Investigation on the Micromilling of Titanium alloys Ti6Al4V

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Abstract

Micro-milling is the most emerging machining process nowadays. Because it just not possibly makes the two-dimensional and three-dimensional shapes of material but it can also manufacture various types of engineering materials. In industries the use of micro-level parts is increasing very rapidly so that is why micro machining is most needed machining type. Micro milling is mostly used micro machining type because of its accuracy in machining, greater surface finish and it can also give greater material removal rate. Other than that this process is preferably good because of its process flexibility in machining of miniature parts. While in selection of workpiece material this process also has no limitations.

This study is intended to focus on the micromachining of aerospace material alloys. Mostly used materials are titanium alloys and nickel based super alloys. Widely used aerospace material is titanium alloy of Ti6Al4V as it has greater strength to weight ratio, good corrosion resistance and it is good for high temperature application. But titanium alloys are is very difficult to machine due to their lower elongation to break ratio and very poor thermal conduction.

Micro level of machining becomes more difficult. Although it gives greater accuracy but some difficulties becomes more prominent at this level. There are many problems during this machining process which are needed to be covered. These are the burr formation and surface finish of workpiece and most importantly tool life which means focus on its wear. In these problems our center of attention is the burr formation and surface roughness of workpiece. In this research to analysis percentage contribution of parameters effecting the surface quality, the statistical analysis method ANOVA is used.

Key Words: *Micro-milling, titanium alloys, burr formation, surface roughness, ANOVA, statistical analysis*

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Chapter 1

INTRODUCTION

As the world is evolving the technology and research work is also changing. Scientists are now more interested in creating miniature parts. So this demand puts high pressure on researchers and engineers to manufacture parts at macro, micro and even at Nano level. These manufactured parts should have high surface finish and superior properties as their demand is increasing in fasting growing industries like automobiles, precision instrument, biomedical, space and electronics.[1] In start their targeted machining level is macro level. Now researchers focused their all interest to micro and Nano level. So machining at this level is very difficult. There are many machining processes like drilling, milling, lathe and cutting while the targeted machining type in this research is micro-milling. Machining at micro level needs high precision which also requires micro level tools. Machining at this level can gives good accuracy and gives high surface finish.

This machining process although gives better surface finish but there are some problems one can face during this machining like friction forces, temperature, machinability of different materials and different loading conditions. The intensity of these conditions is different in different materials.[2] In this research titanium alloy is used for milling. In many applications light weight and cheap materials are preferred but titanium is still extensively used in many applications due to its exceptional properties like high strength, strong resistance to corrosion, easy to machine even at elevated temperature. Its great hardness creates problem in machining specially at micro level. But this problem can be overcame by using different tools.[3]

The milling process has some problems when micro level milling is used. These problems are associated with the surfaces which are in contact, such as formation of burr, surface roughness, wearing of tool, sudden failure of tool. These are the main factors which directly affect the quality of finished surface of material as well as the performance of the process. These factors can be controlled by using some techniques which involve controlling of different parameters and adopting some different techniques. As discussed before the micro-milling has good surface finish so this led researchers to study more about micro-milling and compare this with other conventional machining processes.[4]

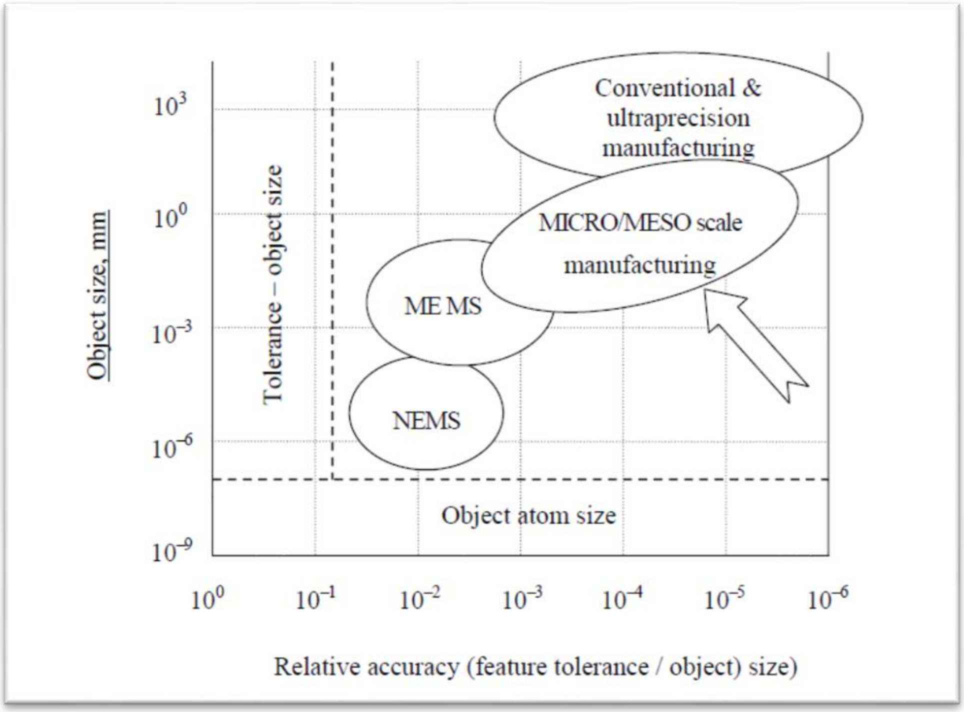


Figure 1: *Micro machined product size\precision comparison with respect to other manufacturing process.*

1.1. Research Background and Motivation:

During the mechanical machining of different materials many problems can be observed. From these all problems Burr formation on the surface, Surface roughness and tool wear. This research is focusing on these three important factors which directly affect the quality of the material. Burr formation is dominant on the metal surfaces especially which can plastically deformed. Burr formation is observed more at macro level than at micro level. This burr effect the surface of material and result in decreasing its surface accuracy involve changing of dimensions and this led to poor surface quality.[5] So this burr formation can be very disastrous at some point. To reduce or remove this burr at this micro level is more challenging so conventional methods are not useful such as cleaning, brushing and etching. Deburring is also not suitable for reducing the effect of burr because it may affect the surface dimensions and residual stress. So researcher are focusing on different experimental techniques to reduce the burr formation during the micro-milling process.[6] According to their research, changing the process parameters may reduce the burr formation during this process as these process parameters are the main controlling factors.

The process parameters were changed according to desire to reduce the burr. This research is on investigation of these process parameters that which parameter has more influence on the formation of burr. This study is on finding the exact value in percentage that which parameter is involved. So by controlling that parameter burr formation can be minimized.[7]

The second factor that is more important to be highlighted in affecting the material accuracy and quality is surface roughness. This factor effect material dimensions and its accuracy this factor can also be controlled by controlling the process parameter involve cutting speed, feed per tooth and depth of cut. In different materials surface roughness is effected by different factors. In some machining processes tool diameter, spindle speed and feed rate are the factors directly effecting the surface qualities.[8] in different research works they concluded different factors which are more influential in defining surface quality and accuracy. According to a researcher feed per tooth is more effective parameter in deciding the surface quality. While in other research work spindle speed is more effective, this is totally depending on the machining environment and process parameters.[9, 10]

As discussed before that feed per tooth, depth of cut and cutting speed are the main parameter which effect the material accuracy and surface finish. So focusing on these parameters titanium alloy Ti6Al4V is selected as a workpiece while the tool is of tungsten carbide.

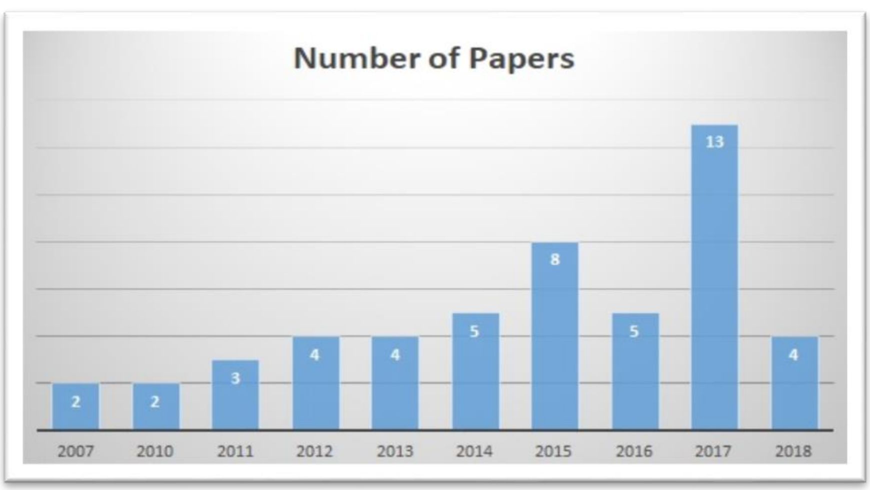


Figure 2: *Number of papers used in this research*

1.2. Research Objectives:

The main objectives in this research work are different parameters and their effect on workpiece.

- Analyze the burr formation on the surface by using Scanning Electron Microscopy (SEM).
- Calculate the surface roughness of workpiece by using Profilo-meter.
- To use the statistical data analysis process ANOVA to find out that which parameter is more influential in defining surface quality such as surface finish and burr formation.
- Select the optimum machining parameter on the basis of ANOVA results.

1.3. Research Scope:

Scope of this research work is restricted to the micro-milling of titanium alloy Ti6Al4V using tungsten carbide tool. While machine limitation is its speed which is not more than 8000 rpm. While micro milling machining and titanium alloys has many application like biomedical, aerospace and electronics. So this research study can also be useful for these applications.

Chapter 2

Literature Review

In the last few years technology has stepped up and scaled down the conventional manufacturing techniques. This new change in technology is due to the fact that engineers are now interested in small size products in every industry. This interest has led them to the manufacturing of miniature parts. So the manufacturing of the miniature parts need different manufacturing techniques, this is the reason researchers and engineers moved from macro to micro and Nano level. So this new change in manufacturing techniques allow researchers to step up from the conventional techniques. Need for the miniature parts now increased in every type of industries including military, biomedical, electronics, aerospace, optical and others. The demand of micro level parts has increased as industries are interested in low cost and light weight products. So to enhance the production quality and properties and reduction in weight as well as cost the manufacturing process is modified.[4] This modified technique of producing miniature parts is called micromachining. This micro level components can be manufactured by different manufacturing techniques like laser machining, electric discharge machining (EDM), focused ion beam machining, micro forming, electro chemical machining and mechanical machining which is mostly used manufacturing technique.[11]

In this mechanical machining the most famous and widely used technique is micro-end milling. Because this technique has more flexibility than any other technique, fast manufacturing of complex shapes and cost effectiveness. Micro machining is recently gaining more attention than other machining process due to its process flexibility, ability to manufacture complex shapes like 3D cavities and arbitrary curvatures. This machining type has very low setup cost and greater material removal rate. The machining method is not limited to any specific type of material or product.[12] The sample preparation for this machining is not too complicated or intricate. As all the manufacturing technique used for the production of miniature parts have their own advantages and disadvantages. But this machining techniques has more advantages which makes these machining methods mostly used methods. [13]

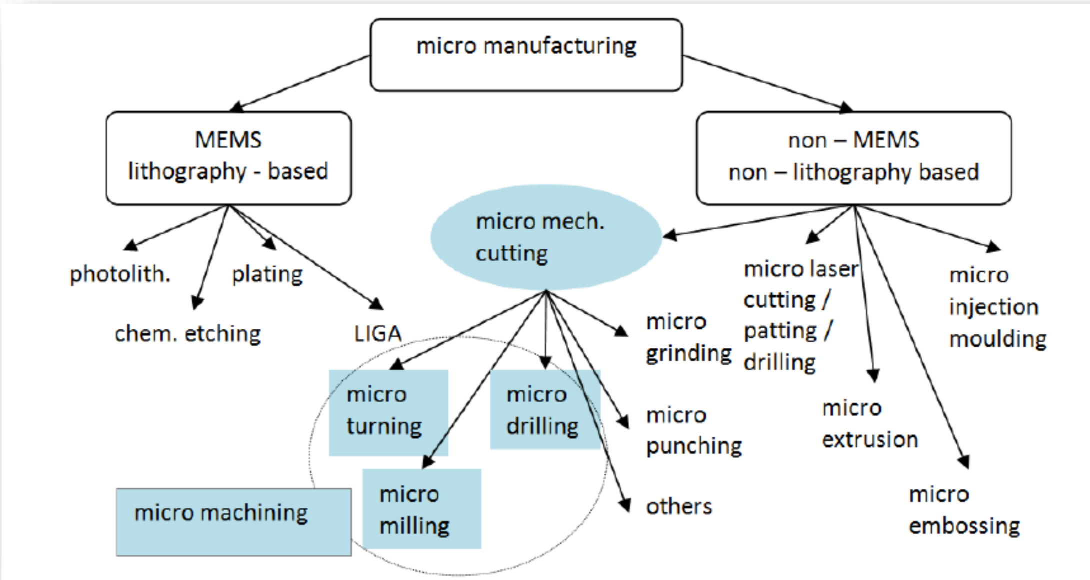


Figure 3: *Types of micro-machining*

2.1. Micromachining advantages and disadvantages:

Micro-machining is mostly used techniques to manufacture the miniature parts to fulfill the high demand of micro level products. So now focusing on the advantages and disadvantages of this process explain its importance.

2.1.1. Advantages:

- Extraordinary properties of material such as surface finish, high strength, high heat resistance and corrosion resistance.
- This technique can made complex 3D shapes mostly used examples are turbine blades.
- This is ideal machining process for the prototypes of micro level products including metals, plastics and composites and all other type of materials.
- Gives more efficient material properties.
- This process can reduce the lead time of machining than the other conventional methods.

- This machining is good for repeated production and gives same and efficient properties for miniature parts.
- This process has high spindle speed which can give cleaner cuts.
- It can gives more precise dimensions and tighter tolerance so which make machined materials to match their requirements.
- It can make more diverse and accurate products. Which make this process best for the large production.
- Smaller size tools have less friction so it does not need any lubrication.[14]
- This process has very low step cost and need very less man power.
- As the sample and tool size is very low so which reduce the vibrations and the noise, useful for workers.
- Energy efficient and this process save the energy as well as material wastage.
- Material waste is easy to remove.
- Tool size is very low as in micro level so the inertia is very low at high speed and acceleration.

2.1.2. Disadvantages:

- Cleaning the sample is very critical as it may affect the material surface.
- Machined materials are difficult to preserve as the machined surface can easily be damaged.
- Machining is done at very small level so to observe these detail at that small level needs high level and expensive testing techniques.
- Tools at micro level are very sensitive. Tool breakage is very common.
- Material Chips are very small so create problem.

2.2. Micro-milling:

Micro milling is mostly used technique in mechanical micro machining. This technique gives its major part in manufacturing of intricate and 3D shapes parts. The range for the micro level milling ranges from as low as 5-10 µm.[4] This process is also very commonly used in making of micro molds. These are the supporting material for the mass production of different types of micro level materials.

Micro milling can be classified by its speed of machining. In research all the focus is on high speed milling because it has high material removal rate and good finish. This speed can be varied from 10,000 rpm to 16,000 rpm. Below these value speed of the machining is low. This research focuses on low speed. Other parameters that define the milling process are chip load, axial depth of cut and radial depth of cut. These parameters are the main factors which are defining the final precision and accuracy of material using this machining process.[15] these parameters make this process more flexible as these parameters are easily controllable.

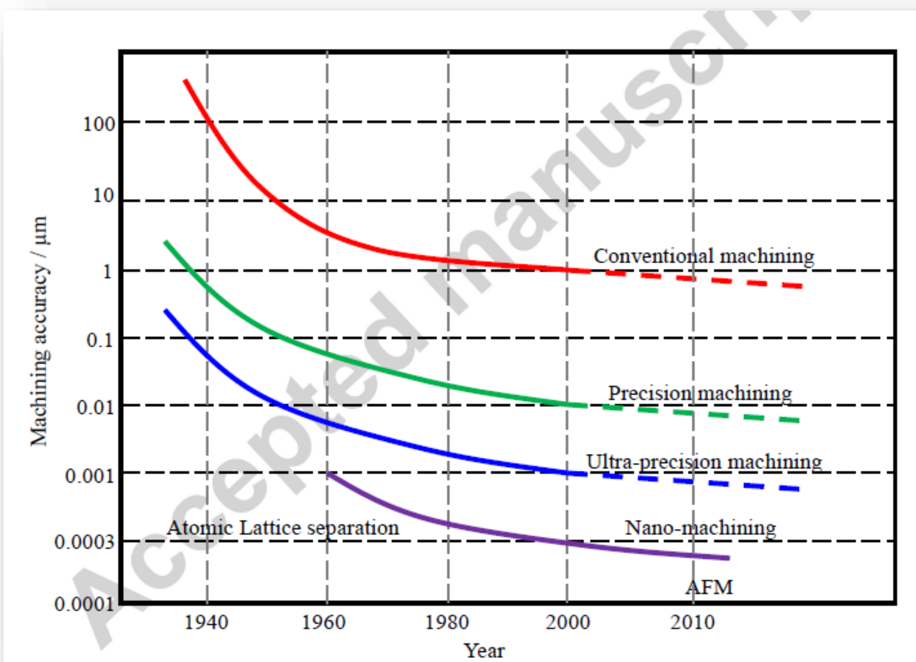


Figure 4: *Machining Accuracy of materials throughout the years*

Fig. 4 shows that the demand of accuracy in machining with the years. This demand make the machining process more precise with time as researchers chooses the smaller level of machining. The machining processes are modified with time to make an accurate and precise product. As we go to smaller level our accuracy level also improved.[16] So this explained that micro and even nano level machining has more precision than conventional methods.

The micro level machining more needs more attention and time that's why this process is easier to control by computer numerical control CNC. This automated machining process male the machining more advance and easy. The controlling parameters are defined by the user then the accurate and precise product can be made.

2.2.1. Surface Roughness:

To characterize the surface integrity and its quality surface roughness plays an important role. The surface roughness gives primary detail about the surface quality and its integration. In micro milling machining process surface quality is in main high light. There are many factors which are effecting the quality of surface. The main factors which are effecting the surface quality directly are feed rate and tool cutting edge radius but in the actual machining process some other factors are also involved which are effect of the tool vibrations, cutting forces and tool wear. In literature this fact is also verified that the surface quality is effected by tool wear, depth of cut, tool geometry and cutting speed.[17] There are different types of parameters in surface roughness peaks included roughness average (Ra), roughness (Rq), root mean square (rms) and peak to valley roughness (Ry). In these surface roughness average (Ra) and surface roughness (Rq) are the mostly used parameters. The average roughness of the surface is actually the total are under the profile and mean line.[18]

2.2.2. Cutting tool:

As micro milling is mostly used micro machining type because of the increase in a demand of micro level finish products. So this micro milling process needs micro level tools to machine the materials. There are many types of milling tools like end mill, engraving, drill and ball nose tool. The material of these tool is either of tungsten carbide or of diamond as these both are hard material so best tool made up these materials useful for micro level milling. As the size of the tool is very small so that led to many problems which make these tools limited to some extent.[19] The size is reduced so which make these tools less stiff, this is the main reason of premature failure of these tools. So there are some major reasons which directly affect the failure of tool.

- **Breakage due to excessive stress:** The breakage of the tool occur when the cutting forces increased than the strength of the tool. The increase in the cutting forces is due two major reasons either the edges of the tool are damaged or the sharpness of the tool is lowered. These damaged edges led to the breakage of tool. Second major reason is due to the chips clogging, now this chips clogging is due to the chips accumulation while machining in the groves made during milling process.[20] This clogging stops the movement of tool which break the tool. High strength steel is better than any other tool to work under this situation.
- **Breakage due to Fatigue:** This breakage occur when combined effect of cutting forces and stress applied on the tool and it stay there for the longer period of time. This fatigue directly affect the movement of the spindle movement which stops the tool and led to breakage.
- **Breakage due to change in Specific Energy:** The specific energy of the tool increased when the chips are thinner. This occur when the required depth of cut is very low which led to the production of thin chips. This create more resistance to the tool due to this resistive forces the energy increased. This resistance has directly effect on the tip of the tool so which make tool weaker and ultimately breaks it.
- **Tool run-out:** This is problem is due to the human error during fixing and alignment of tool. When the tool is not properly adjusted in the spindle then the flutes of the tool are not aligned. So when the tool rotates the force on any one of the flute increased the surface quality also disturbed and the tool is starting to wear. This is the run out of the tool as the forces variation are occurred on the edges of the tool. This effect wear the tool faster.

Tungsten carbide is the mostly used tool in the micro level machining. This is suitable for the machining as this tool is very hard and can be easily survive the high temperature. These tools are commercially available easily and their sizes are available in different diameter size up to 5 µm. but according to the literature the tool diameter size below 100 µm is not suitable and also not reliable as this create more problems in machining. As the size decreases the rigidity also decreased so breakage occurs.[21] To improve the rigidity of the tool different type of coatings are used such as titanium aluminum nickel (TiAlN), titanium nickel (TiN) and nickel

(N). This improves its mechanical, chemical and physical properties of the tool and help in lowering their influence on the workpiece material. One thing that matters the most is tool cutting edge radius. Because it cause the increase in burr formation especially ductile materials. In literature the tool cutting edge radius ranges from 1 to 3 µm.

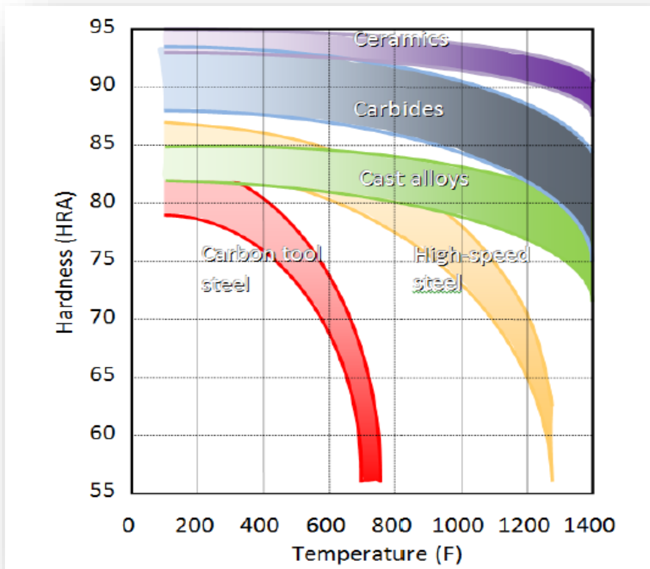


***Figure 5** Importance of Carbide tools compared to other materials*

In fig. 5 the carbides are more efficient tool material according to their hardness and temperature comparison with other tool materials.

2.2.3. Advantages:

- This process has higher aspect ratio.
- The surface quality of material is tolerable.
- Tolerance of this process is very good as ± 2 µm.
- Its application has very wide range of materials.
- It has very high rate of material removal.
- This process gives more flexibility than all other methods.
- It gives good accuracy and precision in the material surface.

2.3. Comparison of Micro and Macro Milling:

When macro and micro level milling is compared then this is not all about the size of the tool and the machining level. Many parameters and factors are involved in these machining types. The main principle is similar in both of the machining types and the factors effecting the machining in both of the processes are same. Some of the main differences between them are discussed below.

2.3.1. Tool diameter and wear:

Tool diameter in micro milling process is mostly below 1mm and while in macro milling process the diameter of the tool is more than 1mm.[19] Mostly used diameter of tool in macro milling process is 3mm and above. As size of the tool is very small in micro milling so the wear and even breakage of tool is more common. The breakage of tool is due to the forces acting on the tool when these cutting forces increased than the total strength of the tool. According to the literature the smaller depth of cut increases the wear and thermal growth because smaller depths may increase the level of friction between tool and workpiece. In micro milling process the depth of cut is at smaller level this the reason micro milling process have greater too wear than macro milling process.

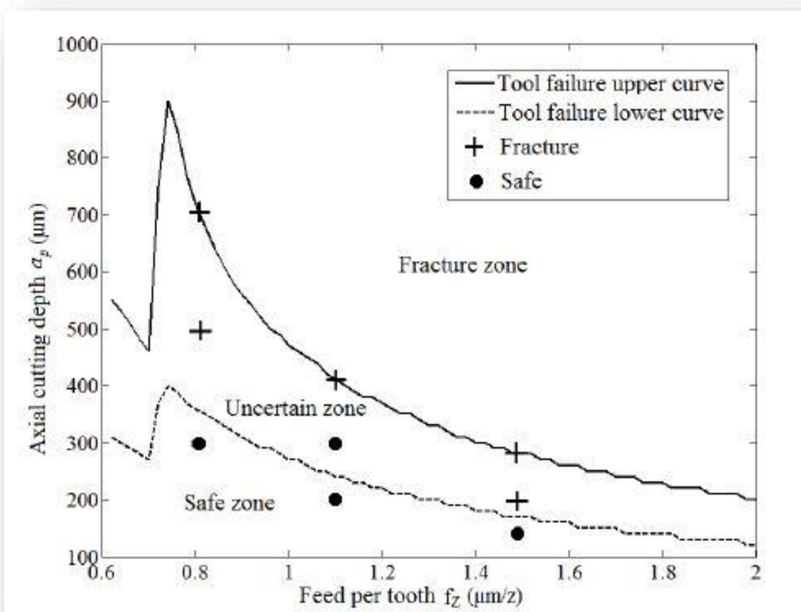


Figure 6: *tool breakage curve with respect to Feed*

While the radius of tool has inverse relation with the surface roughness as the radius of the tool increases the surface quality decreases and the rate at which tool breaks increases.[22] So in macro milling process tool has greater radius which decrease the tool breakage possibility and also decreases surface quality. So micro tools are more efficient. While in macro milling process breakage is not common because the tool size is not that small. So strength is also greater which stops the domination of cutting forces.

2.3.2. Chip thickness:

Chip thickness is the thickness of workpiece removed while machining with the tool which have a specific edge radius. This removed surface is in deformed form and this thickness totally depending on the size of edge radius of tool. The chips are larger in size while machining at macro level as the depth of cut ($\boldsymbol{\alpha}$) is greater than the tool edge radius ($\boldsymbol{r_e}$). While in micro milling process the chip thickness very small because the tool edge radius ($\boldsymbol{r_e}$) is very smaller than the depth of cut ($\boldsymbol{\alpha}$).

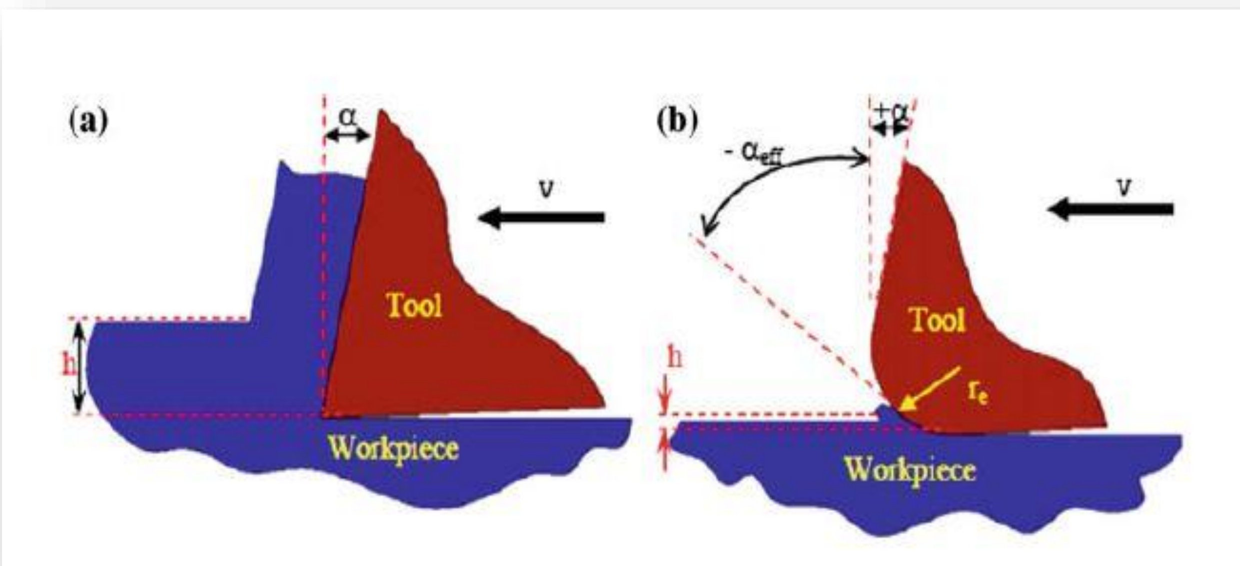


Figure 7: *Relation of depth of cut and Chip thickness (a) Macro milling, (b) Micro milling*

Fig. 7 showing the relation between the depth of cut and edge radius these two decide the thickness of chips during machining. In the micro milling process chips formation is in the shape of three different forms. In first case Fig. 8a the elastic deformation happened in this case there is almost no chip is removed in this case uncut chip thickness is very low as compared to the critical minimum chip thickness (hmin).

This process of minimum chip thickness causes the increase in cutting forces this all increase is because of the slipping of forces and other effect called ploughing of the surface which is being machined.[23] In second case Fig. 8b elastic deformation also occur but this time at lower rate with some amount of shear and this time chip thickness also increases this is because uncut chip thickness is approximately equal to the minimum chip thickness (hmin). In the third case Fig. 8c the elastic deformation is lowered to minimum level and chips are removed at visible level this happened when the uncut chip thickness becomes much greater than the minimum chip thickness (hmin).

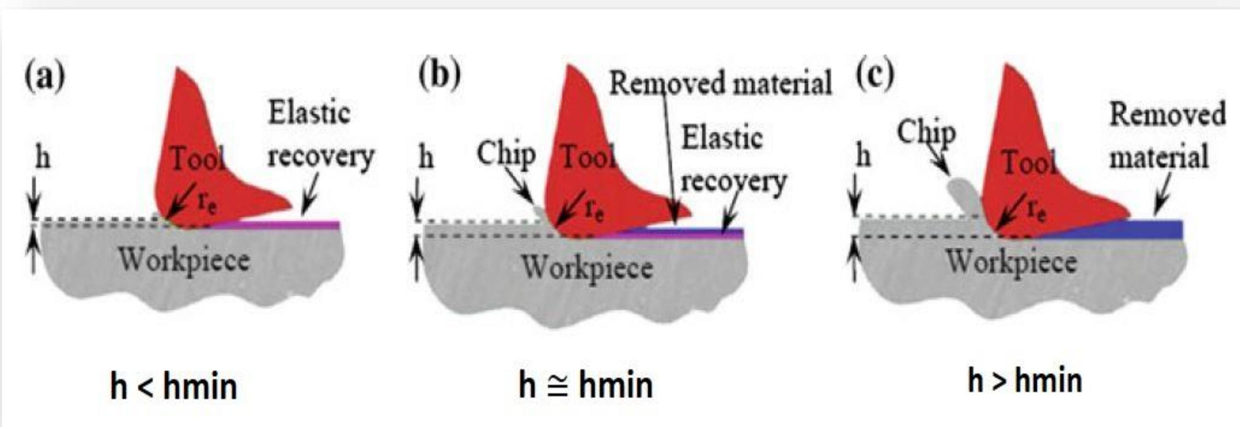


Figure 8: *Micro level machining process formation of chips with different thickness*

So depth of cut is deciding factor in the formation of chips with different thickness and also this is the factor which lower the chances of tool breakage or wear. Ploughing effect increase the chances of wear and breakage of tool. While this effect is on minimum level in macro level machining process.

2.3.3. Surface Finish:

Surface quality and its integration is most important part in milling. Surface finish is different in both milling processes. Some factors like chip removal rate, tool vibration and feed rate are the main influential factors in deciding the surface quality. These factors decide the accuracy and precision of workpiece. In micro level milling process these factor have dominating effect while in the macro level machining process these factor have not a critical effect.[22]

In the literature many researchers discussed that the main factors which directly affect the micro milling are tool edge radius and feed rate. According to their research when the tool edge radius is 2 µm and the feed rate is also decreasing then the surface roughness has direct relation with this. So the surface roughness increases. The surface roughness can also be improved by ensuring the rigidity and accuracy of the equipment using for the milling process. The condition of the tool and workpiece surface before machining these two factors have minimal effect on the surface quality of machined product. So these problems can be solved by extra machined the surface of workpiece before micro level machining is performed.

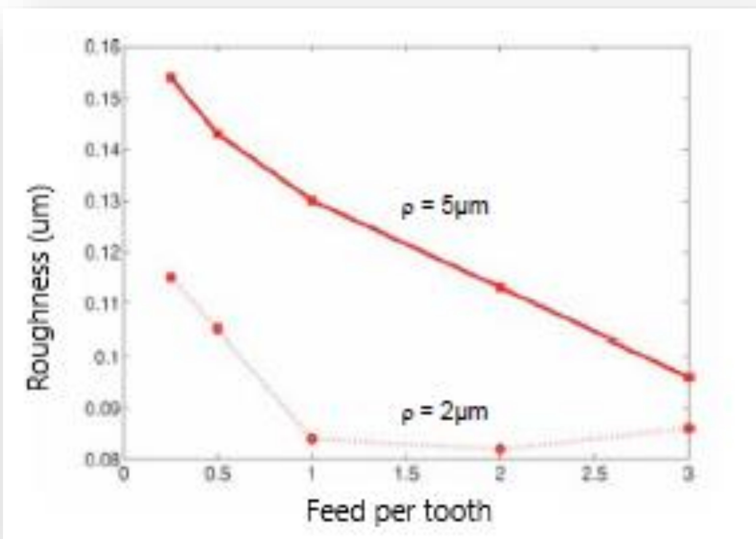


Figure 9: *Effect of tool cutting edge radius on the surface roughness workpiece*

2.3.4. Burr formation:

This phenomenon is the last and important which differentiate the micro milling from macro milling. Burr formation is actually the formation of chips at the end of cut. This basically called the small residue on the surface of machined area this is although very prominent. This burr formed due to the difference created between chips and the surface of workpiece. This burr created on the different locations and sides of machined surface. The burr formed on different sides have different names known as top burr, side burr, up milling burr, down milling burr etc. the main prominent burr formed are side burr and up milling burr.[24] Burr is more visible on these sides which directly affect the surface quality. Tool edge sharpness, workpiece plasticity, feed rate and tool rake angle these are the deciding factors in formation of burrs. Burr is more prominent in micro milling as the tool size is very small and the thickness of the burr is dependent on the tool edge radius.

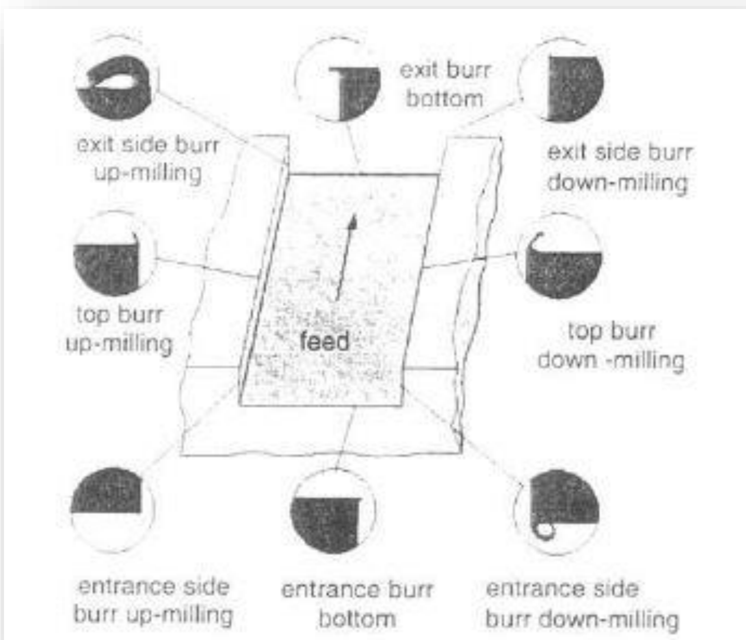


Figure 10: *Different types of burr formed during machining*

Fig. 10 showing the detail images of the burr formation during the milling process. Burr formation in micro milling is prominent and that’s why it is difficult to remove.

According to the research burr formation is more dominant due to main parameter feed per tooth which produce large burr in the direction of feed. The height of the burr is totally dependent on the number of flutes and diameter of the tool. In micro milling process the tool diameter is very low so which produce larger burr than the macro level machining as the tool size increases. The feed rate and the formation of burr have inverse relation.[25] As the feed increases the smaller burr formed.

2.4. Titanium and its alloys:

Titanium and its alloys are very hard materials and have such an outstanding properties especially at elevated temperature. Their high specific strength and corrosion resistance are the dominating properties that is why they are being extensively used in many industries like aerospace, petroleum industries, prosthetic devices, surgical implants, bio medical applications and marine industry.[26] The major application of these materials is aerospace industry as this is a very light material and it has very good strength to weight ratio.

Figure 11: *Applications of titanium and its alloys*

Fig. 11 showing the different applications of titanium and its alloys. Due to its extra ordinary properties make this material perfect for these applications. But some of its drawbacks like its poor machinability, tool wear and burr formation during the milling process produce some difficulties for the researcher and engineers for the production process.

2.4.1. Ti-6Al-4V alloy:

This alloys of titanium are used on extensive level in many applications especially in aerospace industry. This alloy of titanium is an example of alpha and beta (α+β) alloy this is a mix grade alloy. This property of meta-stability is very good in this alloy both the stages alpha and beta (α+β) are stable. Which make this alloys a very good choice for heat treating. Because of this meta-stability these alloys can easily be heat treated. When there is a need of a material with greater finish surface and high strength then this alloy comes in mind. This alloy has greater surface finish while machining like milling and drilling. Sometimes when the machining is done at micro level for example micro milling then burr formation is observed but still surface finish is better on high feed rate.[27]

- **Advantages:**
    - Such a high strength to weight ratio.
    - Moderate to high temperature properties.
    - Great surface finish.
    - Very good Corrosion resistance.
    - It has very good Bio compatibility.

- **Disadvantages:**
    - Poor machinability especially during milling.
    - Formation of burr on the surface of material at micro level.
    - High cost.
    - Difficultly level is high during the extraction process.
    - When rubs with other materials at high temperature then catches fire.
    - In high performance applications they are not suitable.

2.5. Machining of titanium alloys:

The production of titanium is very small as compared to steel which is about 750 million tons annually. Due to its high demand in aerospace industry about 80% of the titanium that is produced is only for the aerospace. It has many other applications which make its demand very high now-a-days. So to satisfy this demand titanium and its alloys should have very good machinability. This material has very good modulus of elasticity, good resistance to high temperature and very high chemical reactivity with other materials especially at high temperature.[28] This material is somehow good at elevated temperature and can easily be machined but there are some problem related to the machining of titanium and its alloys. Which limit the machining mechanism of its alloys to some extent.

2.5.1. Chatter:

Chatter is the type of vibration, when the vibrations produced during the machining process at the highest level then these vibration called the chatter. This is normally known as the movement between workpiece material and the tool during the machining process. This vibration creates wavy effect on the surface of the workpiece.[29] This effect is more visible in machining process like milling, drilling and grinding. Some researcher consider this problem the most delicate and important problem of all. As this process directly affect the surface quality create irregularities on the surface. As some sort of resonance produced between the workpiece and the cutting tool which is harmful for the workpiece surface and tool wear as well. There are many reasons which may cause the chatter in the machining process.

- Number of flutes of the cutting tool.
- Machining parameters such as feed rate or cutting speed.
- Depth of cut either radial or axial.
- Size of the tool as its diameter.
- Machine parts fixers especially tool holder and fixture to hold workpiece.
- Roughness and irregularity of the workpiece surface before machining.
- Spindle speed.

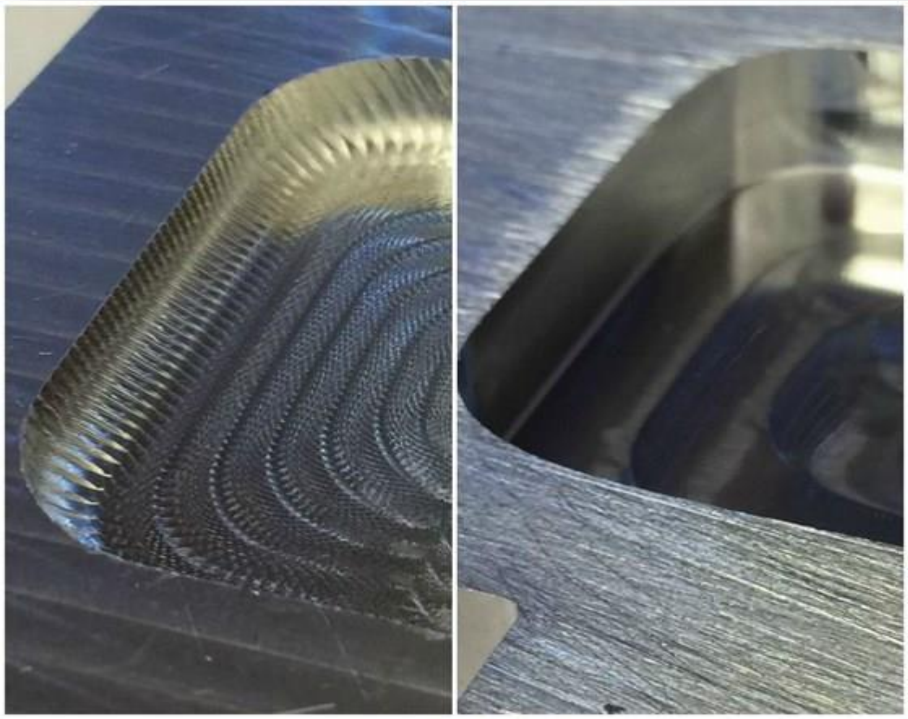


Figure 12: *Difference between chattered surface and smooth surface.*

2.6. Applications of Micro Milling:

As world is moving towards Nano or micro parts and their interactions with human, in future it is to be expected that interactions will become major part of our life.

It is to expect that mini or micro parts production will be increased. That will be able to fulfill our needs of micro assemblies like in the fields of electronics, aero, watches and more.

- Biomedical
- Information technology
- Automobile
- Telecommunication
- Electronic
- Aerospace
- Jewelry
- Watch making
- Turbines

Chapter 3

Methodology

3.1. Workpiece Material:

Ti-6Al-4V is an alloy of titanium used on extensive level in many applications especially in aerospace industry. The workpiece material for this research was Ti-6Al-4V. This alloy is an example of alpha and beta phase (α+β) alloy which is a mix grade alloy [21]. This alloy contain different ranges of alpha and beta phases which define the main properties of these alloy. Range of the alpha phase is between 50 to 90% while the range of the beta phase is between 10 to 40% at room temperature. This property of meta-stability is very good in this alloy, both the stages alpha and beta (α+β) are stable [1, 17, 19]. Because of this meta-stability these alloys can easily be heat treated. To further stabilize this alloy some stabilizer elements are added which contribute in increasing the transformation temperature. To increase the stability of alpha phase some elements like carbon, aluminum and nitrogen are added. While to enhance the stability of beta phase, elements like vanadium, manganese and iron are added [8, 22]. Energy Dispersive X-Ray Spectroscopy (EDS) analysis of the work piece used in this research has observed by using SEM and the results are given in Fig.3 and Table 1.

Table 1. Percentage weightage of sample

Element	Weight%	Atomic%
Al K	5.15	8.81
Ti K	91.03	87.73
V K	3.82	3.46
Totals	100.00	

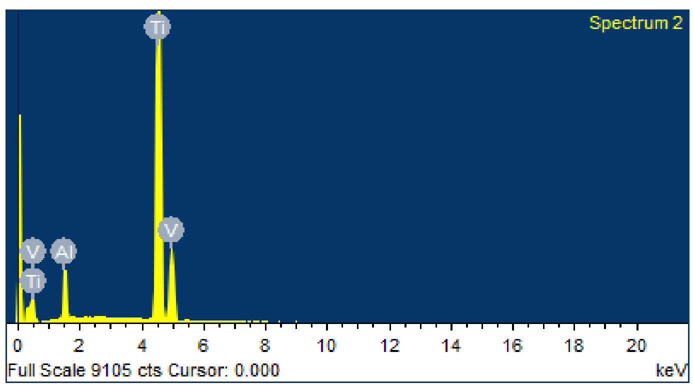


Figure 13: *EDS analysis Graph showing the concentration of different materials*

Table 2: Mechanical properties of Ti-6Al-4V

Tensile Strength (MPa)	Compressive Strength (MPa)	Ductility	Youngs Modulus (GPa)	Shear Modulus (MPa)	Hardness Brinell (HB) max
865-1200	845-1080	0.05-0.18	110-120	41-45	334

Table 3: Physical properties of Ti-6Al-4V

Density (g/cm3)	Melting Point (°C)	Thermal Conductivity (W/m.K)	Latent Heat of Fusion (kJ/kg)	Thermal Expansion (10^{-6}/K)
4.43	11878-1933	7.1-7.3	360-370	8.7-9.1

3.2. Tool Material:

The tool used in the micro milling of Ti-6Al-4V is made up of tungsten carbide. The dimensions of the tool were calculated using tool pre-setter. Its edge radius is calculated by using SEM images as shown in Fig.4. The calculated average edge radius of this tool is 1.5 µm. Some other specifications of the tool and SEM image are given in Table 4.

Table 4: Specifications of the tool material used

Material	Ultrafine Tungsten Carbide
Length	99.64 mm
Diameter	0.50 mm
Type	Flat end mill with two flutes
Helix Angle	30^{0}
Edge Radius	**1.53 µm ± 0.5 µm**

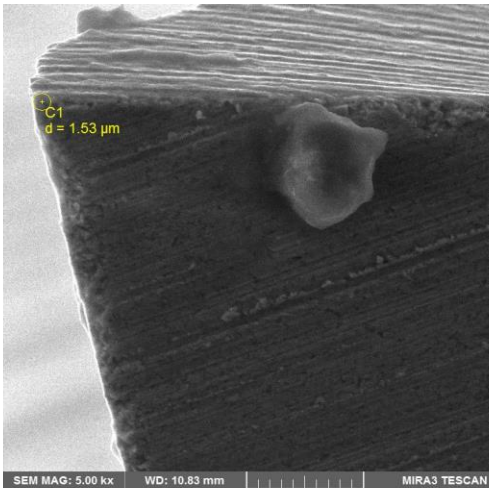


Figure 14: *SEM image of tool showing the value tool edge radius*

3.3. Experimental Setup:

CNC milling machine (MV-1060) was used to perform the experiments of micro milling for two set of batches. The micro level end milling cutting tool was used to make a groove of 10 mm in length on the work piece. The length of the cut selected was 10 mm to avoid the tool wear and breakage. The dimensions of the work piece were 25 mm*10 mm. There were two experimental batch with each batch having different values of their parameters. The detail of experiment is shown in the Fig. 5 and Table 5.

T*able 5:* *Experimental conditions used in this research*

Workpiece	**Ti6Al4V**
Tool of Micro Milling	Tungsten Carbide micro end mill
Milling Type	Full immersion
Fluid for Cutting	Dry Cutting
Diameter of Tool	500 µm
Length of cut	10 mm

Figure 15: *CNC milling machine used for the experiment*

3.4. Design of Experiment:

For the micro milling machining the experiments were designed using Taguchi's Design of Experiments. The array used for this experiment was orthogonal array with the series of L9, which include three levels for each factor. The parameters used in this experiments are cutting speed, feed per tooth and depth of cut. The values for the different levels were selected from the literature and previous research works [1, 19]. Edge radius of tool was measured using SEM and average edge radius was 1.5 µm. Therefore, in this work the range of the feed per tooth selected was greater than the value of edge radius of the tool. The range should be higher so that the effect of residual produced can be lowered, due to this the range of feed per tooth value was selected between 4 and 12 µm/tooth [1, 23].

The value of cutting speed which is mentioned in the literature is between 16 m/min (10,000 r.p.m) and 141 m/min (90,000 r.p.m) [1, 11, 19]. While main concern of this research is on low speed machining. Therefore, the range for the cutting speed was between 5 m/min (3183 rpm) and 10 m/min (6366 rpm). According to Niagara Cutter [24], there is a suggested value of depth of cut which should be used for every tool [19]. This suggested value is referred by diameter of each tool. Therefore, the range for the value of depth of cut was selected between 25 – 125 µm. The two input values for machine are feed speed ($\boldsymbol{V_f}$) and spindle revolutions per minute (N) which can be calculated by using equation (1) and equation (2) respectively. The values are mentioned in the Table 6 and Table 7.

$$N= \frac{\mathrm{Vc}}{\pi \text{ x D}} \quad (1)$$

$$V_f=f\ x\ N\ x\ z \quad (2)$$

Table 6: Experimental batch 1 machining parameters values

Feed per tooth (fz)	Cutting speed (Vc)	Depth of cut (ap)	Feed Speed ($\boldsymbol{V_f}$)	R.P.M (N)
8	5	50	76	3182
8	7.5	75	115	4774
8	10	100	153	6366
10	5	75	89	3182
10	7.5	100	134	4774
10	10	50	178	6366
12	5	100	102	3182
12	7.5	50	153	4774
12	10	75	204	6366

Table 7: Experimental batch 2 machining parameters values

Feed per tooth (fz)	**Cutting Speed (Vc)**	**Depth of Cut (ap)**	**Feed Speed (V_f)**	**R.P.M (N)**
4.5	5	50	29	3183
4.5	7.5	75	43	4774
4.5	10	100	57	6365
6	5	75	38	3183
6	7.5	100	57	4774
6	10	50	76	6365
7.5	5	100	48	3183
7.5	7.5	50	72	4774
7.5	10	75	95	6365

Chapter 4

Result and Discussion

Burr formation is actually the formation of chips at the end of cut. Burr is the small residue of the material on the surface of machined area. Burr formed due to the difference created between tool material and the surface of work piece [13, 17, 19, 25]. As shown in Fig. 6 the burr formed on different sides is not the same distinguish as top burr, side burr, up milling burr, down milling burr the prominent burr formed are side burr and up milling burr [14, 26]. Burr is more visible on up milling side and side burr which directly affect the surface quality.

Tool edge sharpness, work piece plasticity, feed rate and tool rake angle these are the deciding factors in formation of burrs [2, 13]. Burr is more prominent in micro milling as the tool size is very small and the thickness of the burr is dependent on the tool edge radius [23, 27]. The Taguchi experiment is arranged with the values of burr width of up milling side and down milling side. The width of the burr for down and up milling side was measured using SEM images as shown in the Fig. 7 and Fig. 8 and the measure values for all parameters are given in the Table 8 and Table 9.

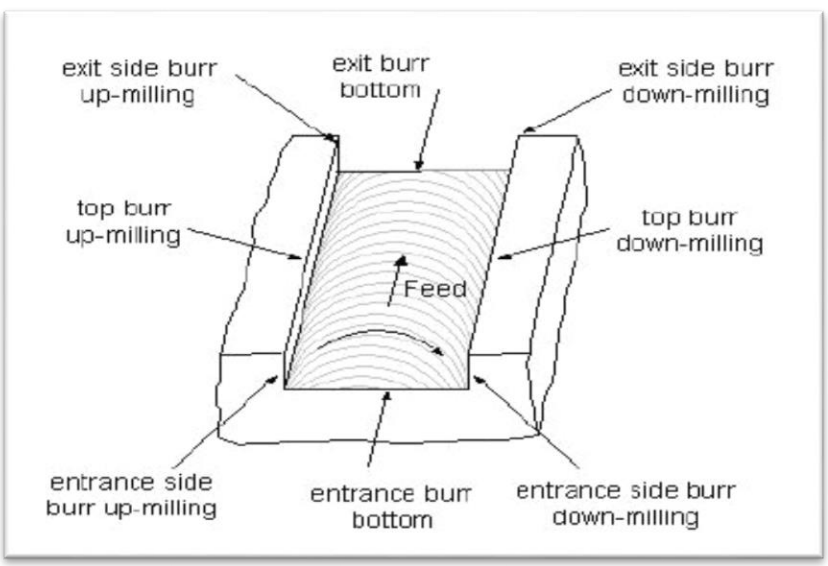
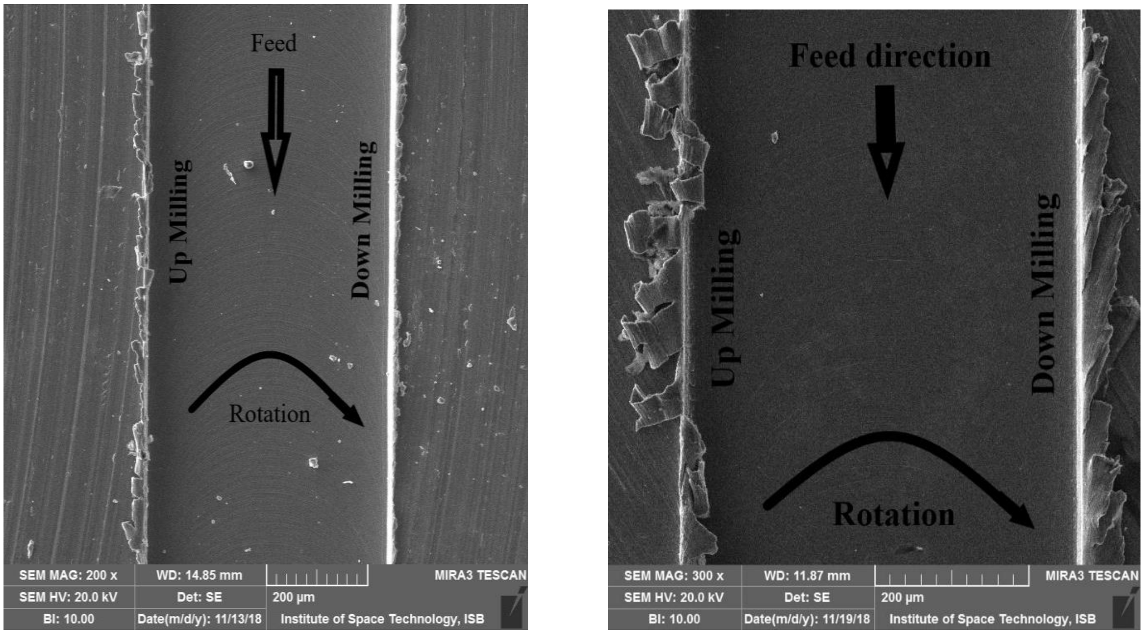


Figure 16: Mentioning the types of burr formed after milling process [13]



(a) (b)

Figure 17: SEM images showing the directions of feed and milling directions (a) batch 1 (b) batch 2

Table 8: Mentioning the burr width of down and up milling side in batch 1

Sr. No.	Feed per tooth	Cutting Speed	Depth of Cut	Feed Speed (Vf)	RPM (N)	Burr width up Milling	Burr width down Milling
1	8	5	50	76	3182	16.01	8.52
2	8	7.5	75	115	4774	17.73	9.84
3	8	10	100	153	6366	15.03	7.63
4	10	5	75	89	3182	15.01	6.22
5	10	7.5	100	134	4774	14.15	5.01
6	10	10	50	178	6366	18.41	7.76
7	12	5	100	102	3182	13.53	6.26
8	12	7.5	50	153	4774	11.08	8.58
9	12	10	75	204	6366	12.05	4.53

Table 9: Mentioning the burr width of down and up milling side in batch 2

Sr. No.	Feed per tooth	Cutting Speed	Depth of Cut	Feed Speed (Vf)	RPM (N)	Burr width up Milling	Burr width down Milling
1	4.5	5	50	28644	3183	10.59	18.27
2	4.5	7.5	75	42966	4774	17.54	16.24
3	4.5	10	100	57288	6365	18.41	15.39
4	6	5	75	38192	3183	11.06	13.23
5	6	7.5	100	57288	4774	13.57	19.93
6	6	10	50	76384	6365	15.12	17.36
7	7.5	5	100	47740	3183	12.33	14.83
8	7.5	7.5	50	71610	4774	16.65	12.76
9	7.5	10	75	95481	6365	13.26	14.29

Surface quality and its integration is most important part in micro milling. Surface finish is different in micro and macro level milling processes. Some factors like chip removal rate, tool vibration and feed rate are the main influential factors deciding the surface quality [17, 28]. These factors decides the accuracy and precision of final machined product. In micro level milling process these factors have dominant effect while in the macro level machining process these factor are not that significant [1, 29].

According to Rehman et al. [19] as feed rate decreases than the edge radius, surface roughness increases (when the tool edge radius is 2 µm). Two factors that greatly affects the surface quality of the product are condition of unused tool and work piece surface [1, 19, 30]. So the roughness problem can be solved by extra machined the surface before micro level machining is performed. The surface integrity can also be improved by ensuring the rigidity and accuracy of the equipment used for the milling process as well as cleaning the tool before use. Surface roughness values were calculated using profile-meter, the calculated values are shown in the Table 10 and Table 11.

Table 10: Values of surface roughness using Profilo-meter for Batch 1

Sr. No.	Feed per tooth	Cutting Speed	Depth of Cut	Feed Speed (Vf)	RPM (N)	Surface Roughness 1	Surface Roughness 2
1	8	5	50	76	3182	252	233
2	8	7.5	75	115	4774	300	291
3	8	10	100	153	6366	275	273
4	10	5	75	89	3182	298	256
5	10	7.5	100	134	4774	227	247
6	10	10	50	178	6366	287	264
7	12	5	100	102	3182	245	302
8	12	7.5	50	153	4774	233	254
9	12	10	75	204	6366	272	288

Table 11: Values of surface roughness using Profilo-meter for Batch 2

Sr. No.	Feed per tooth	Cutting Speed	Depth of Cut	Feed Speed (Vf)	RPM (N)	Surface Roughness 1	Surface Roughness 2
1	8	5	50	76	3182	164	172
2	8	7.5	75	115	4774	173	154
3	8	10	100	153	6366	131	144
4	10	5	75	89	3182	181	167
5	10	7.5	100	134	4774	141	152
6	10	10	50	178	6366	179	173
7	12	5	100	102	3182	146	181
8	12	7.5	50	153	4774	159	174
9	12	10	75	204	6366	161	188

4.1. Application of ANOVA:

The SEM images were used to calculate the burr width and profilo-meter was used to calculate the surface roughness value. After obtaining these results the ANOVA technique was used to analyze the data statistically [1, 19]. ANOVA is a statistical technique which can be used to find out the impact of process parameters on the final results. ANOVA uses some set of equations which are equation 3, equation 4 and equation 5. Finally, equation 6 was used to calculate the contribution value of each process parameter. Sequential sum of square of each parameter SS_A. Which is shown as equation (3).

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

In this equation (3), *A* donates process parameter, at an each level the number of experimental runs is n, *i* is the level, response value at each run is T, j represents number of run and the experimental runs number is N. Sum of squares for total values is (SS_T) was calculated by using equation (4).

$$SS_T = \sum_{j=1}^{N} T_j^2 - \frac{(\sum_{j=1}^{N} T_j)^2}{N} \quad (4)$$

The equation (5) is for the Sequential sum which of error with their squares (SS_e).

$$SS_e = SS_T - \sum_{i=A}^{Z} SS_i \quad (5)$$

Minitab software was used to perform ANOVA for the significance of process parameters. The significance can be observe using the F-test ratio and *P*-value. If the value of F-test ratio for each parameter is small, that means that parameter has low impact on the outcome values. Similar case is with *p*-value which is the probability that gives the estimation either results values would fail or not. If the P-value is less than 0.05 then this means that the chances of failure of test are 5% and chances of success are 95% [1, 19]. After obtaining these values percentage contribution of process parameters can be calculated using an equation (6). In this equation df is degree of freedom and residual mean sum of square is (MSS_{Res}).

$$\%CR = \frac{SS - (df \text{ x } MSS_{Res})}{SS_T} \text{ x } 100 \quad (6)$$

4.2. Burr Formation Analysis:

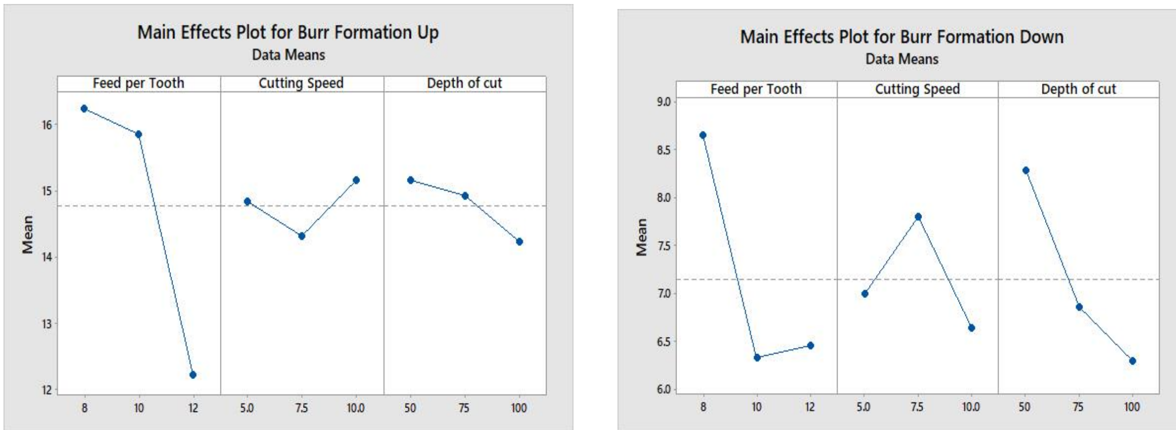
After obtaining the F-value and P-value from ANOVA the contribution ratio of each parameter was calculated. P-value tells us the significance of each parameter that either the specific parameter has influential effect on the outcomes or not. The values of contribution percentages for batch 1 are given below in the Tables 12 and Table 13. Feed per tooth has influential effect on up milling burr reduction in batch 1 experiments with the contribution ratio of 78% and cutting speed with 9% of contribution. While less significance by depth of cut as 3%. All the parameters are significant in the reduction of down milling burr in batch 1. As feed per tooth has 48% contribution while cutting speed has 4% and depth of cut has 35%. For batch 1 the main effect plots of the burr width relation can be seen in Fig. 9.

While unlike trend was observed in batch 2 experiments all the parameters are significant in the reduction of up milling burr. As feed per tooth with 35% of percentage contribution while cutting speed with 24% and depth of cut with 29% contribution. For down milling burr reduction feed per tooth has influential effect 54% of percentage contribution and depth of cut with the contribution value of 34%. While no significance by cutting speed as 3%. The contribution ratios for batch 2 are given in Table 14 and Table 15 and the main effect graphs for each parameter with respect to the burr width in up milling and down milling are given in Fig. 10 for batch 2.

Table 12: *Statistical analyzed values of up milling burr formation for Batch 1*

Source	Df	Adj SS	Adj MS	F-Value	P-Value	Significance	CR %
Feed Per Tooth	2	156.28	78.12	72.06	0.002	Significant	78%
Cutting Speed	2	16.06	8.10	9.23	0.0045	Significant	9%
Depth of cut	2	35.48	17.25	3.42	0.256	Non-Significant	3%
Error	20	205.35	10.21				10%
Total							100%

Source	Df	Adj SS	Adj MS	F-Value	P-Value	Significance	CR %
Feed Per Tooth	2	245.65	122.31	81.06	0.0030	Significant	48%
Cutting Speed	2	32.65	16.32	26.56	0.0042	Significant	4%
Depth of cut	2	45.35	22.21	5.64	0.0050	Significant	35%
Error	20	310.42	3.04				13%
Total							100%



(a) (b)

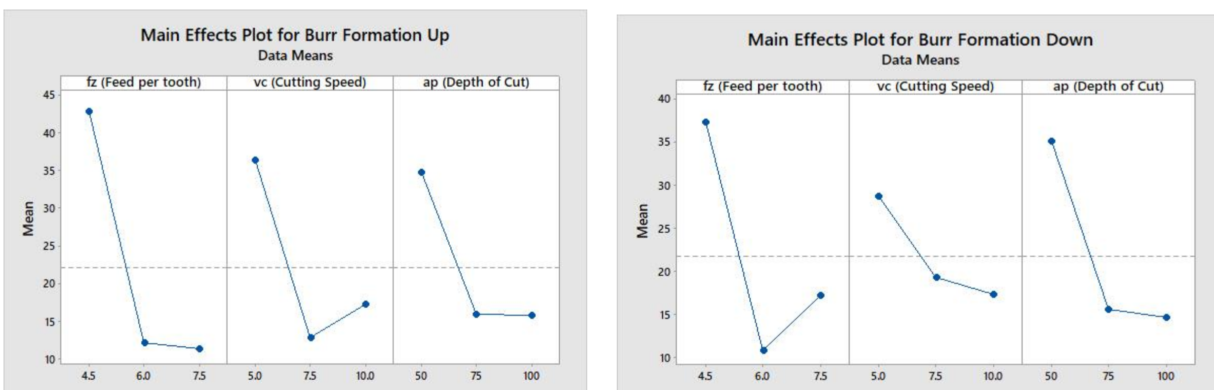
Figure 18: Main effect plot of burr formation for Batch 1 (a) up milling side (b) Down milling side

Table 13: Statistical analyzed values of up milling burr formation for Batch 2

Source	Df	Adj SS	Adj MS	F-Value	P-Value	Significance	CR %
Feed Per Tooth	2	542.35	270.52	125.06	0.0010	Significant	35%
Cutting Speed	2	61.35	31.52	52.62	0.0050	Significant	24%
Depth of cut	2	78.35	35.22	4.65	0.0045	Significant	29%
Error	20	682.35	7.4595				12%
Total							100%

Table 14: Statistical analyzed values of down milling burr formation for Batch 2

Source	Df	Adj SS	Adj MS	F-Value	P-Value	Significance	CR %
Feed Per Tooth	2	324.51	165.35	145.63	0.0025	Significant	54%
Cutting Speed	2	78.24	35.35	62.14	0.2513	Non-Significant	3%
Depth of cut	2	35.54	17.56	8.35	0.0033	Significant	34%
Error	20	460.56	10.534				9%
Total							100%



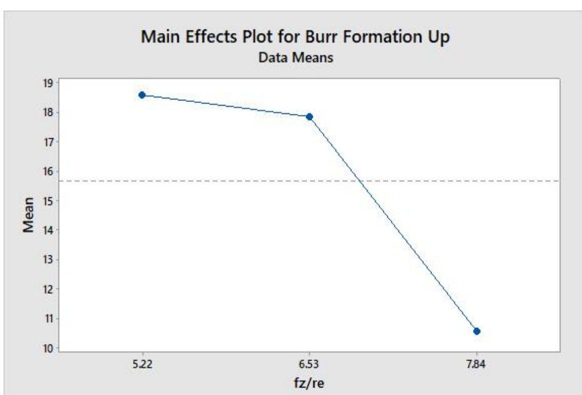
(a) (b)

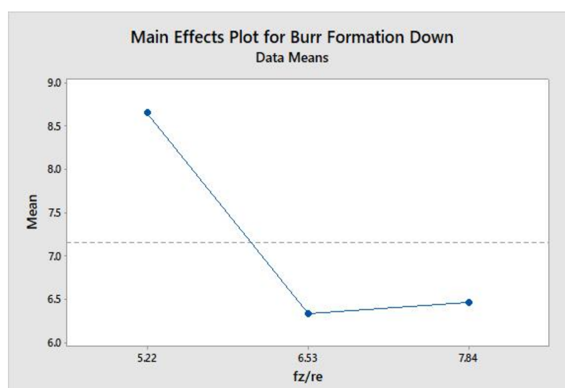
Figure 19: Main effect plot of burr formation for Batch 2 (a) Up milling side (b) Down milling side

In the formation of burr especially on the top side of the micro milling grooves some factors have direct affect. The main factor is the ratio of feed per tooth and edge radius of the tool (f_z/r_e) [1]. If the value of cutting edge radius tool is greater than feed per tooth then this will give best results as it directly affect the chip formation, material deformation and material flow [19, 23]. According Jaffery et al. [1] The range of the ratio should be between 0.9 to 3.0 µm. Furthermore, the plots shown in the Fig.11 and Fig.12 shows that the range of the ratio (f_z/r_e) is greater than the proposed range.

Although, the burr formation is showing decreasing effect. Thus the range of the (f_z/r_e) ratio can be greater and in fact this ratio is the more influential factor in deciding the burr width. Moreover this can be concluded that in the micro milling of Ti-6Al-4V burr formation decreases if feed per tooth value range is one to three times of the value of cutting edge radius of tool. The speed of machining higher or lower but the feed per tooth value followed this trend. After observing the results obtained from the plots in Fig.9 and Fig. 10, it was concluded that not only feed per tooth but the cutting speed and depth of cut were also effecting the reduction in burr width.

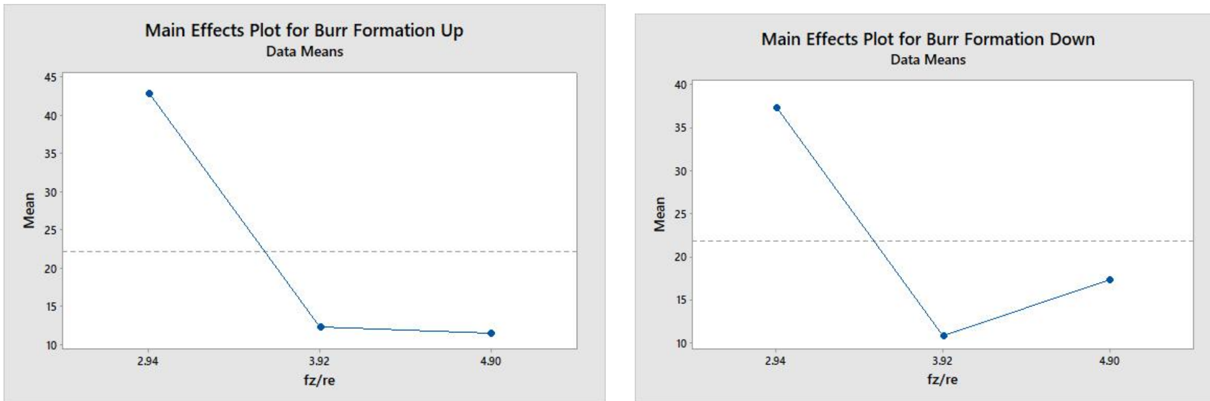
As the cutting speed increases the temperature in shear zone rises while the friction between the chip and the rake face of a tool reduces. [19]. Due to the rise in temperature the welding phenomenon is also reduced between the work piece and the chip [1, 23] After machining the residual material from the work piece is remained attached with surface producing burr on the surface of workpiece. This phenomenon led to the less generation of heat in the chips formation, this results in a reduction of the width of burr formed on the top side of grooves, as can be observed in Fig. 11 (a) and Fig. 11 (b) and Fig. 12 (a) and Fig.12 (b). When the value of cutting speed was low then the burr is formed in larger size as shown in the Fig. 14 and 15. When the value depth of cut is high the chips size is higher because higher depth cut decreases the temperature of the surface and most of the heat generated in this process is absorbed by the chips formed. The larger size of chips reduce the burr formation.





(a) (b)

Figure 20: Main effect plot between the burr width and ratio of (fz/re) of Batch 1 (a) up milling (b) down milling



(a) (b)

Figure 21: Main effect plot between the burr width and ratio of (fz/re) of Batch 2 (a) up milling (b) down milling

4.3. Surface Roughness analysis:

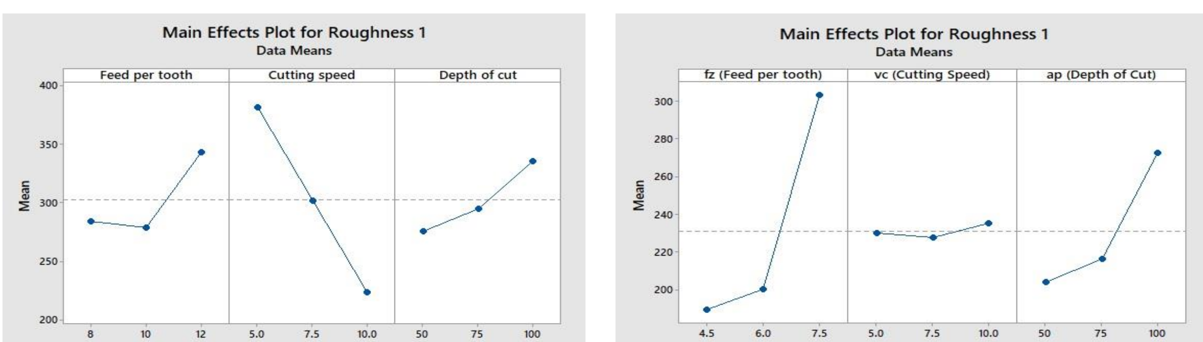
ANOVA for the surface roughness for batch 1 is shown in Table 16, for surface roughness values of batch 1 experimental data the more influential parameter is cutting speed with the percentage contribution value of 76%. While feed per tooth and depth of cut are non-significant parameters with 8% and 2.5% of contribution ratio. As the machining speed increases, the temperature also increases due to which the chips formed remained attached to the surface effecting the surface quality of the workpiece. This heating process effects the surface integrity on higher level. While in surface roughness values for batch 2 which is shown in Table 17 the more influential parameters were feed per tooth and depth of cut with the percentage contribution values of 47% and 37%, respectively. While the cutting speed has no effect on the roughness value with only 1% contribution. The feed per tooth and depth of cut were the main influential parameters during the lower machining speed. The chips size formed during this process was smaller which created problem during machining and the surface become rougher. While comparing the roughness values of batch 1 and batch 2 this was concluded that the level of roughness was higher in batch 2 as can be seen in Fig.13 (a) and Fig.13 (b).

Table 15: Statistical analyzed values of surface roughness for Batch 1

Source	**Df**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Significance**	**CR %**
Feed Per Tooth	2	361.64	180.63	1253.35	0.0723	Non-Significant	8%
Cutting Speed	2	49.54	25.89	213.53	0.0043	Significant	76%
Depth of cut	2	78.35	35.67	35.55	0.5845	Non-Significant	2.5%
Error	20	489.36	15.36				13.5%
Total							100%

Table 16: Statistical analyzed values of surface roughness for Batch 2

Source	Df	Adj SS	Adj MS	F-Value	P-Value	Significance	CR %
Feed Per Tooth	2	247.36	170.35	4568.62	0.0026	Significant	47%
Cutting Speed	2	37.95	17.38	853.52	0.8546	Non-Significant	1%
Depth of cut	2	94.35	46.8	137.52	0.0055	Significant	37%
Error	20	398.58	18.35				15%
Total							100%

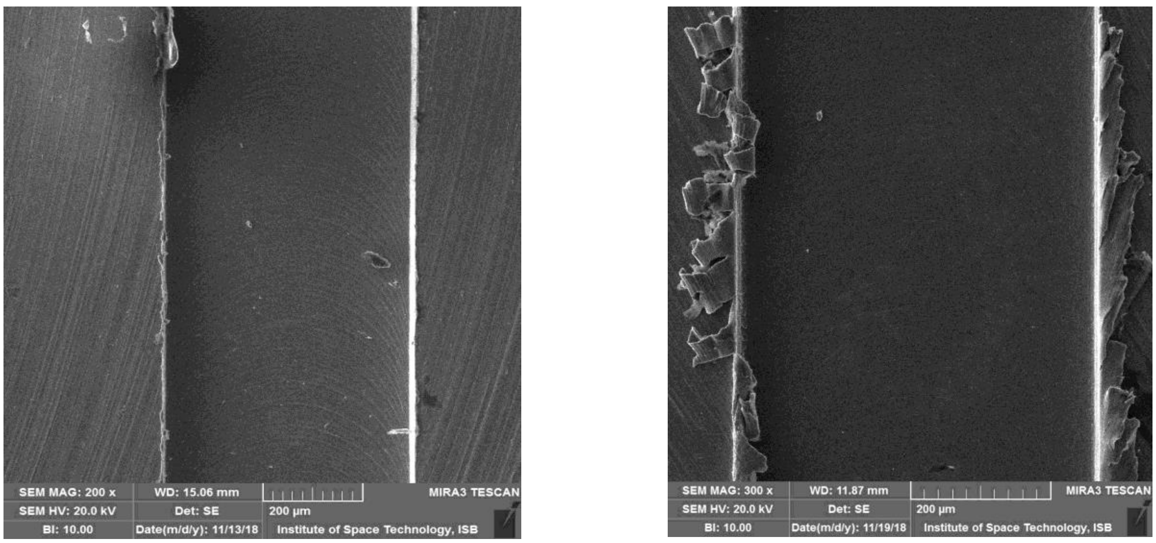


(a) (b)

Figure 22: Main effect plot between the surface roughness and ratio of (fz/re) (a) Batch 1 (b) Batch 2

4.4. Confirmation Test:

After performing the ANOVA analysis and observing the main effect plot it was clear that the depth of cut, cutting speed and feed per tooth, were more effective if the machining speed was kept at optimum level. Burr width was greater on both level when the value of the parameters were either higher or lower. So the optimum level of values were best solution for the minimum burr width as mentioned in Table 18. While the maximum width of burr is observed when the values were too low. To confirm this analysis the confirmation test has run to check the burr width on the top side of milling. The SEM images can easily be shown in Fig.14.



(a) (b)

Figure 23: SEM image for the minimum burr width (a) Minimum Burr (b) Maximum Burr

In the Table 18 the two values of parameters are given for maximum burr width and minimum burr width on both up and down milling side. In the above Fig. 14 and Fig. 15 the burr width can clearly be seen for these values of parameters.

Table 17: optimum values for the best results of burr formation

Function	Process Parameter at Optimum Level			Final Results	
	f_z(µm/tooth)	V_c(m/min)	a_p(µm)	Top Burr Width	
				Up(Avg.)	Down(Avg.)
Maximum Burr width (Batch 1)	4.5	5	50	80.59	65.27
Minimum Burr width (Batch 2)	12	10	75	9.50	7.53

The values mentioned in Table 8 showing the maximum and minimum values of the burr width. After running these test the surface roughness was also calculated. So the relation between burr width and surface roughness can be easily developed. The relation between them can be shown in the conclusion.

Chapter 5

Conclusion

The process parameters are the deciding factors for the surface quality in the micro milling process which can be influential in lowering the productivity and increasing the product processing time. Optimum results for surface integrity and burr width can be achieved by changing the values of process variables. In this research the process parameters selected were cutting speed, depth of cut and feed per tooth. The values for these process parameters were changed to higher and lower levels to observe the influence on burr formation and surface quality of the titanium alloy. By computing the results there are some concluded observations.

1. In experimental batch 1, clear decreasing effect is observed in burr formation for up milling. Feed per tooth has influential effect on up milling burr in batch 1 as 78% and secondly cutting speed with 9% of contribution. While no significance by depth of cut as 3%.
2. While in down milling burr formation is effected by more than one parameter that are feed per tooth and depth of cut. As feed per tooth has 48% contribution while cutting speed has just 4% and depth of cut has 35%.
3. In experimental batch 2 the machining speed is very low the burr formation is observed on a high rate on up milling side. As all the parameters are significant in the formation of up milling burr 1.e. feed per tooth with 35% contribution while cutting speed has 24% and depth of cut has 29%.
4. While for down milling burr formed at lower level hence the feed per tooth has influential effect of 54% and secondly Depth of cut with the contribution value of 34%. While no significance by cutting speed as 3%.
5. So low machining speed setup gives best results for less burr formation on down milling side.
6. Moderate machining speed setup is good for less burr formation on up milling side.

7. In experimental batch 1, when machining speed is slightly higher than cutting speed is more effective in decreasing the surface roughness. The cutting speed has the contribution

of 76%, feed per tooth and depth of cut were non-significant parameters with 8% and 2.5% of contribution ratio.

8. While in experimental batch 2, when machining speed was lowered then feed per tooth and depth of cut was more effective in increasing the roughness values. As feed per tooth and depth of cut have the contribution values of 47% and 37%. While the cutting speed has no effect on the roughness value with only 1% contribution.
9. After concluding this is clear that high machining speed setup is good for better surface finish.

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