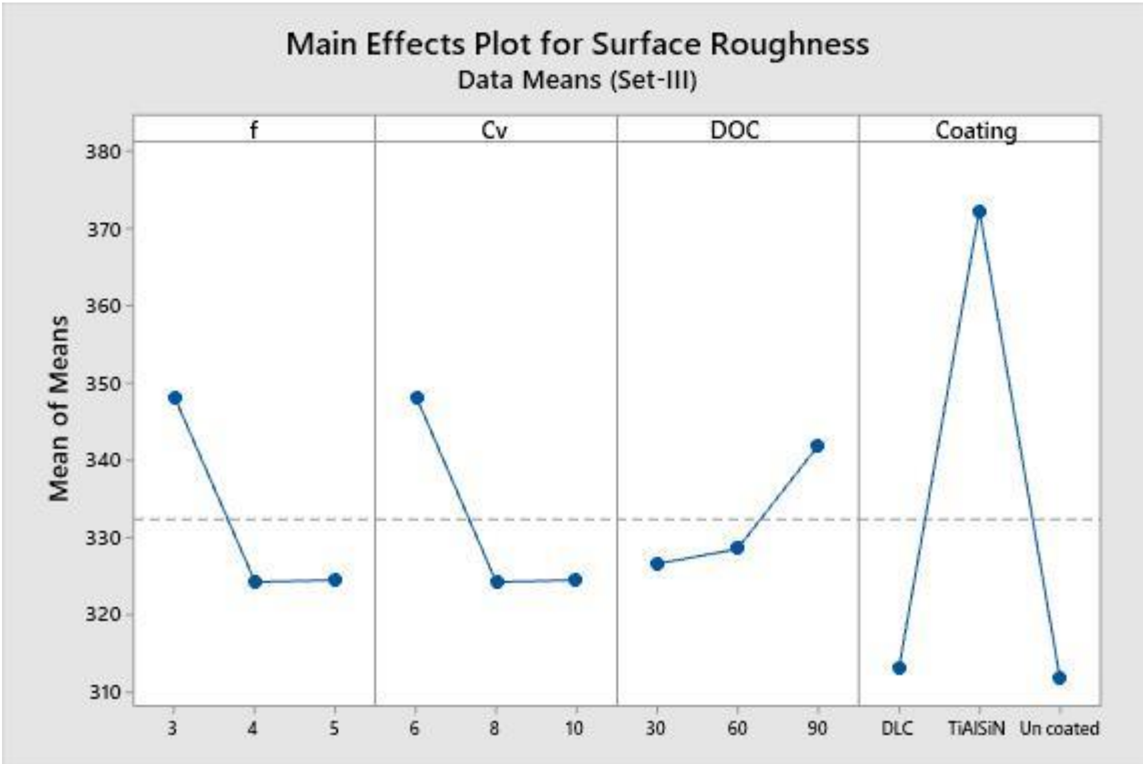
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
f	2	1132.2	9.35%	1132.2	566.1	0.33	0.749
DOC	2	414	3.42%	414	207	0.12	0.891
Coating	2	7182.1	59.29%	7182.1	3591	2.12	0.32
Error	2	3384.3	27.94%	3384.3	1692.1		
Total	8	12112.5	100.00%				

Response Table for Signal to Noise Ratios (Smaller is better)

Level	f	Cv	DOC	Coating
1	-50.74	-50.74	-50.26	-49.9
2	-50.21	-50.21	-50.33	-51.38
3	-50.2	-50.2	-50.56	-49.87
Delta	0.54	0.54	0.3	1.5
Rank	2.5	2.5	4	1

Regression Equation

Surface Roughness = 332.4 + 15.9 f_3 - 8.1 f_4 - 7.8 f_5 - 5.7 DOC_30 -3.8 DOC_60+ 9.5 DOC_90 - 19.4 Coating_DLC + 39.9 Coating_TiAlSiN - 20.6 Coating_Uncoated



First table is showing surface roughness results for set-III gotten from both trials and their average value. Second table is showing ANOVA results while third table is showing response table for signal to noise Ratios (Smaller is better) followed by regression equation. In last effects plot is drawn to check individual effect of each input parameter.

In this set tool coating (59% CR) is most influencing input parameter followed by feed and cutting velocity while depth of cut has least influence.

Depth of cut has direct relation with roughness value while roughness value is lower on higher feed and cutting velocity levels.

Non-coated tools have best response along closely followed by DLC coated tools while TiAlSIN coated tools have shown very high surface result.

4.2.4 Set 4 (Above cutting edge radius with higher RPM)

Sr.No	Feed	Vc	DOC	Tool Coating	Trail 1	Trail 2	Avg. (nm)	Deviation
T-28	3	19	30	Un coated	329.5	276	302.8	37.8
T-29	4	21	60	TiAlSiN	433.5	337.5	385.5	67.9
T-30	5	23	90	DLC	378	265	321.5	79.9
T-31	3	19	60	DLC	304.5	275.5	290.0	20.5
T-32	4	21	90	Un coated	291.5	346	318.8	38.5
T-33	5	23	30	TiAlSiN	393.5	371.5	382.5	15.6
T-34	3	19	90	TiAlSiN	460	468.5	464.3	6.0
T-35	4	21	30	DLC	323	311	317.0	8.5
T-36	5	23	60	Un coated	275.5	276.5	276.0	0.7

Analysis of Variance

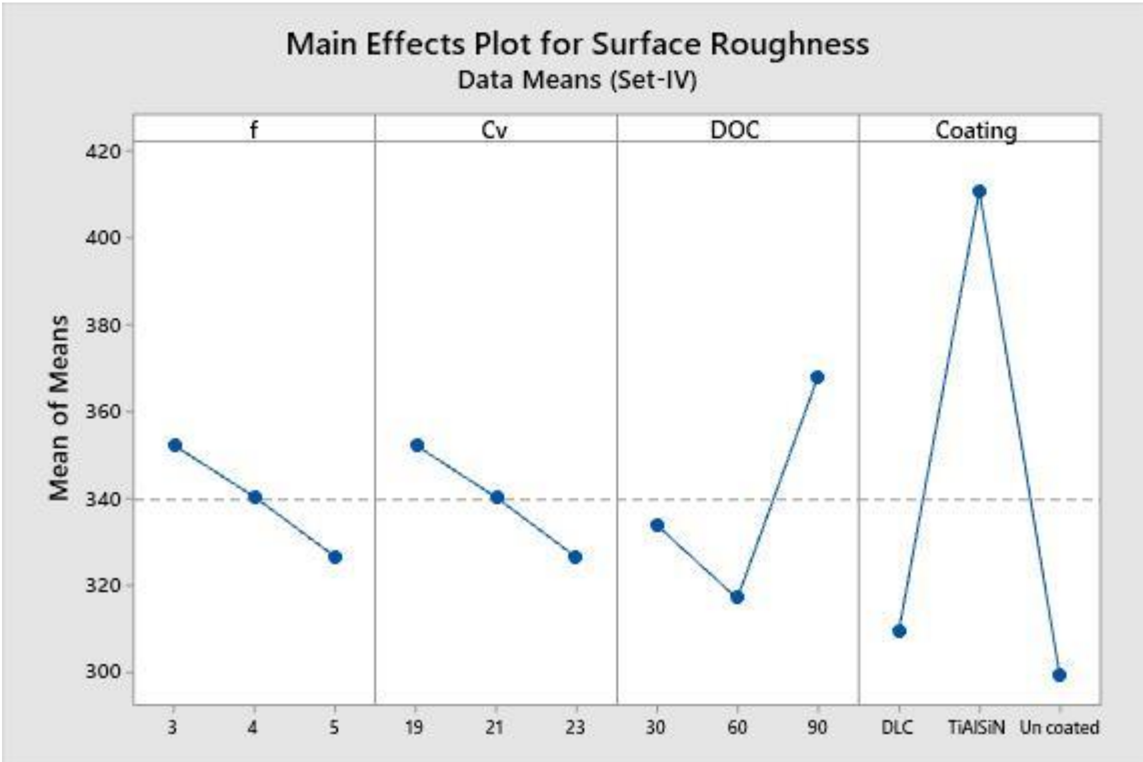
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
f	2	989.8	3.46%	989.8	494.9	1.28	0.438
DOC	2	4048.8	14.15%	4048.8	2024.4	5.24	0.16
Coating	2	22809.2	79.69%	22809.2	11404.6	29.52	0.033
Error	2	772.7	2.70%	772.7	386.4		
Total	8	28620.6	100.00%				

Response Table for Signal to Noise Ratios (Smaller is better)

Level	f	Cv	DOC	Coating
1	-50.73	-50.73	-50.43	-49.8
2	-50.6	-50.6	-49.93	-52.24
3	-50.2	-50.2	-51.18	-49.5
Delta	0.53	0.53	1.25	2.73
Rank	3.5	3.5	2	1

Regression Equation

Surface Roughness = 339.81 + 12.53 f_3 + 0.61 f_4 - 13.14 f_5 - 5.72 DOC_30 - 22.64 DOC_60+ 28.36 DOC_90 - 30.31 Coating_DLC + 70.94 Coating_TiAlSiN- 40.64 Coating_Un coated



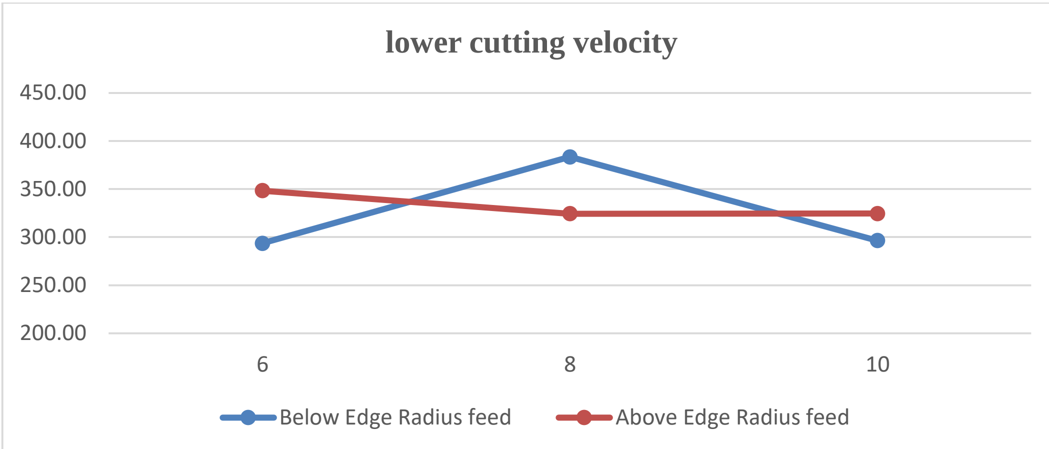
First table is showing surface roughness results for set-IV gotten from both trials and their average value. Second table is showing ANOVA results while third table is showing response table for signal to noise Ratios (Smaller is better) followed by regression equation. In last effects plot is drawn to check individual effect of each input parameter.

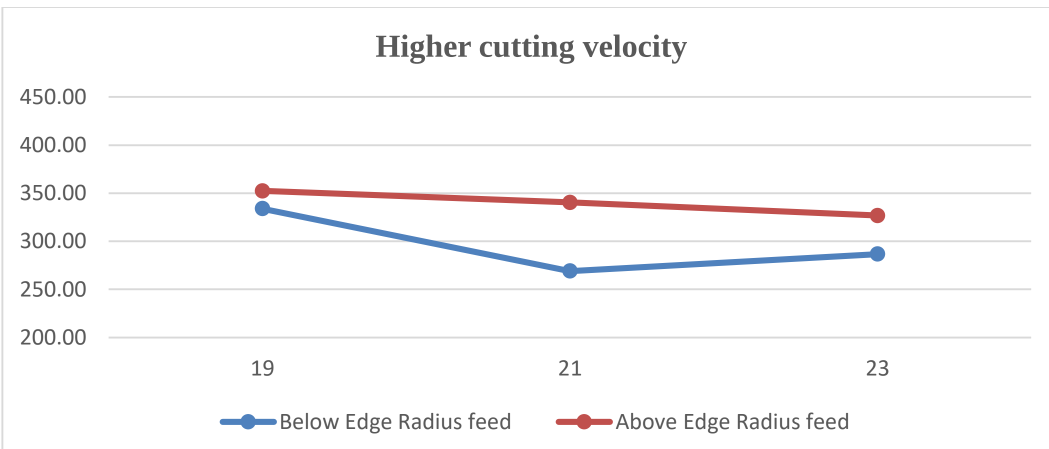
For this set feed and cutting velocity have inverse relation with surface roughness. Lower level values lead to higher roughness while higher level values result in lower roughness value.

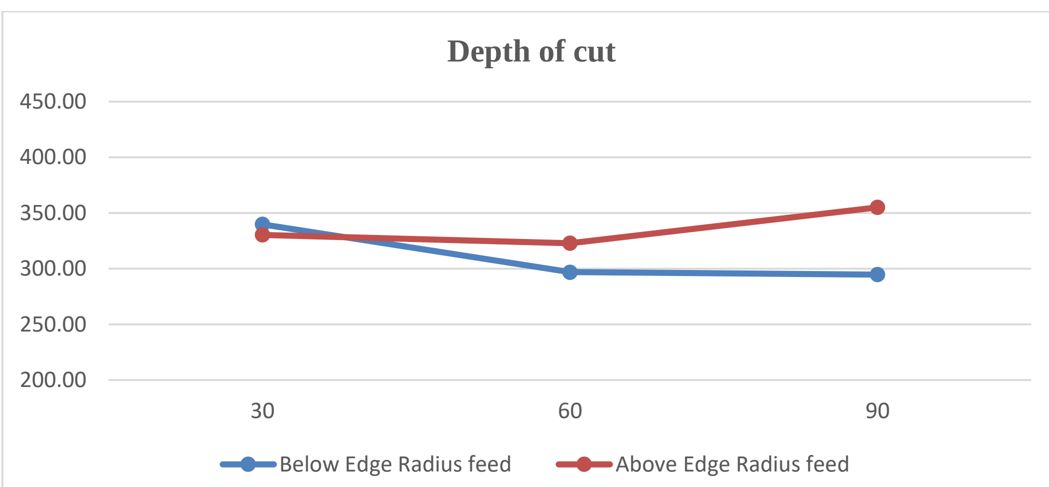
Non-coated tools have best response along closely followed by DLC coated tools while TiAlSIN coated tools have shown very high surface result.

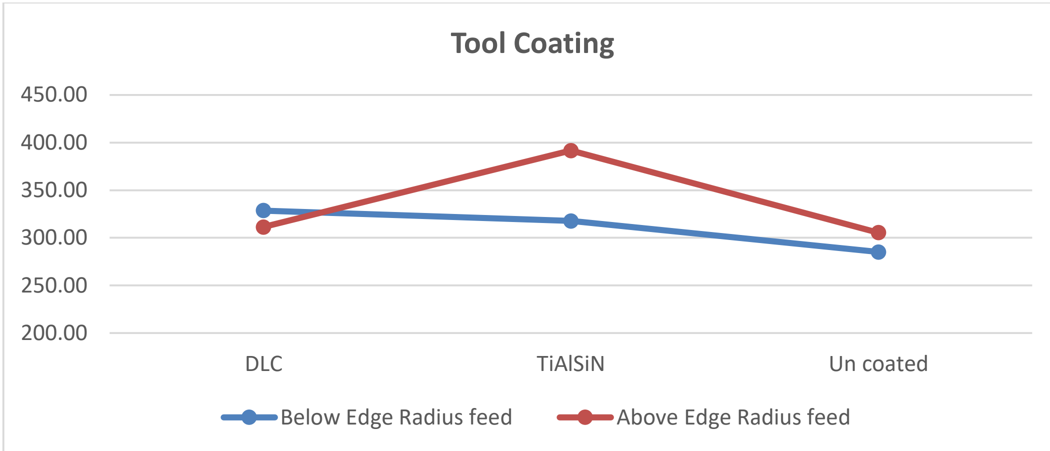
Depth of cut level 60 have lower roughness result as compared to other two levels.

4.2.6. Effect of Below vs. Above Edge Radius on Surface Roughness:







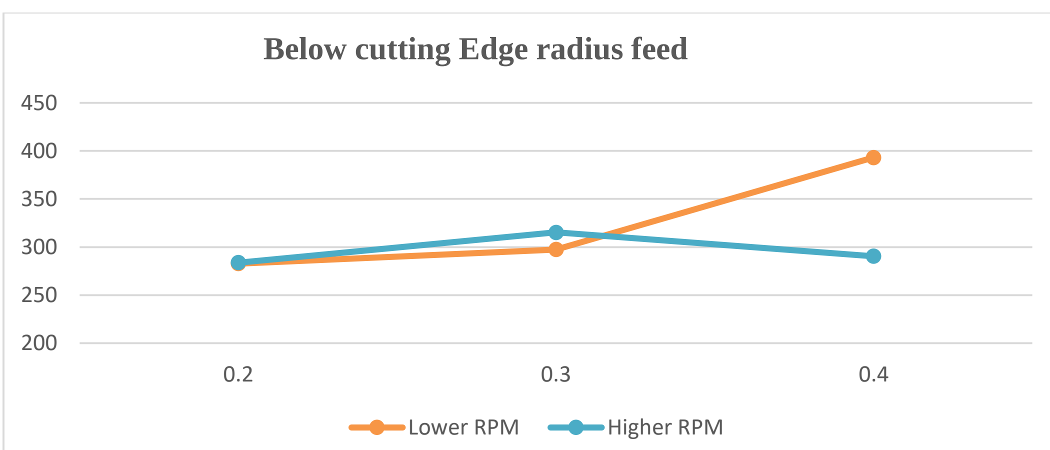


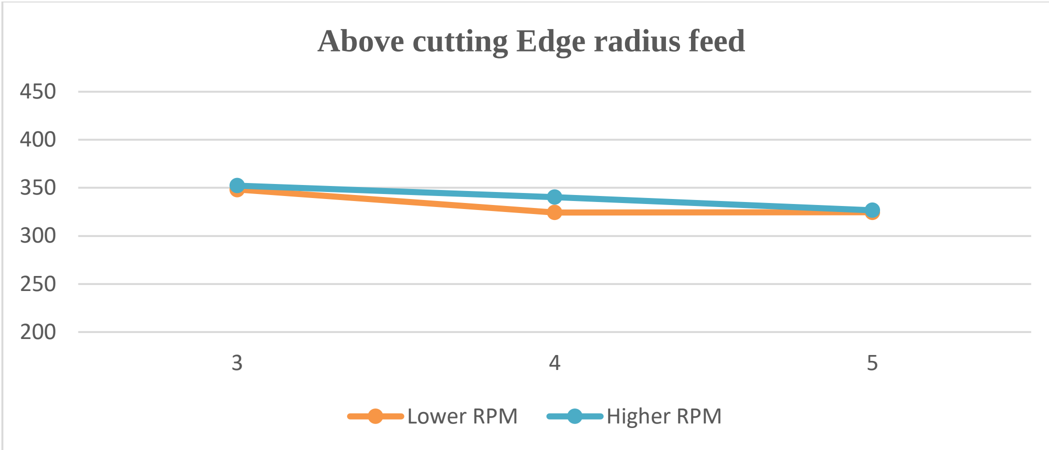
In these graphs blue lines are showing below edge radius feed while red lines are showing above edge radius feed. It shows us effect of feed on other input parameters in reference to surface roughness response.

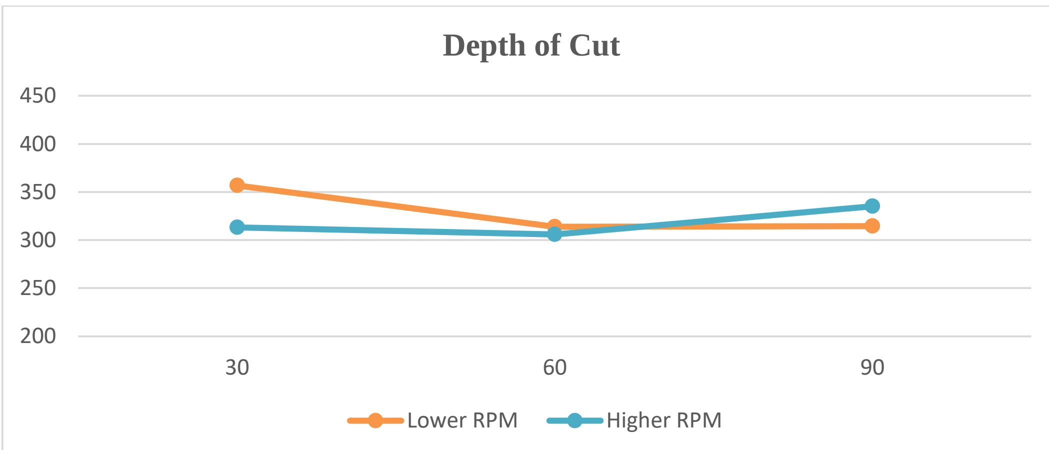
In these graphs below edge radius feed have comparatively lower (average of 310) as compared to above edge radius feed (average of 336). Lower feed in combination with higher cutting velocity is showing lesser surface roughness as compared to other combinations.

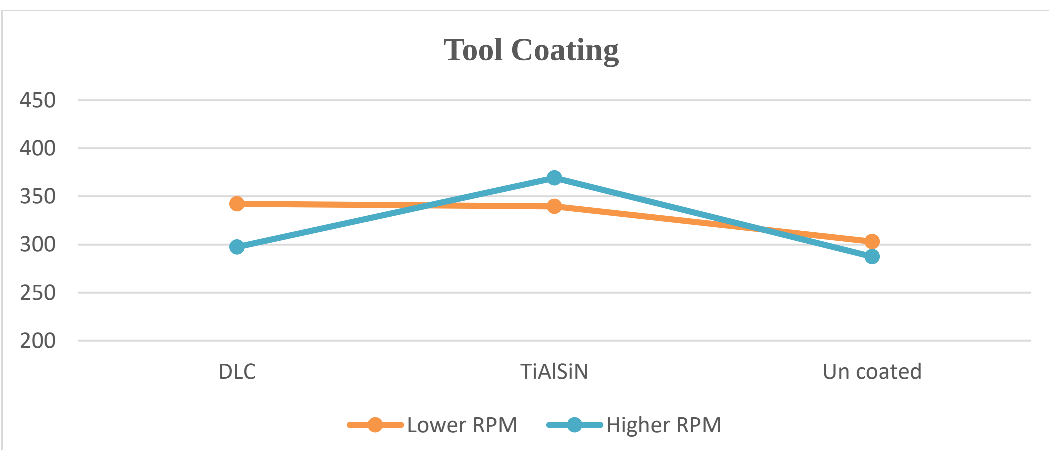
4.2.5 Effect of Higher vs. lower RPM on Surface Roughness:

In these graphs orange lines are showing lower cutting velocity (RPM) while Turquoise lines are showing higher cutting velocity (RPM). It shows effect of cutting velocity on other input parameters in reference to surface roughness response.









From these graphs it can be concluded that higher cutting velocity have better results on lower depth of cut while lower cutting velocity have better on higher depth of cut. Higher cutting velocity in combination with lower feed have less roughness response as compared to other combinations.

4.3 Surface Roughness Summary:

4.3.1 Percentage contribution in Surface Roughness

set	Feed	Cutting Velocity	Depth of cut	Coating
Set 1	33	24	27.3	15.8
Set 2	12.5	51	1.2	35.2
Set 3	9.35	9.4	3.42	59.3
Set 4	3.4	3.5	14.1	79

4.3.2 Optimistic Parameters for Surface Roughness

set	Feed	Cutting Velocity	Depth of cut	Coating
Set 1	0.2	6	90	Un coated
Set 2	0.2	21	30	Un coated
Set 3	4	10	30	Un coated
Set 4	5	23	60	Un coated
overall				Un coated

4.3.3 Surface Roughness result comparison:

Set	Description	Minimum Roughness	Average Roughness
1	Below cutting edge radius with lower RPM	264.8	324.5
2	Below cutting edge radius with higher RPM	248.3	296.5
3	Above cutting edge radius with lower RPM	292.5	332.4
4	Above cutting edge radius with higher RPM	276	339.8
1 & 2	Below cutting edge radius	248.3	310.5
3 & 4	Above cutting edge	276	336.1
1 & 3	Lower RPM	264.8	328.5
2 & 4	Higher RPM	248.3	318.2
1 - 4	overall	248.3	323.3

4.4 Burr Width Summary:

4.4.1 Percentage contribution in burr width:

Set	Feed	Cutting Velocity	Depth of cut	Coating
Set 1	1.41	7.92	50.26	40.41
Set 2	12.46	43.07	41.01	3.45
Set 3	8.67	8.67	27	6.14
Set 4	6.02	6.02	63.88	3.42

4.4.2 Optimistic Parameters for burr width:

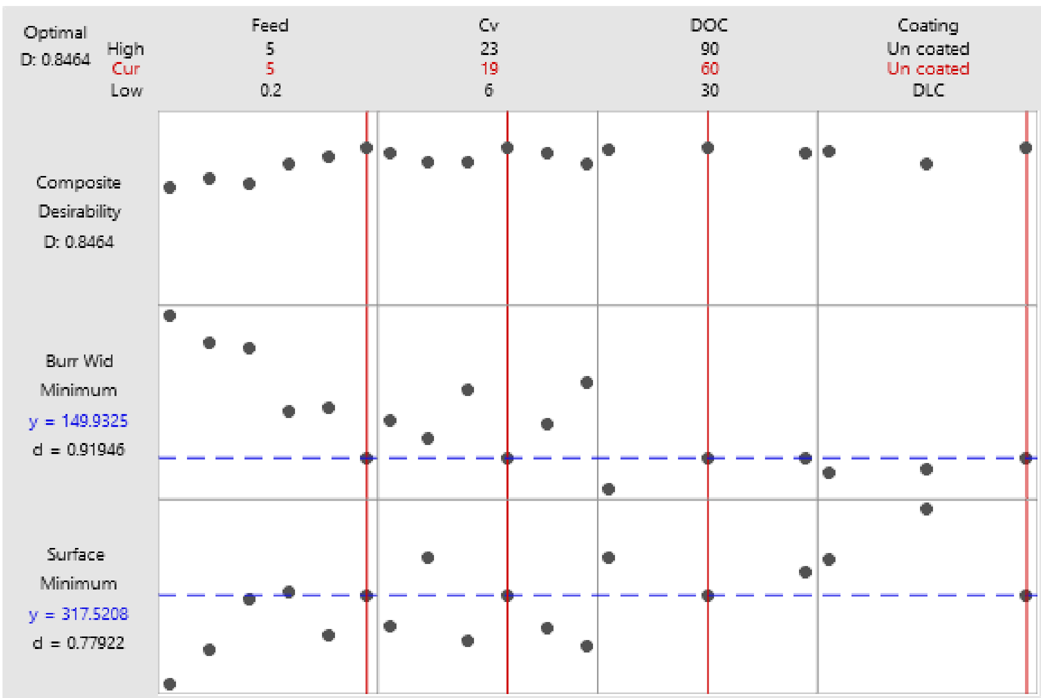
Set	Feed	Cutting Velocity	Depth of cut	Coating
Set 1	0.3	8	90	TiAlSiN
Set 2	0.4	19	30	Un coated
Set 3	4	8	60	DLC
Set 4	5	23	30	DLC

4.4.3 Burr width result comparison:

Set	Description	Min Burr Width (µm)	Avg. Burr Width (µm)
1	Below cutting edge radius with Lower RPM	217	267
2	Below cutting edge radius with higher RPM	164	234
3	Above cutting edge radius with lower RPM	140	173
4	Above cutting edge radius with higher RPM	134	211
1 & 2	Below cutting edge radius	164	250.5
3 & 4	Above cutting edge	134	192
1 & 3	Lower RPM	140	220
2 & 4	Higher RPM	134	222.5
1 - 4	overall	134	218.5

4.5 Reponses Optimization:

Both surface roughness and burr formation are critical and minimizing both is main aim during machining process but both these responses are effected by same input parameters. So minimizing surface roughness may lead to increase in burr formation and vice versa. Optimization of both responses is solution in order to get both results in optimistic range. Minitab response optimizer is used to get optimistic levels of input parameters by giving equal weightage to both responses.



These solutions were obtained from response optimizer. Each solution has optimized value of surface roughness and burr width against levels of input parameters.

Solution	Feed	Cv	DOC	Coating	Burr Width	Surface Roughness	Composite Desirability
1	5	19	60	Un coated	149.932	317.521	0.846437
2	5	21	30	Un coated	151.603	319.646	0.838789
3	5	19	30	Un coated	127.173	342.75	0.835945
4	5	6	30	Un coated	153.66	320.583	0.832269
5	5	19	60	DLC	139.619	342.167	0.825555

CHAPTER 5: CONCLUSION

Burr width was majorly affected by feed per tooth. Depth of cut and cutting velocity also have significant influence while tool coating is least significant.

Above cutting edge radius feed has shown 30% lesser size of burr width as compared to below edge radius feed while lower cutting velocity have shown slightly (1%) lesser size of burr width as compared to higher cutting velocity. So higher feed in combination with lower cutting velocity (Set-I) have 35% lesser burr width size as compared to below edge radius feed in combination with higher feed (set-II). Higher feed rises cutting forces hence tool vibration are increased which leads to higher cutting temperature of material being removed. During machining of ductile materials a transition from ductile to brittle behavior occur when machined surface is hardened. This thing results in reduced burr size as observed by Rangarajan [27]

Depth of cut level 30 (µm) have shown 11.2% & 10.6% better results than level 60 and 90 while diamond like coating results are 1% better than TiAlSiN coated tools and 5% better than non-coated tools.

Tool coating is most influencing input parameter for surface roughness while cutting velocity, feed per tooth have significant influence whereas depth of cut have least influence over surface roughness. Non-coated tools have shown 8.3% & 20% better surface roughness results than diamond like coated TiAlSiN coated tools while depth of cut level 60 have shown 5%& 8% better results than depth of cut level 90 and 60 orderly.

Below cutting edge radius feed has shown 8.2% lesser surface roughness value as compared to above edge radius feed while higher cutting velocity have shown 3.2% lesser surface roughness value as compared to higher cutting velocity. Below cutting edge radius in combination with higher RPM (set-II) has 12% lesser value of surface roughness as compared to above cutting edge radius with lower RPM (set-III). As discussed above higher feed rate and lower cutting velocity leads to higher cutting load in machining process because cross sectional area of chip is also enlarged. These higher cutting load/forces have bad impact on suracse roughness as observed by Gandjar Kiswanto during low speed micro milling of Inconel-718 [28].

Future Work Recommendation:

There are a lot of research opportunities after this research, some of which are given below

- Effect of tools coating and process parameters on tool wear
- Comparison of micro vs. Macro milling
- Effect of grain size of work piece on surface roughness, burr formation and buildup edges

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