Statistical Analysis of Burr Formation in Low-Speed Micro-Milling of Monel-400 (Nickel-Based Alloy)

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ISLAMABAD
AUGUST, 2021

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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

Monel-400 is nickel-based alloy, which due to its high resistance to corrosion, hardness, and its ability to withstand high temperatures etc. through rapid tool wear, which leads to poor surface quality and burr formation. That being said, the demand for micro components in the electronics, aerospace, biomedical, and automotive industries has increased, which has opened a door where there is strong research potential in micromachining.

In this research, an experimental investigation has been carried out to examine the effect of different process variables such as feed/tooth (fz), cutting speed (Vc), depth of cut (DOC) and cutting conditions during micro-milling of Monel-400 in order to obtain minimum burr width. Effects of all these process variables on formation of burrs are analyzed using statistical technique of analysis of variance to find key process variables (KPV). Results revealed that feed is the most significant parameter causing burr formation (81.7% contribution ratio), DOC is second significant factor (9.67% contribution ratio) while cutting speed (3.88% contribution ratio) and cutting condition (3.78% contribution ratio) are third and fourth significant parameter respectively. Machining at optimum process variables resulted in minimum burr width. It is evident that in order to reduce burr formation in micro-milling of Monel-400, better results can be attained by low speed machining setup with variation in feed per tooth instead of using high speed machining setup.

Key Words: Monel-400, Micro-Machining, statistical analysis, feed per tooth, cutting speed, depth of cut, key process variables, contribution ratio

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CHAPTER 1: INTRODUCTION

The formation of burrs is a similar phenomenon to chip formation. Burrs are undesirable because they represent a hazard when handling machine parts and can interfere with subsequent assembly processes. Therefore, they have to be eliminated in subsequent de-burring processes so that the part can meet the specific tolerances. As modern technology advances and tries to reduce the size of components as much as possible, manufacturing operations and techniques are shifting their focus to small-scale components. With the increasing demand for small-scale components, research must be carried out on a micro and nano scale. Micromachining, which includes milling, turning and drilling on a micro scale, are processes that remove material in the form of chips and in dimensions from 0.1 µm to 100 µm. High-precision instruments and equipment are required to maintain the increased accuracy of small parts. Much research has been done on macro-machining tools, processes, techniques, and materials in the past few decades, and moving to the micro-domain is not as straightforward as scaling down the properties of the macro-domain. Therefore, further research should be conducted to understand the micromachining techniques.

Nickel-based alloys are now widely used in nuclear, aerospace, marine and automotive industry because of higher resistance to corrosion and high temperature resistance, etc. [1] Nickel-based alloys are considered difficult to machine material due to low thermal conductivity, chemical reactivity with tool material (at high temperature), hardness and low elastic modulus, etc. Generally, the formation of second phase particles in nickel-based alloys makes the alloys stronger, abrasive and difficult to machine. [2] Nickel-based alloys are broadly categorized in Figure 1.

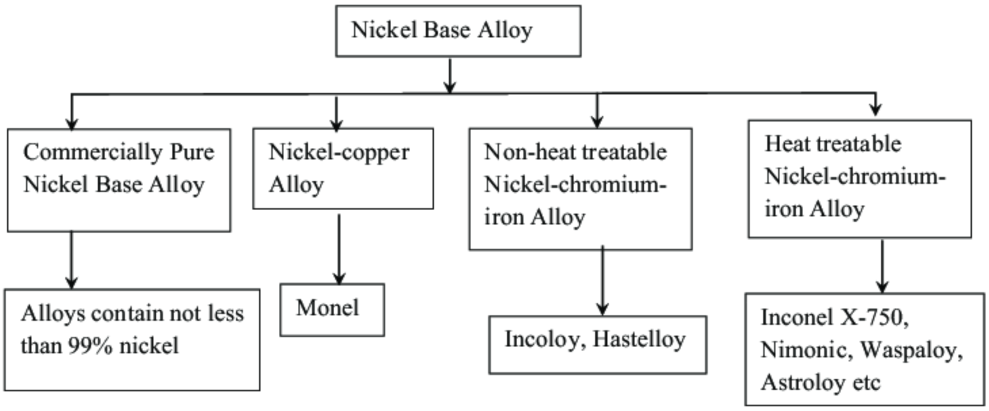


Figure 1: Classification of Nickel Based Alloy

Monel-400 is a mixed crystal solution of nickel and copper with high strength and toughness over a temperature range. Due to its high resistance to corrosive and acidic environments, Monel has vital role in chemical industry, food industry, in heat exchanger tubes, crude oil stills and distillation towers, submarine and ship propellers, etc. [3]

Its strength and resistance to corrosion make it worthy for use in aerospace industry. Monel-400 is able to retain its shape and strength up to 1300˚C which make it suitable for aerospace industry. After cold working, Monel-400's tensile strength increases to 125,000 psi, while its corrosion resistance makes it ideal for exhaust manifold and carburetor applications. Monel can also withstand intense heat and pressure in combustion chambers. Monel-400 is a standard material for manufacturing of nuclear reactors. [4] The chemical composition of Monel-400 (UNS N04400) is shown in Table 1.

Nickel (Ni)	63.0 %
Copper (Cu)	28.0-34.0%
Carbon (C)	3.00 %
Manganese (Mn)	2.00 %
Sulfur (S)	0.024 %
Silicon (Si)	0.50 %
Iron (Fe)	2.50 %

Table 1: The composition of Monel-400

As far as mechanical properties of Monel-400 are concerned a broad range of strength and hardness is obtained depending on form and condition. Some mechanical properties are given in Table 2.

Density:	8.8 (g/cm^3)
Tensile Strength	512-620 (MPa)
Elastic Modulus	179 (GPa)
Hardness	110-150 (HB)
Thermal Conductivity	21.8 (Wm^{-1}K^{-1})
Specific Heat	427 (J Kg^{-1} K^{-1})
Elongation to break	48 (%)

Table 2: Mechanical Properties of Monel-400

1.1. Research Motivation

In mechanical machining (macro-machining or micro-machining) burr formation always occurs. De-burring (removal of burrs) is much difficult in micro-machining as compared to macro-machining due to smaller size of burrs; machined component may be damaged during de-burring process. Furthermore, cost of de-burring in micro-machining is much higher due to the requirement of complex assembly operations [5-6]. Extra measures are adopted for minimum burr formation during micro-machining process.

AJ Mian studied the formation of burr in micro machining of Nickel based alloys, the optimum parameter was at minimum chip thickness and transition cutting speed for AlTiN coated tool of 0.5mm diameter. From the literature research it was confirmed that higher cutting speeds are more successful during micro machining, a lot of work has been done at high speed and less literature is available on low cutting speed. [7]

Plenty of work has been done on burr formation of different super alloys but there is no literature found on formation of burr in micro-milling of Monel-400. As low speed setup is easily available and economical than high speed machining setup. So, we are going to work on lower cutting speeds (range of conventional machining) and will see the impact of input parameters on burr formation at low cutting speeds in different cutting conditions.

1.2. Research Objectives

i. Examine the impacts of machining parameters on burr formation
ii. To analyze the effect of each cutting parameter using ANOVA
iii. Finding the optimum process parameters for minimum burr formation

1.3. Research Scope

This research is limited to micro end-milling of Monel-400 using carbide end mill tools of 0.5 mm diameter with AlTiN coating on them and cutting speed in range of 12m/min to 18 m/min below 12000 rpm. Cutting conditions are selected as dry, flooded and mist machining. As lower speed machining setup is easily available and economical as compared to high speed machining setup. So, we are going to work on low cutting speed and will see the effect of feed, cutting speed, DOC and cutting condition on burr formation.

1.4. Why Research on Burr Formation

Tool life is increased if burr formation is minimized in milling and drilling processes. Burr formation is an important problem in micro-machining as compared to macro-machining because unlike macro-machining de-burring is very much difficult task due to accuracy requirement in micro components. Moreover, restrictions in part geometry and material characteristics de-burring techniques cannot be applied in micro-machining.

CHAPTER 2: LITERATURE REVIEW

Micro-machining process is used to manufacture small mechanical components. There is an increased demand for accurate and precise micro components in industries. Micro-machining process produces small parts and components in mass production. In recent days demand of micro components has been increased in many sectors such as medical, aerospace, automobile, electronics etc. due to shift of technology.

The manufacture of micro components requires reliable, precise and more repeatable processes with a precise tool system. Semiconductor processing techniques are commonly used to manufacture these micro components, such as laser fabrication, photolithography, ultrasound, and ion beam. Micro-milling is an unconventional machining method that is capable of producing three-dimensional and complex micro-components. Although micro-milling is better than other unconventional machining techniques in terms of high removal rate, process flexibility, low set-up costs and the production of complicated shapes, it is associated with some problems such as burr formation, poor surface quality, breakage of tool and rapid tool wear. As a result, it is difficult to achieve the required results with micro-milling.

2.1. Micro-Machining

Micro-machining can be divided into following different types.

i. Mechanical Micro-machining
ii. Laser Technology
iii. Micro-Ultrasonic Machining
iv. Micro-Electrochemical Machining

Out of all above, mechanical micro-machining is superior to other technologies as it is capable to manufacture parts of different sizes and shapes with a variety of material which is not possible by other stated technologies. Due to its high material removal rate, it is suitable for mass production.

Development in micro-machining processes over the years is shown in Figure 2. [8]

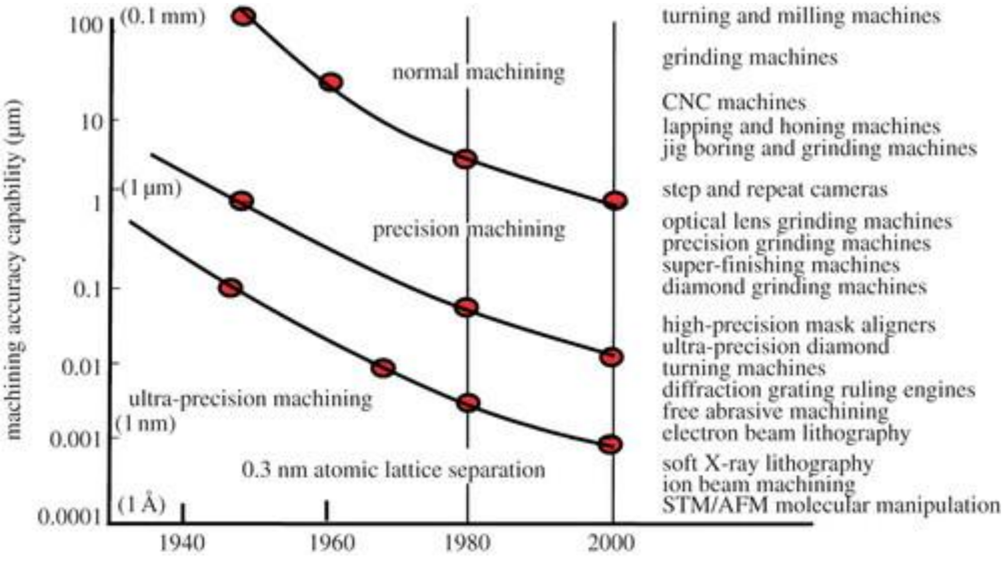


Figure 2: Development in Micro-Machining over the years

This figure shows that achievable machining accuracy is reaching the precision machining level for normal machining. With new research, better processes and techniques these curves would continue to move downwards.

2.2. Micro-Milling

Micro-milling is a process of manufacturing small components by removing material in chip form which ranges from tens of micron to few millimeters. Micro-milling can produce more accurate components in relatively less time. [9] This process can produce small components from variety of material i.e. composites, ceramics, polymer and metallic alloys.

Some problems are also associated from micro-milling because of small size of tools, parts and processes. Micro end mills are affected by minor vibrations and extreme forces which has adverse effect on tool life and tolerance of component being manufactured.

There are some factors related to the workpiece, tooling and machine tool which affect the quality of components in micro-milling. These input variables are identified in Figure 3.

Part testing, handling and assembly are difficult tasks to do in micro-machined components as compared to macro-machined components. Micro-milling mostly depends on feed, depth of cut, cutting speed, tool material, tool coating and cutting conditions.

Work Material

- Grain Size
- Hardness
- Homogeneity
- Defects
- Impurities
- Built-up-edges
- Elastic recovery

Tooling

- Material
- Sharpness
- Grain Size
- Coating
- Batch consistency

Machine Tool

- Spindle speed and run out
- Position accuracy
- Stiffness
- Damping
- Thermal stability
- Error compensation

Figure 3: Input Variables for Micro-Milling

2.3. Nickel-Based Alloys

Nickel-based alloys cover a broad spectrum of microstructure, chemical composition and mechanical properties. They have a higher corrosion resistance than stainless steels. Most Ni alloys are not heat treatable, but can be strengthened by cold working. Nickel alloys can contain non-metallic inclusions and numerous secondary phases. Nickel itself has moderate corrosion resistance, but its resistance increases with the inclusion of alloying elements such as copper, chromium, molybdenum, iron and tungsten.[10]

2.4. Cutting Tools

Parameters which influence the cutting tool’s performance during the machining of Monel-400 are as following.

i. Fracture Toughness

ii. Wear Resistance

iii. High Hardness

iv. Chemical Inertness

Ceramic tools are on top priority if we consider first three properties mentioned above. Carbide and high speed steel tools have higher fracture toughness than ceramic tools. If high feed rates are considered tungsten based carbide tools are preferred. Coated carbide tools are used for its strength and high wear resistance. [11]

2.5. Minimum Chip Thickness

Formation of chip is basically nonlinear in nature. Minimum chip thickness can be described as smallest chip thickness in un-deformed condition. In macro-milling depth of cut is greater than radius of cutting tool edge (re) while in micro-milling it is closer to edge radius of tool. [12] The value of minimum chip thickness usually lies in 5%-38 % of tool radius [13].

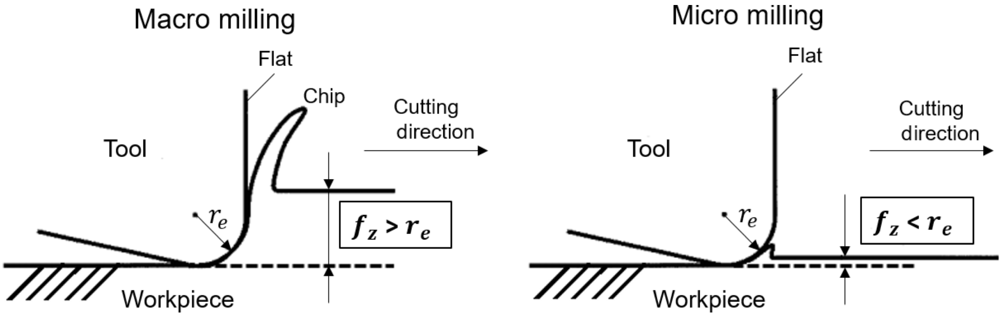


Figure 4: Macro and micro milling process

2.6. Burr Formation and its classification

Burr is the unwanted deformed material which remained on the surface or edge of machined part. It is formed in almost all machining processes. It appears in the form of sharp cutting strips at the edge of work piece after cutting process. Burr has to be removed from the machined part for proper functioning of that part.

Burr formation in micro-machining need to be minimized or removed because de-burring process for micro components is costly and difficult. Burr formation is also influenced by tool’s run out.

Lee and Dornfeld et al. made it clear that the entrance and exit burrs in micro-milling were larger compared to macro-milling, taking into account the ratio of burr size to chip. They also found that tool wear is related to burr height and burr height is proportional to feed. Increasing the r_e (edge radius) of the end mill creates enlarged burrs. [14]

Lekkala et al. analyzed the formation of burrs during micro-end milling of aluminum and steel and found during his investigations that the burr height increases with decreasing cutting tool diameter and the number of flutes. [15]

In their research, Fang and Liu identified cutting and other machining variables, tool sharpness and un-deformed thickness are important influencing factors in determining the height of burr. [16]

Kiswanto et al. in his research described the types of burrs as under. [17]

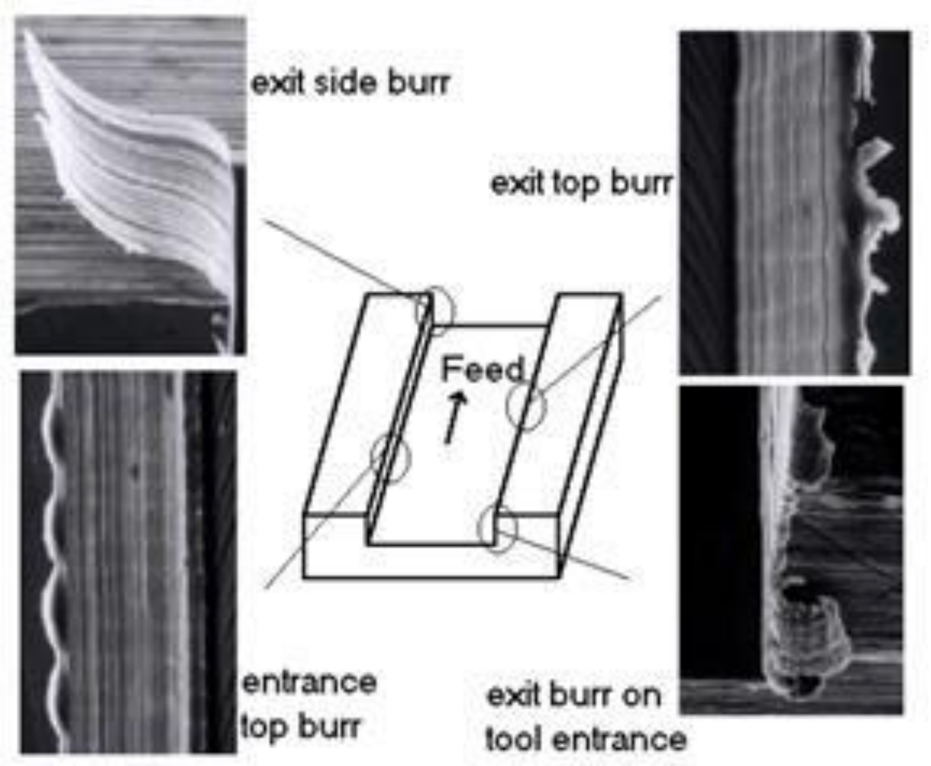


Figure 5: Different types of Burr Formation

2.7. Cutting Condition

Cooling lubricants are used because of their function in lubrication and cooling in metalworking. By using cooling lubricants, cutting forces can be lowered at lesser cutting speed and machining at comparatively higher cutting speed can be made possible.

Cutting fluids can be applied in following ways as shown below.

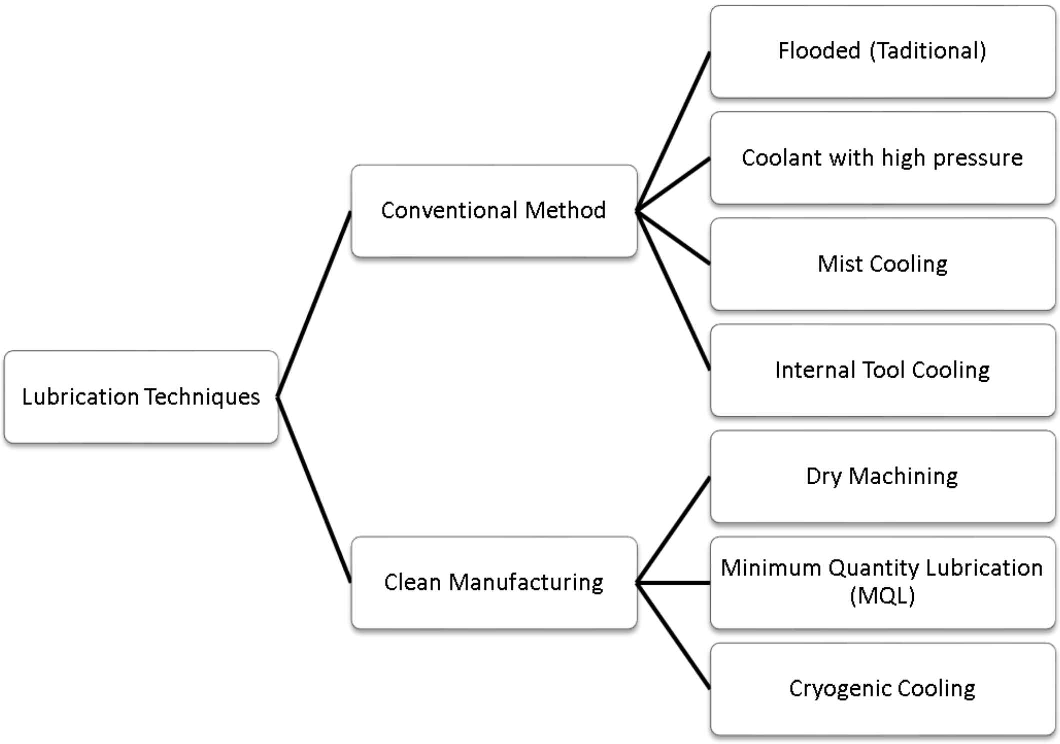


Figure 6: Lubrication Techniques

Dry machining promises a high level of sustainability, since machining can be carried out without the use of cooling lubricant. It is appropriate for some cutting materials such as carbide and ceramic tools due to their ability to sustain hardness at high cutting temperatures. The surface quality of the workpiece is better in a dry environment with carbide tools and higher cutting speeds compared to lower cutting speeds. [18]

The The most common is the flooded technique, in which a large volume of liquid is pumped to the interface for metal removal. The liquid is collected and then reused many times. In the flooded state, cutting fluid can never get into the warmest area at the end of the cutting tool, so a uniform temperature is not maintained on the cutting tool, which is the main limitation in this state.

Another method, micro-lubrication or mist, supplies the cut surface with liquid in the form of a mist, which provides the lubricating effect. Due to the small volume used, the liquid is not collected for reuse. The liquid is atomized, often with compressed air, and delivered to the cut surface through a series of nozzles. Because the fluid is being applied at such low rates, most or all of the fluid used will go with the part. [19]

CHAPTER 3: EXPERIMENTATION

3.1. List of Equipment

Different types of equipment's were used for the experimentation for different purposes as mentioned below;

i. Band Saw Machine (Behringer)
ii. Manual Lathe Machine (DMTG)
iii. Shaper Machine
iv. Milling Machine (Deckel FP-01)
v. Surface Grinding Machine (Jones & Shipman)
vi. CNC Vertical Machining Center Sky Master VL-1100
vii. Scanning Electron Microscope (JSM-5910 LV, JEOL)

Figure 7: Scanning Electron Microscope (JSM-5910LV)

3.2. Tool Specification

Ultrafine tungsten carbide with AlTiN coating flat end-mills (Manufactured by North Alloy Tools, China) of 500 µm diameter were used in the experiments. The average tool edge radii were measured 3.5 µm with standard deviation of 0.5 µm. Some specifications are mentioned below;

Brand Name: North Alloy Tools, China
Diameter: 500 µm
Shank Diameter: 4mm
Hardness: 60 HRC
Usage: High Speed Cutting

Material: Tungsten Carbide
Type: Square End-Mill
Flutes: Two
Cutting Length of Flute: 1mm
Helix Angle: 30°

Figure 8: Cutting Tools used in Experimentation

3.3. Workpiece Material

Nickel-Based Alloy Monel-400 (UNS N04400) is used in the experimentation as workpiece material during this research. Monel-400 was available in rod form which was cut using behringer machine. Lathe, shaper and milling machines were used to bring it into a rectangular workpiece and then surface grinding machine was used to attain the required parallelism and flatness of the workpiece. Final dimensions of the workpiece were 20 mm in length, 20 mm in width and 10 mm in thickness.

Element	**Minimum %age**	**Maximum %age**
Nickel	63	70
Copper	28	34
Manganese	2.0	2.0
Carbon	0.3	0.3
Iron	2.5	2.5
Sulfur	.024	.024
Silicon	0.5	0.5
Cobalt	1.0	1.0

Table 3: Composition of Monel-400

3.4. CNC Machining Center

CNC Machining Center is used to make slots by using different parameters for the experimentation. Specifications of CNC Machining Center are given below.

Company: SKY MASTER

Model: VL-1100

Control: FANUC 0i MD (Dos Based)

Spindle Speed: 12000 RPM

3.4.1. Technical Specifications

i. Rapid traverse x-axis: 30,000 mm/min
ii. Rapid traverse y-axis: 30,000 mm/min
iii. Rapid traverse z-axis: 24,000 mm/min

3.4.2. Working Area of Machine

i. Surface Area: 1250 x 600 mm^2
ii. Maximum Load: 1,000 Kg
iii. x-axis travel: 1100 mm
iv. y-axis travel: 630 mm
v. z-axis travel: 630 mm

3.4.3. Tool Specifications

i. Maximum Number of Tools: 24 Tools
ii. Maximum Weight for one Tool: 8 Kg
iii. Maximum Diameter of Tool: 66 mm

3.4.4. Machine Accuracy

i. Positioning: ± 0.005 mm
ii. Repeatability: ± 0.003 mm

3.5. Cutting Edge Radius

The cutting edge radius of selected tools was measured using Scanning Electron Microscope. It was required to set the depth of cut per tooth. An image of two tools was taken through microscope then this image was 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 radius. Cutting edge radius was found to be 3.5 µm.

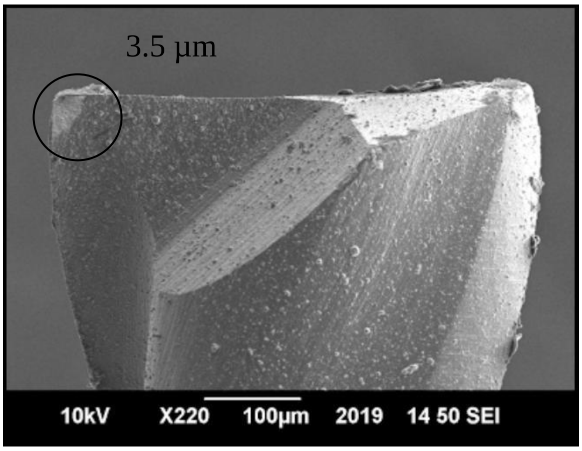


Figure 9: Cutting Edge Radius of End Mill

3.6. Cutting Parameters

Three different levels of parameters were used to find their effect on burr formation. Following criteria is used for selection of different levels of parameters.

3.6.1. Depth of Cut

Every tool as per its dimensions has its own recommendations for depth of cut. The depth of cut is set by using following procedure by Niagara cutters. [20]

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

$$\text{Depth of Cut (DOC)} = a_p = \text{Tool Diameter (D)} \times (0.05 \text{ to } 0.25)$$

$$\text{Min } a_p = 0.5 \times 0.05 = 0.025 \text{ mm} = 25 \text{ µm}$$

$$\text{Max } a_p = 0.5 \times 0.25 = 0.125 \text{ mm} = 125 \text{ µm}$$

Now, the range of depth of cut is 25 µm to 125 µm so we take the depth of cut to be 50 µm, 75 µm and 100 µm in this research.

3.6.2. Feed per tooth

Jaffery et al. found that the residual effect was more significant when the f_z was chosen below the edge radius. [21] Therefore, in this study, to minimize the effects of residual effects, the feed rate above the tool edge radius was selected between 8 µm / tooth and 12 µm / tooth.

3.6.3. Cutting Speed

At the micro level, the material properties become inhomogeneous, which leads to fluctuations in the micro hardness, which lead to vibrations in the tool. This is low at high cutting speeds and feed speeds. In micromachining, a high speed is mostly used to minimize burrs. Now high-speed machines are also presenting micromachining with new challenges. The dynamics of machine tools change at higher speeds, with an unbalanced spindle producing centrifugal and gyroscopic effects.

Tool run-out and imbalance are usually a minor problem in macro machining processes. However, the problem is seriously exacerbated when the diameter of the tool decreases and the spindle speed increases significantly. [22]

The maximum available RPM of the available machine is 12000. So, we selected three different levels of cutting speed as 12, 15 and 18 m/min to see its effect on burr formation. Formula used for converting cutting speed to revolution per minute is;

$$N=Vc/\pi D$$

3.6.4. Cutting Condition

Cooling lubricants are used because of their function in lubrication and cooling in metalworking. By using cooling lubricants, the cutting forces can be reduced at lower cutting speeds and machining at moderately higher cutting speeds can be made possible.

Out of many lubrication techniques as indicated in Figure 6 earlier, three are selected to be used in this research.

i. Dry
ii. Flooded
iii. Mist

3.7. Design of Experiment

Taguchi method for experimentation has become strong tool for robust design and improving productivity during research and development phase so that high quality of research can be done in short amount of time with minimal cost. It is useful to study complete parameter space with a limited number of experiments using orthogonal arrays.

In this research, experiments were designed based on Taguchi’s L9 orthogonal array with 4 (four) factors and 3 (three) levels. The parameters selected for the micro-milling of Monel-400 is given in the below Table 4.

Factors	**Level-I**	**Level-II**	**Level-III**
Feed/tooth (f_z), (µm / tooth)	8	10	12
Cutting Velocity (V_c), (m/min)	12	15	18
Depth of cut (a_p), (µm)	50	75	100
Cutting Condition	Dry	Flooded	Mist

Table 4: Cutting Parameters

Experimental Plan using an L9 orthogonal array is given below in Table 5.

Trial	**Feed per tooth** µm/tooth	**Cutting Velocity** m/min	**Depth of cut** µm	**Cutting Condition**	**N** RPM	**Feed** mm/min
Exp-1	8	12	50	Dry	7645	122.29
Exp-2	8	15	75	Flooded	9550	152.87
Exp-3	8	18	100	Mist	11465	183.44
Exp-4	10	12	75	Mist	7645	152.87
Exp-5	10	15	100	Dry	9550	191.08
Exp-6	10	18	50	Flooded	11465	229.3
Exp-7	12	12	100	Flooded	7645	183.44
Exp-8	12	15	50	Mist	9550	229.3
Exp-9	12	18	75	Dry	11465	275.16

Table 5: L9 Orthogonal Array

3.8. Methodology

A group of experiments of micro-milling were conducted on Nickel-Copper Alloy Monel-400 (UNS N04400). All these experiments were conducted using a vertical machining center Sky Master VL-1100. This machine was equipped with a FANUC 0i MD controller to control relative motion between end mill tool and workpiece.

Ultrafine tungsten carbide with AlTiN coating flat end-mills (Manufactured by North Alloy Tools, China) of 500 µm diameter, having two flutes and a helix angle of 30˚ were used in the experiments. The average tool edge radii were measured as 3.5 µm.

Workpiece dimensions were 20 x 20 x 10 mm. The length of the slot is selected as 10 mm but in some trials it is exceeded to see its behavior on the burr formation. Experimental state for these tests is given in Table 6.

Workpiece Material	Monel-400
Tool Diameter	0.5mm
No. of Flutes	2
Tool overall length	50mm
Cutting Conditions	Flooded, Dry and Mist
Milling Type	Full Immersion

Table 6: Experimental Conditions

3.9. Experiments

i. Workpiece was clamped on machine vise and flattened by using dial indicator of 1µm least count.
ii. Tool pre-setter is used for the accurate depth of cut.
iii. Each slot is 1.5 mm apart from each other.
iv. All nine experiments of first trail were done on workpiece 1 and then repeated on the workpiece 2 to minimize error.

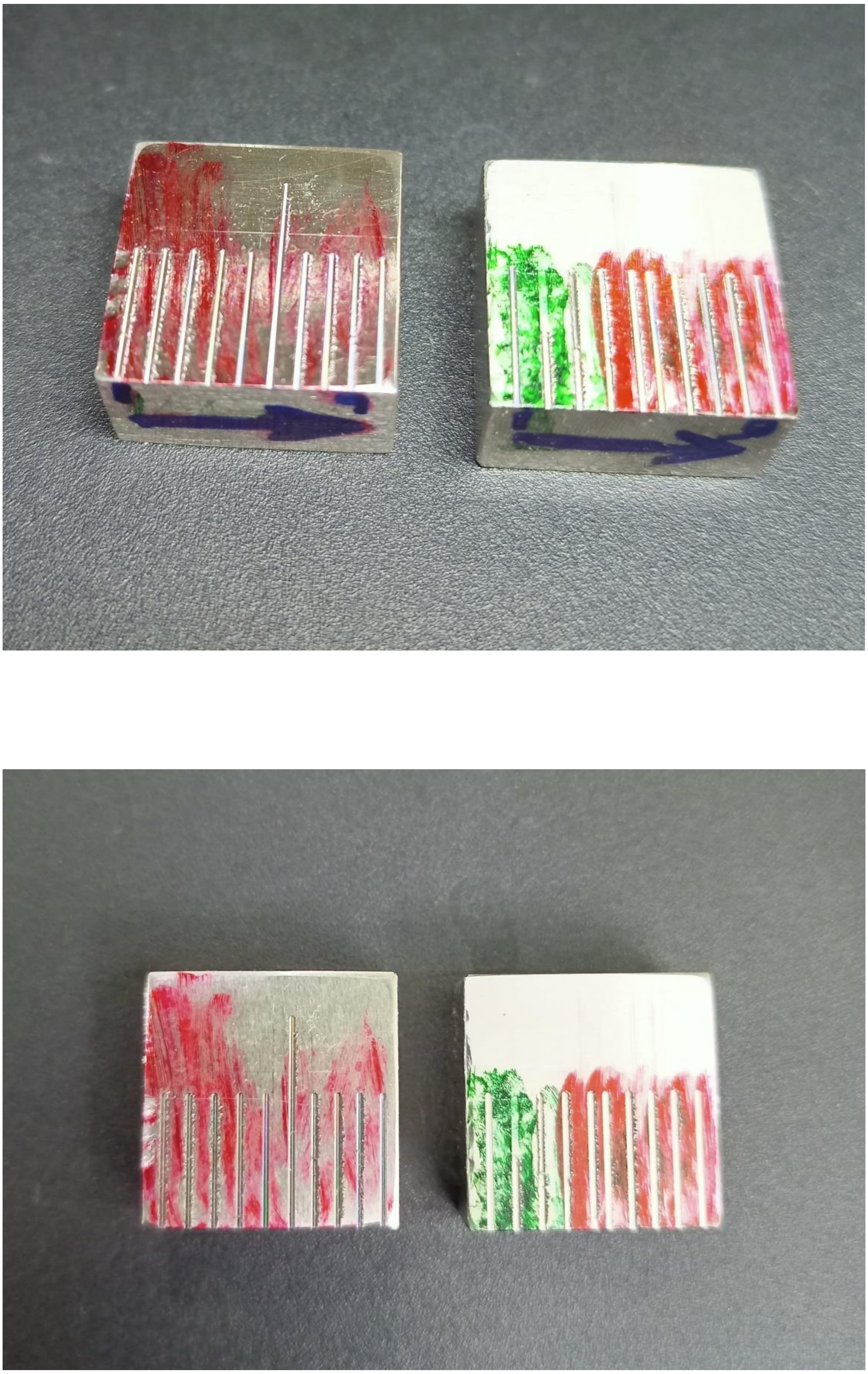


Figure 10: Micro-Machined Workpieces

CHAPTER 4: RESULTS AND DISCUSSION

With micro-milling, different types of burrs upper burr, exit burr, entry burr and lower burr are formed depending on the cutting direction and tool-workpiece interaction as shown in Figure 11 [17].

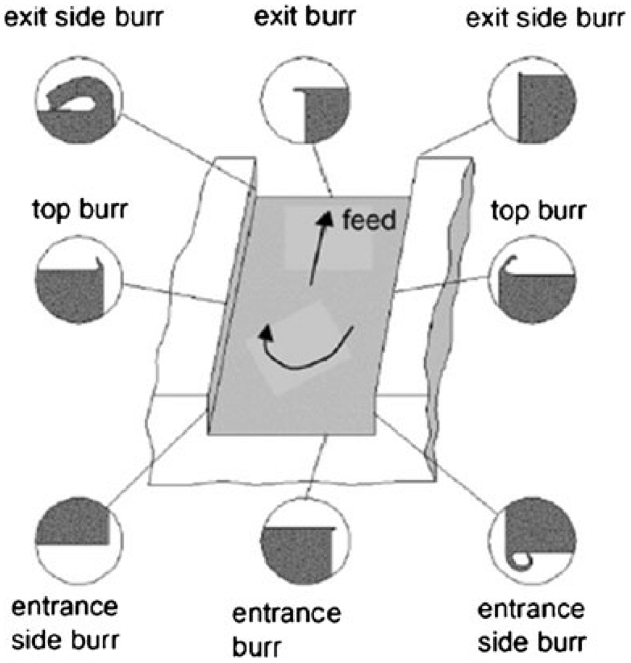


Figure 11: Types of Burrs

Top burr formation was given special attention which is important burr mechanism during micro-milling process. Top burr is measure horizontally from groove wall. Burr width on down and up milling side is shown in Figure 12 and it is visible that burr width is greater on down milling side.

This is because the speed of the localized cutting edges on the up-side would always be greater than on down-side. This is also observed by Jaffery et al. in his research [21]. In this research top burr width at down milling side is measured through SEM to consider the worst condition.

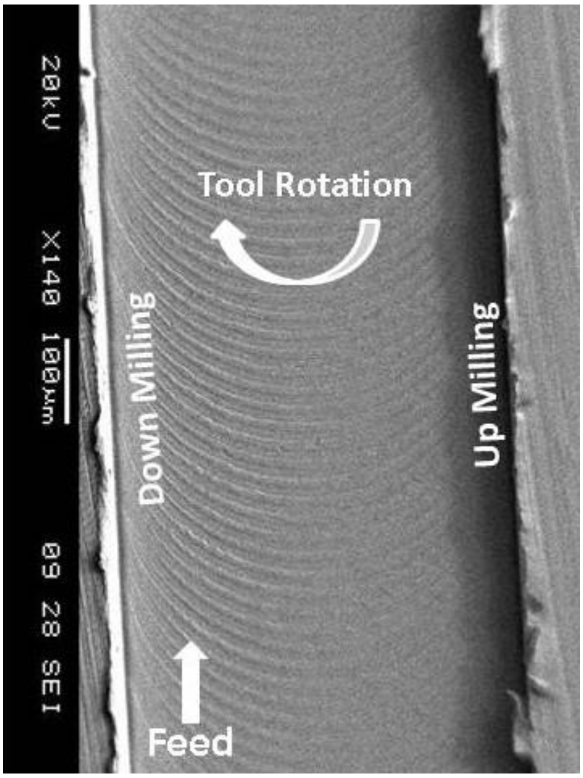


Figure 12: Formation of Burr

In this research, top burr is measured on down milling side by using Scanning Electron Microscope. In this burr formation analysis maximum burr length is measured on each machined slot. All the machined slots are analyzed on SEM to find the impact of selected machining variables on burr width.

The Taguchi technique is used to find the influence of machining parameters on burr formation and optimal parameters for minimal burr formation. ANOVA is used to analyze the influence of machining parameters on burr formation in percentage.

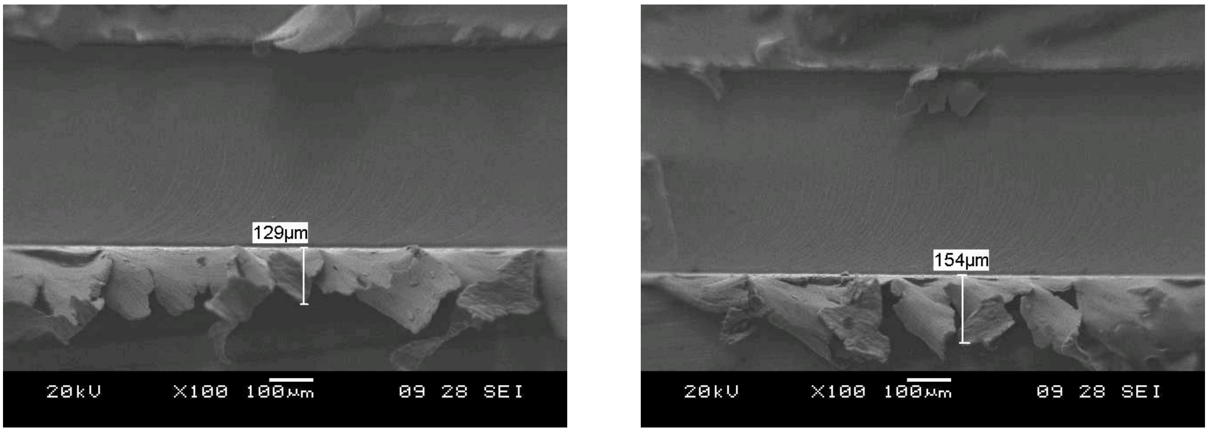
Results in the form of top burr width were obtained in each experimental run. Two runs for each trial were conducted in order to minimize the chances of error. Table 7 gives results outlined in the form of L9 array.

Feed per tooth µm/tooth	**Cutting Velocity** m/min	**Depth of cut** µm	**Cutting Condition**	**N** RPM	**Feed** mm/min	**Burr width** (Down Milling side), µm	
						Run-1	**Run-2**
8	12	50	Dry	7645	122.29	129	154
8	15	75	Flooded	9550	152.87	135	155
8	18	100	Mist	11465	183.44	145	153.4
10	12	75	Mist	7645	152.87	31	26.6
10	15	100	Dry	9550	191.08	104.4	111.1
10	18	50	Flooded	11465	229.3	24.4	27.6
12	12	100	Flooded	7645	183.44	37.3	54
12	15	50	Mist	9550	229.3	23.8	21.9
12	18	75	Dry	11465	275.16	25	26.3

Table 7: L9 Array (Machining Parameters and Results)

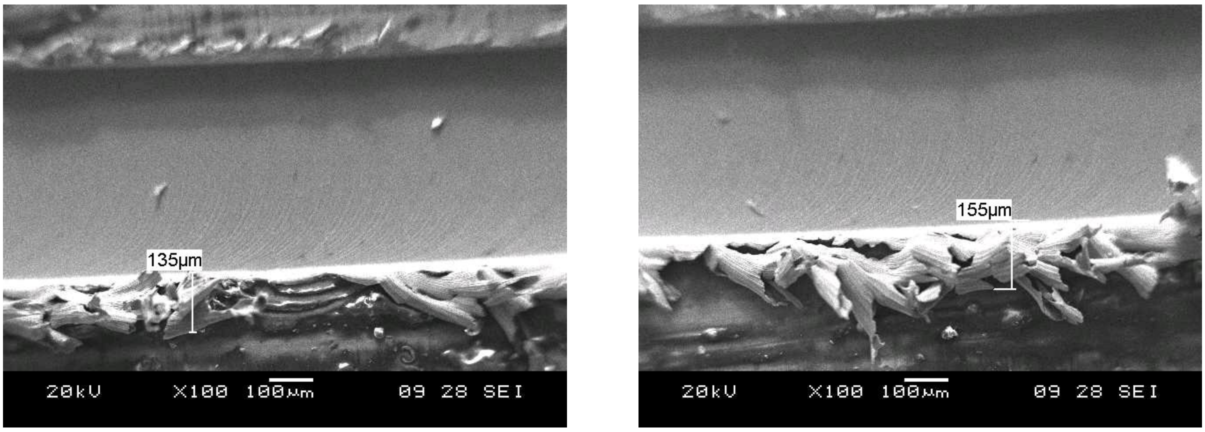
4.1. Images of Burr obtained from SEM

Scanning Electron Microscope (Make: JEOL, Model: JSM-5910 LV) is used to analyze the top burr width after machining of slots at different machining parameters. Each trial is performed twice to minimize the chances of error. Images obtained at defined parameters are shown below;



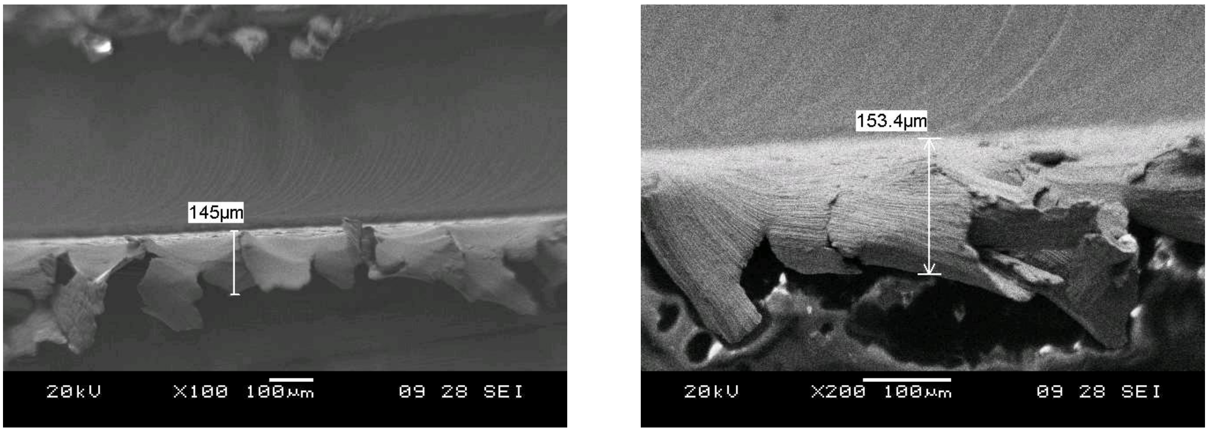
Run-1 **Run-2**

Figure 13: SEM images at fz=8µm/tooth, Vc=12 m/min, ap=50 µm and dry condition



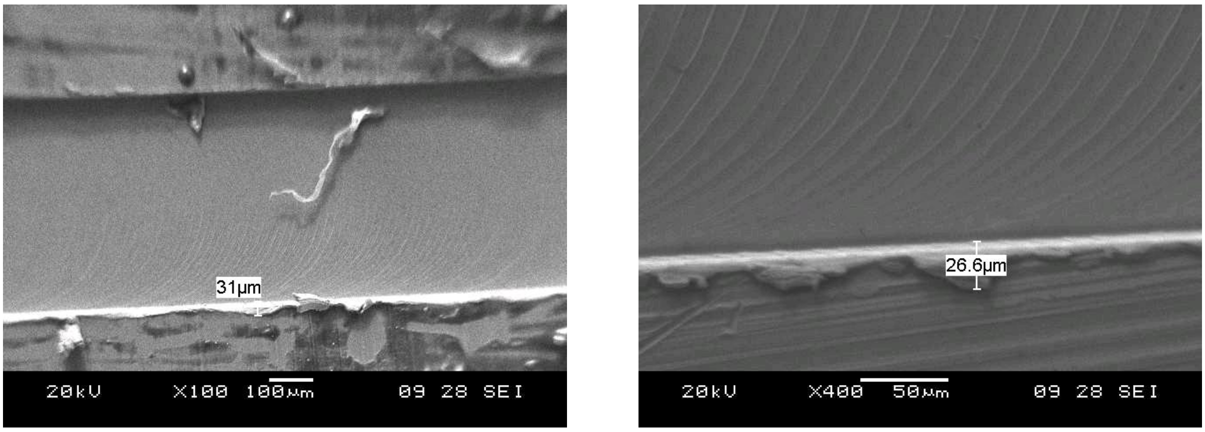
Run-1 **Run-2**

Figure 14: SEM images at fz=8µm/tooth, Vc=15 m/min, ap=75 µm and Flooded condition



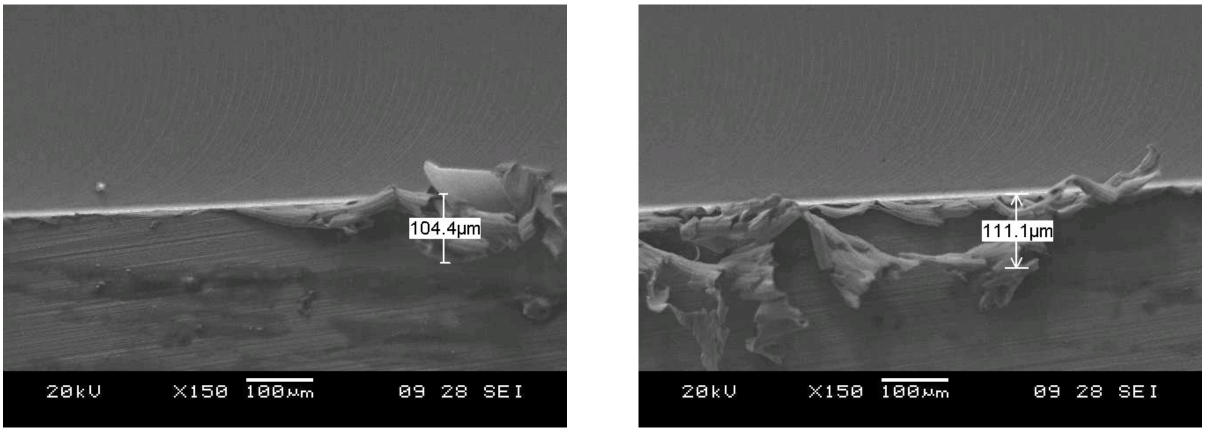
Run-1 **Run-2**

Figure 15: SEM images at fz=8µm/tooth, Vc=18 m/min, ap=100 µm and Mist condition



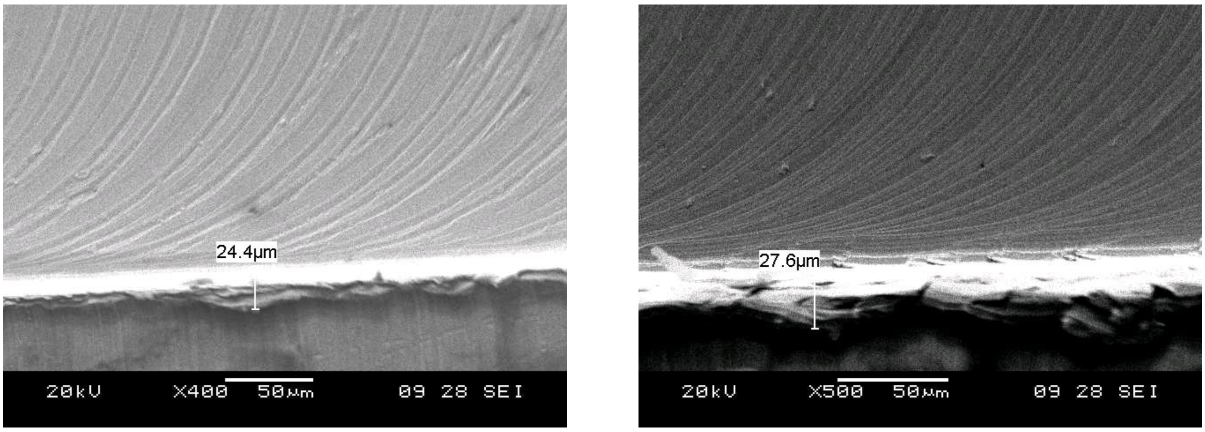
Run-1 **Run-2**

Figure 16: SEM images at fz=10µm/tooth, Vc=12 m/min, ap=75 µm and Mist condition



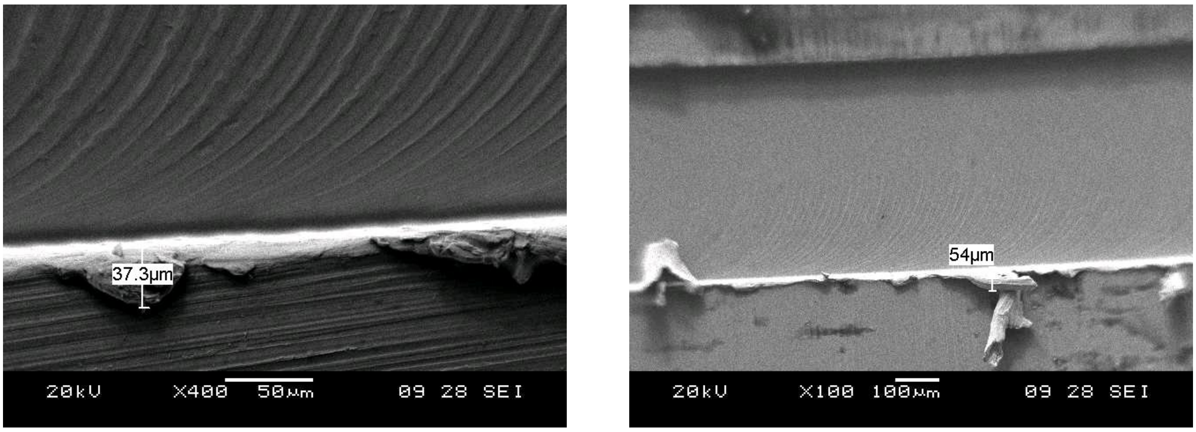
Run-1 **Run-2**

Figure 17: SEM images at fz=10µm/tooth, Vc=15 m/min, ap=100 µm and Dry condition



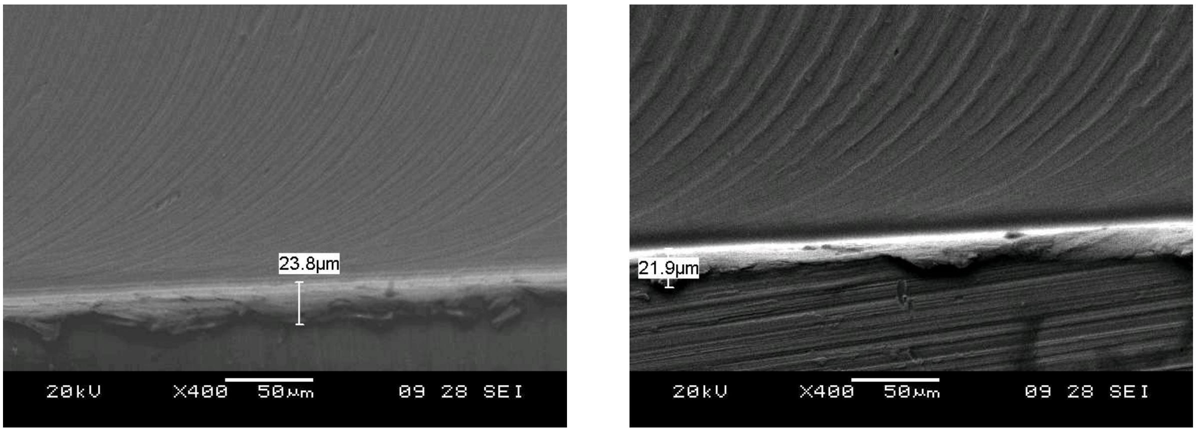
Run-1 **Run-2**

Figure 18: SEM images at fz=10µm/tooth, Vc=18 m/min, ap=50 µm and Flooded condition



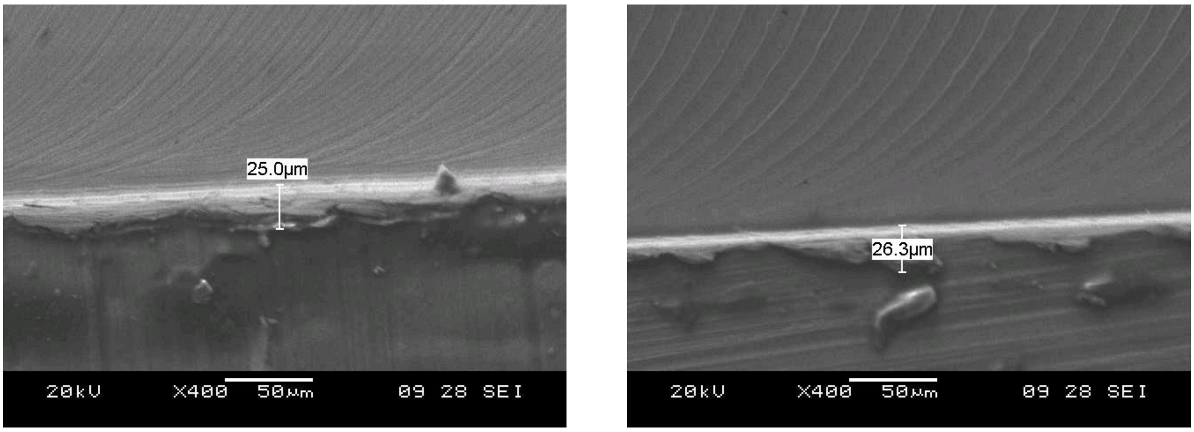
Run-1 **Run-2**

Figure 19: SEM images at fz=12µm/tooth, Vc=12 m/min, ap=100 µm and Flooded condition



Run-1 **Run-2**

Figure 20: SEM images at fz=12μm/tooth, Vc=15 m/min, ap=50 μm and Mist condition



Run-1 **Run-2**

Figure 21: SEM images at fz=12μm/tooth, Vc=18 m/min, ap=75 μm and Dry condition

4.2. ANOVA

ANOVA is used for statistical analysis of the width of the burr after obtaining results of burr formation from SEM. ANOVA is statistical tool to determine the importance of input variables on output.

To calculate out impact of each input parameters at the output response, sequential sum of squares (SS) is computed using equation.

$$SS_A = \sum_{i=1}^{3} \frac{A_i^2}{n} - \frac{(\sum_{j=1}^{N} T_j)^2}{N}$$

A is input variable, n number of iterations on certain level, i is level, T is answer value for each iteration, j is number of iterations, N is total number of iterations.

Total sum of squares is calculated using following equation.

$$SS_T = \sum_{j=1}^{N} T_j^2 - \frac{(\sum_{j=1}^{N} T_j)^2}{N}$$

Sequential sum of squares of errors is calculated using following equation.

$$SS_e = SS_T - \sum_{i=A}^{Z} SS_i$$

%age contribution of each variable is calculated using following equation.

$$\%CR = \frac{SS-(df \text{ x } MSS_{Res})}{SS_T} \text{ x } 100$$

4.3. ANOVA Calculations

Minitab is used for the said calculations and to obtain required plots, as these calculations are complex to do manually.

Source	**DF**	**SS**	**MSS**	**F-Value**	**P-Value**	**CR**
Feed	2	43543.5	21771.8	269.48	0.000	81.7%
Vc	2	2083.0	1041.5	12.89	0.002	3.88%
DOC	2	5182.8	2591.4	32.08	0.000	9.67%
Cutting Condition	2	2028.0	1014.0	12.55	0.002	3.78%
Error	9	727.1	80.8			1.35%
Total	17	53564.6				100%

Table 8: Analysis of Variance

Level	Feed/Tooth fz	Cutting Speed V_c	Depth of cut DOC	Cutting Condition
1	-43.26	-35.20	-32.85	-37.30
2	-32.73	-37.03	-33.55	-34.97
3	-29.57	-33.33	-39.15	-33.29
Delta	13.69	3.70	6.30	4.00
Rank	1	3	2	4

Table 9: Response Table for Signal to Noise Ratio (Smaller is better)

Level	Feed/Tooth fz	Cutting Speed V_c	Depth of cut DOC	Cutting Condition
1	145.23	71.98	63.45	91.63
2	54.18	91.87	66.48	72.22
3	31.38	66.95	100.87	66.95
Delta	113.85	24.92	37.42	24.68
Rank	1	3	2	4

Table 10: Response Table for Means

4.4. Analysis of Burr Formation

ANOVA was used to identify the influence of process variables on burr width. Burr width was larger on down milling side, so the burr width was only measured on the down milling side to take into account the worst situation.

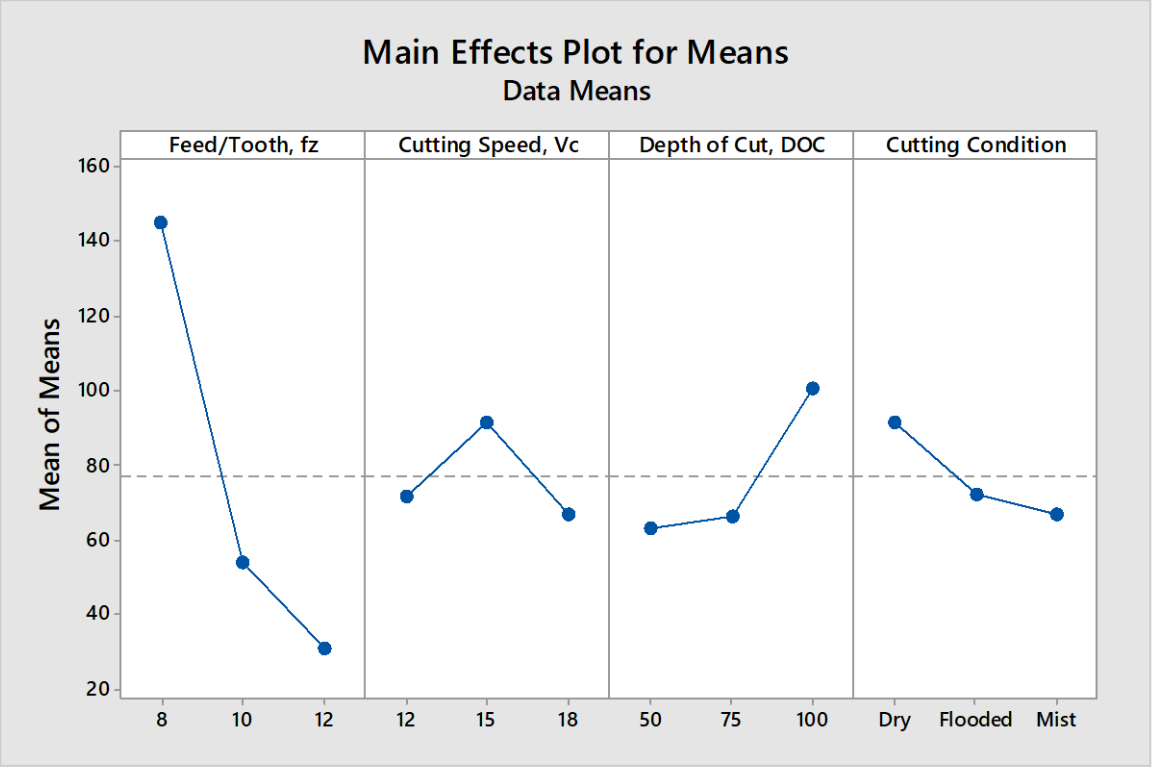


Figure 22: Main effect plots for burr width with respect to process parameters

The feed rate (fz) is the main input parameter contributing 81.7% to the top burr, and the depth of cut (DOC) is the second most important input parameter contributing 9.67% to the top burr, while the cutting speed (Vc) as third significant input parameter to 3.88% contributes followed by the cutting condition as the fourth most important input parameter.

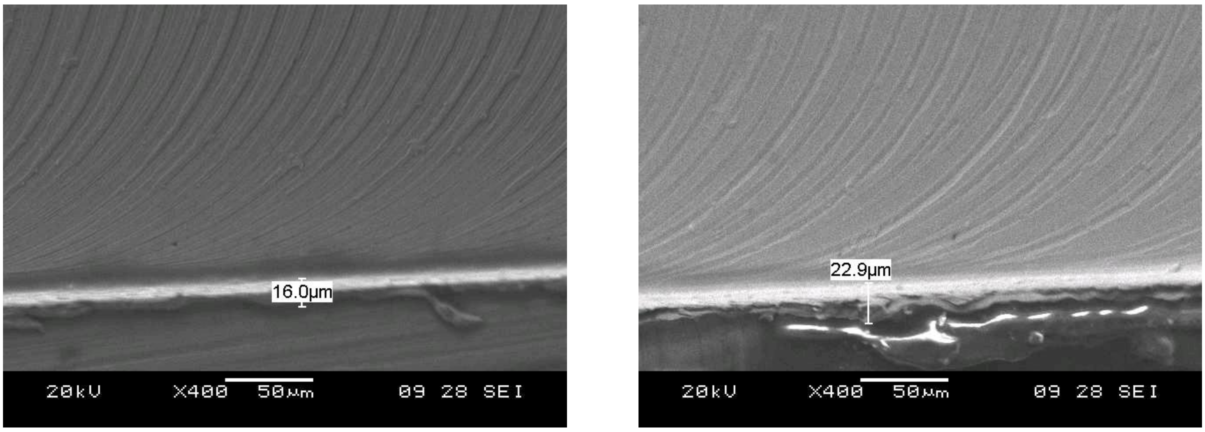
Main effect plot for top burr were generated using Minitab software as in Figure 22. Each point in the plot indicates mean burr width for specific level of input parameters i.e. fz, Vc, DOC and cutting condition.

From Figure 22 it can be seen that the top burr reduces with the increase in f_z (feed per tooth). Some similar studies gave same results where researchers investigated inverse relationship between feed rate and burr width and described that f_z (feed per tooth) is the most significant input variable effecting top burr width. With increasing the depth of cut burr width increases, indicating a direct relationship between DOC and burr formation.

4.5. Confirmatory Tests

From Figure 22 it is clear that setting feed per tooth and cutting speed at their high level and depth of cut at its low level at mist cutting condition yields minimum burr width. The benefit of Taguchi design of experiment is that it reduces the number of experiments.

That’s why, to ensure the repeatability of the process, a confirmatory experiment is necessary to check the minimization of results coming from the optimization process. A confirmatory test was performed for minimum top burr width against the levels of optimal process parameters.



Run-1 **Run-2**

Figure 23: SEM Images at optimum conditions for minimum burr formation

A summary of input process parameter and experimental results is given in Table11, which shows that optimum condition yields best results.

Objective Function	Optimal Process Parameters				Results		
	f_z (µm/tooth)	V_c (m/min)	a_p (µm)	Condition	Run-1 (µm)	Run-2 (µm)	Average (µm)
Minimum top burr width	12	18	50	Mist	16.0	22.9	19.4

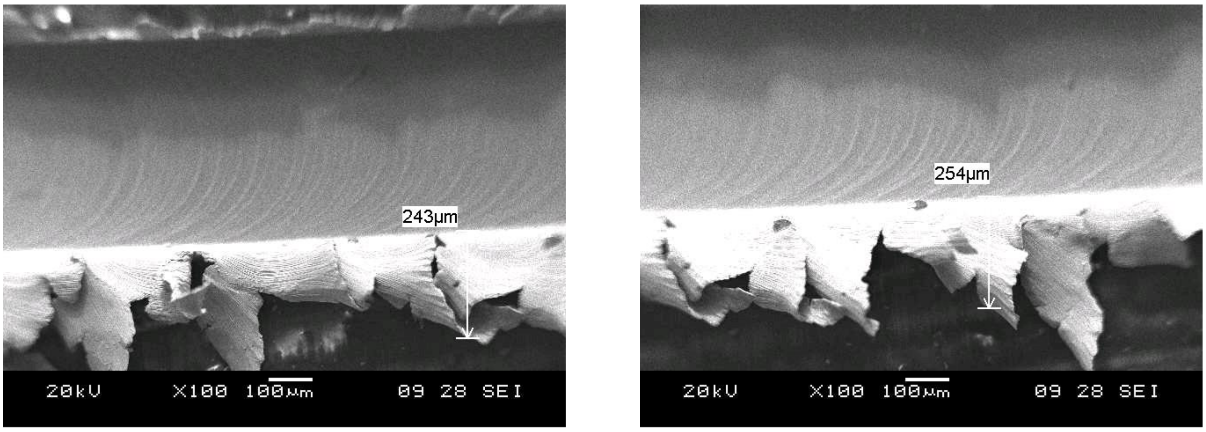
Table 11: Experimental Results at optimum conditions

To check the results of worst case, there was a need to perform a confirmatory tests by setting feed on its minimum value, cutting speed at its worst condition with maximum depth of cut and dry cutting condition.

A summary of input process parameter and experimental results is given in Table12, which shows that worst condition yields worst results in the form of larger burrs.

Objective Function	**Worst Process Parameters**				**Results**		
	f_z (µm/tooth)	V_c (m/min)	a_p (µm)	Condition	Run-1 (µm)	Run-2 (µm)	Average (µm)
Minimum top burr width	8	15	100	Dry	243	254	248.5

Table 12: Experimental results at worst conditions



Run-1 **Run-2**

Figure 24: SEM images at worst conditions

Hence, it is confirmed that optimum cutting conditions resulted minimum burr width and worst cutting conditions resulted maximum burr width which authenticates previous results.

CHAPTER 5: CONCLUSION

This research was conducted to identify the key process variables when micro-milling the Monel-400 in order to minimize the formation of burr. It is very important to identify the key process variables because it results in enhancement of product quality as well as productivity which results in reduced manufacturing costs.

In this research different process parameters i.e. feed/tooth, cutting speed, DOC and cutting condition were altered to study effect on formation of burr in detail.

i. It was observed that larger top burrs on the edges of machined slots were formed on down milling side.
ii. Feed/tooth (f_z) was the most important process parameter contributing 81.7% in formation of burr. Increasing feed per tooth results in reduction in burr formation. Hence, an inverse relation was found between feed per tooth and burr width.
iii. Depth of cut (a_p) was the second most important process parameter in burr formation. By decreasing DOC, burr width also decreases. Hence, a direct relation was found between DOC (depth of cut) and burr width.
iv. Cutting speed and cutting condition proved to be third and fourth most important process parameters respectively.
v. It is evident that in order to reduce burr formation in micro-milling of Monel-400, better results can be attained using lower speed machining setup with variation in feed per tooth instead of using high speed machining setup.
vi. Using the optimum process parameters in micro-milling gave best results of minimized burr on the edges of machined slots.

5.1. Recommendations

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

i. Analysis of surface roughness and tool wear in low speed micro-milling of Monel-400.
ii. Analysis of un-coated and coated tools in low speed micro-milling of Monel-400 with respect to surface roughness, tool wear and burr width.

iii. Analysis of subsurface damage in low speed and high speed micro-milling of Monel-400.
iv. Analysis of effect of different coated tools over subsurface damage, tool wear, burr formation and surface roughness in low and high speed micro-milling of Monel-400.
v. Analysis of the effect of grain size of workpiece on surface roughness and burr formation.

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