ANALYSIS OF MICRO MILLING CUTTING PARAMETERS & TOOL WEAR OF TITANIUM ALLOY (TI-3AL-2.5V) MACHINING

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.

Abstract

With exigent demand, and requirement of miniature products in medical, aerospace, and electronic industry, it is growing need to introduce new low cost, high quality, and high accuracy process capable of producing miniature products. Despite of many advantages and very suitable process for miniature devices, there are still some challenges in micro- milling. Formation of burr is one of the major problems which is being faced in micro milling. Extensive research has been conducted to minimize its formation. Titanium alloys possesses excellent properties which make them first choice for medical & aerospace applications. Titanium grade-5 (Ti-6Al-4V) alloy abounds in literature for most of the applications but there are some applications, where due to excellent properties of titanium grade 9 (Ti-3Al-2.5V), it becomes an attractive choice for precision production applications i.e., pacemaker in medical and honeycomb in advanced aerospace applications.

The current work in this research study aimed to analyze the influence of various process parameters of micro milling operation on the surface quality, burr formation and tool flank wear in micro machining of titanium grade 9. Three levels of each process parameter were taken into consideration. Process parameters were statistically analyzed by employing ANOVA (analysis of variance) for key process parameters. Results of this study show that feed rate is major factor influencing the surface roughness & burr formation with contribution ratio of 62.96 % & 54.05 % respectively, whereas cutting speed and depth of cut were also significant factors for surface roughness with contribution ratio of 20.32 % & 9.27 % while contribution of these two parameters for burr width stood at 21.63 % & 10.91% respectively. Cutting speed is major influencing factor for tool flank wear with contribution ratio of 54.02 % while feed rate contribution stood at 33.18 %. Depth of cut found insignificant factor for tool flank wear. Feed rate was only significant factor in length of burr with contribution ratio of 45.14%. Confirmation tests were conducted at optimum parameters which showed minimum value of burr width, length, surface roughness and tool flank wear.

Key words: Ti-3Al-2.5V, titanium alloy (grade-9), micro-milling, analysis of variance, burr formation

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LIST OF NOMENCLATURE

Notation	**Description**
a_p	Axial depth of cut
f_z	Chip load or feed per tooth
Ra	Average surface roughness
rpm	Revolution per minute
Vc	Cutting velocity
α	Effective rake angle
D	Tool diameter
Df	Degree of freedom
f	Feed rate
F-ratio	Fisher’s ratio (variance)
p	*P* value at 95 % confidence
V_f	Feed speed/velocity
MSS	Mean sum of squares
$\alpha + \beta$	Alpha + Beta
SS	Sum of squares
CR	Contribution ratio
UCT	Uncut chip thickness
DM	Down-Milling

CHAPTER 1: INTRODUCTION

Due to the outstanding combination of properties that Titanium & its alloys possess, its use has increased recently in a number of different industries. Titanium alloys are the best option for use in aerospace applications because they have a high specific strength (the ratio of their strength to their weight) at elevated temperature ranges and exceptional corrosion resistance. It is a suitable option for usage in biomedical applications like surgical implants due to its excellent biocompatibility and resilience to physiological fluids. Its uses have been found in several different industries, including the paper and pulp sector, the food sector (processing), the nuclear sector (waste storage), the electrochemical sector (cathodic protection and extractive metallurgy), and maritime applications, in addition to these key sectors. [1]

Because of a number of the material qualities it has, titanium is difficult to machine. During the machining process, titanium has a tendency to weld to the tools, which may result in chipping off and early tool failure. This tendency is caused by titanium's high degree of chemical reactivity. In addition, since the material has a low thermal conductivity, a rise in temperature at the point where the tool and the workpiece come into contact has a detrimental effect on the life of the tool. It has been discovered that titanium alloys are challenging to manufacture due to the low elastic modulus and strong thermal strength of these materials. Because of these properties, titanium alloys are often considered to be one of the most challenging materials to cut. [2]

It is becoming increasingly important to provide unique techniques that can create microproducts and can do so at a cheap cost, with a high quality, and with a high degree of accuracy due to the growing demand for and requirement of small things in the medical, aerospace, and electronic sectors. One of the most significant uses for the micro manufacturing sector is in the biomedical sector. For these purposes, in tissue engineering micro-devices must be used in addition to minimally invasive tools like stents and aneurysm clips. These micro devices need exact texturing, delicate features, and strict tolerances in order to be manufactured. Due to certain restrictions, such as the complexity of the shape, the geometric tolerances of the product to be created, and the material of the product to be formed, some of the manufacturing technologies now on the market are not suited for the manufacture of tiny things. [3]

Micro milling is an essential manufacturing technology that may be used to make micro size things that have very small features and a high-quality surface. These items can be made in very small quantities. Process Micro-milling presents a number of challenges, despite the fact that it offers a multitude of advantages and is an excellent method for the production of tiny devices. The formation of burr is one of the most significant challenges associated with micro milling. It brings down the quality of the machined product's surface while also lowering the performance of the product itself. As a direct consequence of this, a significant amount of research has been conducted on the elimination and mitigation of burrs. Burr is produced in every subtractive manufacturing process (machining), however the size of burr produced by micro milling is far smaller than that produced by macro scale machining hence removing burr from the product of micro milling may be accomplished with a considerable amount of effort. [4]

1.1 Micro Milling Characteristics

The diameter of the cutting tool is the primary determinant of whether the process is considered macro or micro machining. In micro milling, the tools used for the machining process have a diameter of less than 1 millimeter, while in macro milling, the tools used for the machining process have higher diameters. [5] In contrast to macro milling, micro milling necessitates the consideration of a wide variety of factors in order to get the desired results. Because of the reduction in size of both components, extra studies and research are required to have a better understanding of the relationship between the work piece and the tool while micro milling is being performed. It is impossible to think of the material being cut at the micro level as being homogenous and isotropic, and the grain structure plays an essential role in the process of micro machining. [6]. For example, in their numerical study of orthogonal cutting of steel AISI 1045, Simoneau et al [7] believed the material to be made up of two different behaviors', the first of which was pearlitic and the second of which was ferrite. These behaviors were pearlitic and ferrite, respectively.

The ability of micro machining, in comparison to other micro level techniques, which are utilised for the production of tiny products, offers more flexibility in the production process. Because there are no limitations placed on the cutting of such shapes, the micro machining technique is capable of producing intricate structures such as arbitrary curvatures, three-dimensional cavities, and high aspect ratio features such as long shafts and microchannels.

Micromachining techniques offer a competitive edge over processes that are based on micro electro-mechanical systems because of the cheap costs associated with their setup and the high rates at which they remove material. Because of this, it is an option worth considering for the production of things with individualized specifications or in small batches. In addition, there are limitations placed on the kinds of materials that may be used for the workpieces in micro-machining procedures. This is in contrast to micro-electromechanical system activities, which can utilise a wider variety of materials based on silicon. The very versatile micro-end milling technique is a member of the family of processes that are classified as mechanical machining operations. It is advantageous for the production of tiny devices with complicated properties, such as those found in implants and other types of medical equipment, and it offers a number of advantages in this regard. The standard macro-milling process, on the other hand, is challenging and problematic to perform at a smaller scale. In addition, in contrast to the operations of micro electro-mechanical systems, which can only be performed on a select few materials based on silicon, there are restrictions placed on the types of materials that may be used for workpieces in micro machining processes. The very versatile micro-end milling technique is a part of the family of machining methods that are classified as mechanical. It offers a lot of benefits and is useful for a variety of applications, including the production of intricately designed small devices, such as those used in implants and other types of medical equipment. However, typical macro-milling presents a number of hurdles and difficulties when reduced to a smaller scale. [8] [9] [10]

1.2 Process Fundamentals

Because conventional milling may be thought of as a scaled-down version of micro milling, the two processes have many characteristics in common. These characteristics include tool geometry, lubricants, and coolants, sometimes known as cutting fluids, as well as setup and machine components. Nevertheless, the phenomenon of material removal in the two different machining techniques is not the same and cannot be related in any way. Because shearing stresses are applied on the tool's rake face during conventional macro milling, there is less of a ploughing mechanism. The primary component that contributes to this outcome is the stability of the machine's chatter. The first main regime of any cutting operation is characterized by shearing, while the second major regime is characterized by ploughing. In material removal mechanisms where material is removed by virtue of plastic deformation under tool flank face without the formation of chips, the ploughing dominant region is undesirable On the other hand, cutting devices that remove material along the rake face in the form of recognizable chips favor the shearing dominated zone. During the ploughing dominant phase of machining, temperatures rise, cutting and frictional forces increase, and surface quality decreases; all of these factors contribute to an increased rate of tool wear. Micro milling, which differs from precision milling in that it requires long shearing and ploughing cycles, these two distinct regimes are brought about by a number of different characteristics, such as chip formation, the deflections of the cutting tool, the size effect un-deformed chip thickness (UCT), and the stability of the manufacturing process. It is particularly difficult to predict which mechanism for removing material will be dominant during the micro-milling process because these components may interact with one another throughout the cutting process, creating a more complex and dynamic impact. This makes it particularly difficult to predict which mechanism will be dominant. [11] [12]

CHAPTER 2: LITERATURE REVIEW

2.1 Surface Quality

Surface roughness is the most important factor that contributes to enhance component quality, especially in finishing processes. When producing high precision items with narrow tolerances, the micro milling process calls for a surface finish that is very robust. The primary focuses of surface roughness research have been on modelling the surface roughness or selecting appropriate parameters. In contrast to traditional milling, research investigations looking at the effects of process parameter optimization found that decreasing feed rate and chip thickness may result in ploughing phenomena in micro milling, which in turn increases cutting forces and surface roughness. These findings were discovered as a result of looking at the effects of process parameter optimization. [13] [14] [15]. Because of the significance it plays in the process of micro milling, surface roughness has been the focus of a significant amount of study. A number of different models were chosen for the proposal for the research study, and a number of different parameters, such as tool and process geometry, cutting duration, chip formation dynamics, and special dynamics for micro milling like the ploughing effect and minimum chip thickness, were taken into consideration. It has been discovered via an in-depth assessment of surface roughness research that the three primary cutting parameters that have the greatest effect are federate, minimum chip thickness, and the ploughing process. This conclusion was reached as a result of the enquiry. These three cutting factors were proven to have the biggest influence, according to all of the models that analyzed surface roughness. According to the findings of another piece of research, the cutting-edge radius of the instrument has an effect on the surface roughness. It does this by increasing both the surface roughness and the critical chip thickness. The critical chip thickness is the smallest value that a tool is able to cut away, and it varies from 20 to 40 percent of the cutting-edge radius. [16] [17] [18] [19]

It is frequently claimed that the technical aspects of the micro-end milling process provide one of the biggest challenges to retaining control over the milled surface. This is because the surface topography of microfeatures is at the sub-micrometer level; as a result, it is rather difficult to apply finishing procedures to these microfeatures of tiny goods. The reason for this is due to the fact that microfeatures are very small. The topography of the surface that has been machined has a major impact on the functional performance of micro-objects, such as the amount of friction and lubrication that occurs. It's possible that this impact will show up in the functional performance of very little things. Studies have shown, for instance, that micro milling titanium alloys may produce surfaces that are free from impurities for use in biomedical applications, most notably implants. This can increase the material's biocompatibility and make it more suitable for usage. Patients might get advantages as a result of this in the long term. [20] [21]. As a consequence of this, surface quality, in addition to tolerances and component characteristics, has to be considered throughout the manufacturing process of micro-products. For instance, impacts of lubrication on surface finish improvements, process parameter optimization, and surface generation modelling and simulation methods have all been used in various parametric research studies to obtain control over surface finish in micro size product characteristics. This was done in order to obtain a better understanding of the relationship between surface finish and micro size product characteristics. Surface roughness and burr development should be concurrently regulated so that improvements may be made to the surface quality of microfeatures. [22] [23] [24] [25].

There are a number of studies that have been published in the academic literature about surface formation in micro end milling. According to the findings of a number of parametric research studies, the minimum chip thickness seems to be the most important factor impacting surface roughness. [16]. Single phase materials, such as pearlite and ferrite, achieve a surface quality that is superior to that of multiphase materials. In order to successfully remove chips from the workpiece when doing micro-milling, it is necessary to maintain a minimum chip thickness that is more than some predetermined value. If this does not happen, the tool will cause the workpiece to exhibit elastic or plastic deformations. Because the chip thickness of the previously produced surface will be smaller than the chip thickness of the surface that has not been cut, elastic or plastic deformation may occur when a tool is passed through the previously formed surface. As a direct result of this, both the surface that was generated earlier and the surface that was cut most recently would contribute to the surface profile.

2.2 Chip Formation

Numerous studies have demonstrated that the minimum chip thickness is one of the most important variables in determining whether or not material flow will occur along the rake face of the cutting tool, chip formation will result from the shearing mechanism, or elastic/plastic deformation, also known as the ploughing phenomenon, will occur beneath the flank face of the cutting tool, and this will depend on the material. Other important variables include the minimum chip thickness. [26] [27] [28]. As a consequence of this, it may be thought of as the minimum UCT, given that the generation of stable chips below the value of the specified chip cannot be guaranteed. It's possible that other factors, such as the microstructure of the material, the qualities it has, and the parameters of the process, might all have an effect on this very important number. [29]. If the UCT is lower than a minimum critical value, the ploughing prevalent mechanism of material removal rate will not induce chips to form because it cannot remove enough material to do so. The production of specified chips, on the other hand, would result if the chip thickness was more than the minimum critical value, and the process could be linked to a conventional milling operation. [26]. As a direct consequence of this, chip removal during the micro end milling process would be impossible at shallow cutting depths. Instead, the material removal rate is determined by the elastic deformation of the material caused by the passage of a tool through it. This distortion causes the material to return to its original height after the tool has passed through it. As the depth of the incision is increased, plastic deformation will begin to take place in the material. When the UCT, also known as the threshold value, is achieved, the method of material removal changes from plastic deformation to the development of shear chips. This occurs as the depth of the cut continues to increase. Chips are able to form and be removed from the surface of the material if the depth of cut is greater than the minimal UCT. [30].

The UCT, which is influenced by a wide range of factors, is one of the most important characteristics in the micro milling process since it helps to identify which form of material removal will be used most often. It is possible that there will be a significant runout of tools in relation to the workpiece as a consequence of the combined effects of difficulties such as incorrect toolholder and spindle setup in addition to tool setup concerns. [31]. However, the primary factors that affect the minimum chip thickness UCT are the form and material of the tool, the microstructure of the work piece's material, as well as the microstructure of the work piece's material. A research model for AISI 1045 was also developed when it was determined what the conclusions of the experiments were. It was found that the minimal UCT decreased by a substantial amount when the cutting velocities and edge radii were increased. These prediction models may be used to estimate the minimum UCT ploughing-dominated material removal and cutting parameters, and they can also be used to enhance those parameters. One application of these models is to estimate the minimal UCT ploughing-dominated material removal. [32]. Consequently, the significance of these prediction models cannot be overstated. One of the most prominent instances is engaging in activities involving the use of combustible minerals such as magnesium, which may catch fire when it is in the liquid state and exposed to oxygen. When cutting at fast speeds, there is a risk of starting a fire due to the operation parameters. According to the findings of one piece of research, the importance of having a model that can precisely predict the temperature at the point where the tool and the work piece meet cannot be overstated. [33]

2.3 Build Up Edge

When milling ductile materials at the micro scale level, such as aluminum, steel, and even some titanium alloys, BUEs may be visible on the rake face of the tool. Examples of these materials include: These BUEs are observable on the instrument itself. These BUEs may be seen on the rake face of the milling cutter. This issue is often brought on by chip or substance adhesion on the cutting tool face, which not only diminishes the quality of the finished product but also makes the surface more abrasive. Because of this, there is a negative effect that this problem has on the outputs of the process. In addition to this, as a consequence of this, issues such as increased cutting pressures and shorter tool lifetimes are formed as a result of this. [34]. The BUE is to blame for this problem since it is constantly growing and breaking on the tool face. This also has an effect on the UCT, leading it to have smeared patches, deposits, and surfaces with a surface quality that is below standard machining rates that are low and conventional milling procedures. BUE may be easily recognizable in certain cases. When machining is done on a micro scale, BUEs become a significant issue since even minute deposits of the adhering material have the potential to have a significant effect.

Experts have been studying the phenomenon of BUE formation since the 1970s. It is a well-known phenomenon that has been for a very long time. BUE formation has been around for a very long time. [35]. There has been a significant amount of research conducted on the conventional approach to the machining process. Recent research into the phenomenon of orthogonal cutting has provided data revealing that BUEs impact chip production and cutting ratios under a variety of cutting scenarios. These findings may be seen in the table below. However, up until this point, there has not been any in-depth research done on the influence that BUEs have on the micro level milling process. [36]. Using 3D finite element simulation and modelling of the titanium alloy micro milling process, the authors of one research investigated the impacts of tool edge radius due to wear on the overall efficacy of the process. This was done using the titanium alloy micro milling process. This was done in order to get a better understanding of the influence that tool edge radius wear has on the efficiency of the operation. This was done in order to determine whether or not the procedure was impacted by the edge radius of the tool, which had shrunk owing to repeated use. They have hypothesized that the very high levels of wear that the instrument was subjected to might have been a contributing factor in the BUEs, and they consider this to be a real possibility. [37].

One of the most recent studies looked at the effect that BUEs had on the surface quality of 316L stainless steel when it was being micro milled. This was one of the most current research projects. It was discovered that BUEs were primarily responsible for both the high chip load as well as the poor surface quality. In addition, during the course of their study, they were able to show that theoretical models were capable of accurately anticipating an adequate surface quality even in the absence of BUEs, which was a significant achievement on their part. [38]. According to the findings of another research, the presence of BUEs is the primary factor responsible for the uneven chip load and chip growth that might take place as a consequence of the range of tooth contacts. In addition, they reached the realization that BUEs had a negative influence on the height of the burr. [39]. Other research has shown that coated tools may increase surface integrity by reducing the number of BUEs that are present on the surface. The BUE serves as a cutting edge in addition to lowering the amount of friction that occurs at the interfaces between the tool and the workpiece. Because of this, it is possible to remove cutting tool residue from the surface that has been machined without causing harm to the chip. Based on these findings, it seems that a continuous BUE creation may be able to shield the tool from experiencing quick wear, which would result in increased machining efficiency. Using an experimental method Oliaei and Karpat [40] while micro milling Ti-6Al 4V, the link between steady BUE production and process outputs was investigated. This took place throughout the process. The researchers made sure to take into consideration surface roughness, tool shape, and process forces in their investigation.

It may be beneficial for machine materials to have the capacity to foresee and manage BUE size in addition to having a specific design for the tool. In the future, research on micro-milling absolutely has to include simulations and prediction models that characterize the dynamic dynamics that lead to BUE formation. The workpiece material qualities, tool wear, process parameters, and tool coating are all included in these methods. In addition, understanding the production of consistent and homogeneous BUE as well as chip morphology will have a significant impact on the tool life, efficacy of the machining, and surface quality.

2.4 Burr Formation

One of the biggest issues with employing the micro milling technique is the development of burrs. When material builds up and creates a raised edge on the surface of a workpiece, a burr is created. The accumulation of material is what gives rise to a burr. Burr development is one of the most frequent side effects of the micro milling process, as shown in Figure 1.

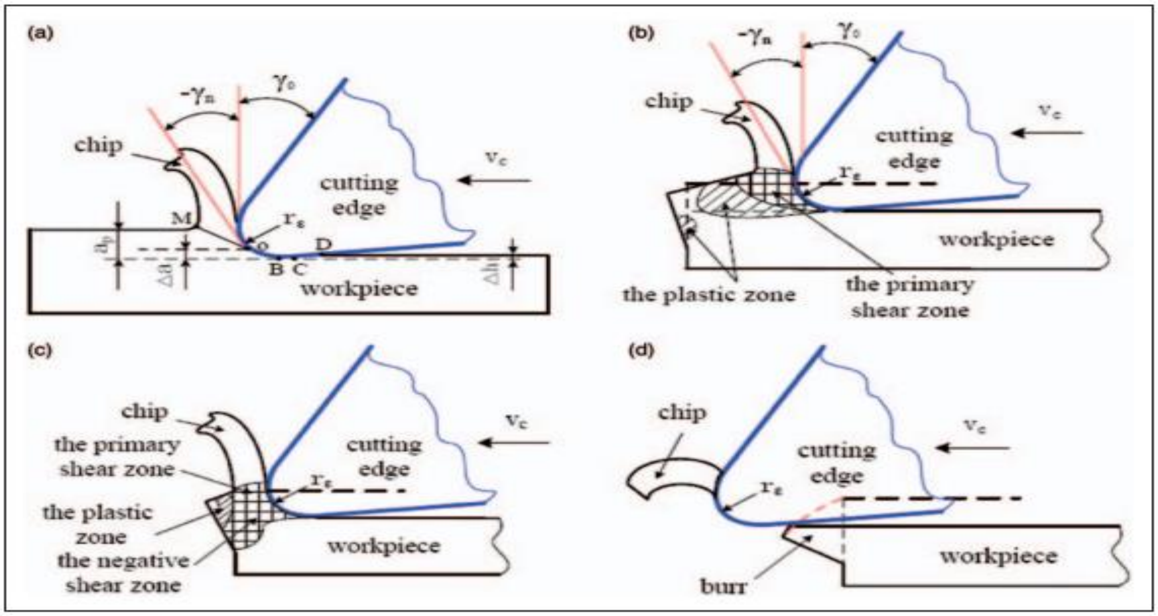


Figure 1: Burr formation in micro milling process adapted from wan, Yi [171] (a) effect of re/ap on burr formation (b) commencement of formation Initiation. (c) Developed burr formation (d) Final exist of burr.

The complicated phenomenon of burr creation, which involves both elastic and plastic deformation, can be influenced by a variety of variables, such as the characteristics of the materials that are used, process instabilities such as tool runout, and the shape of the tool. Burrs are created when a material is deformed in a way that is neither elastic nor plastic. [41] [42] It has a detrimental effect on the quality of the machined surface and substantially reduces the component's ability to provide the required performance and, ultimately, functionality. This influence becomes more obvious during the micro level milling procedure that is used for precision and freeform components. The micro level milling process presents a number of challenges, the most significant of which are the characterization, reduction, and evaluation of burrs. In addition, the formation of burrs results in a decrease in the surface quality of objects that have been machined and may lead to an increase in the cost of machining of up to 9%. This is because the machined parts underwent further labor known as secondary machining, also known as deburring, in order to remove burrs from the holes and edges of the components. The difficulty, need, and degree of deburring would change based on the size, location, and substance of the burr. The design of tool geometry, tool path optimization, and appropriate machine settings should be the key focuses of the research project, with the overarching objective of reducing and ultimately eliminating burr formation that occurs during the process of micromachining (milling). [43] [44]. In one of the studies, it was discovered that while burr cannot be fully eliminated with cutting parameter optimization, it may be decreased to a height of 25 millimeters if the cutting parameters are optimized. UCT and tool sharpness are two further pieces of data suggesting that burr formation may be reduced by adjusting the tool geometry appropriately. [45].

When using the micro milling technique, one of the most significant issues that might arise is the production of burrs. A burr is formed on the surface of a workpiece whenever material builds up and leaves behind an edge that is elevated above the surrounding surface. Because of the steady accumulation of debris, a burr will eventually form as a result of the process. One of the most common unintended consequences of the micro milling process is the formation of burrs, as seen in Figure 1. Saptaji et al. [46] discovered that increasing the amount of taper angle on the micro-milling tool or stiffening the side edge of the workpiece may both reduce the number of top burrs. According to the findings of their study, the tools that create the fewest number of burrs are those that have a large tool taper as well as a large side edge angle. Mold machining requires a draught angle, which is often referred to as a tapering wall angle. While a draught angle is required, it is not always preferred. in accordance with the angle of departure from the plane. Chern [47] devised a method in order to categories the five distinct ways in which burrs may be formed. These methods are referred to as knife-type burrs, wave-type burrs, curl-type burrs, edge breakout burrs, and secondary burrs, respectively. Hashimura et al. classified burrs into a few different groups according to their location, shape, and the processes that led to their creation. Bottom burrs were recognized by Litwinski et al. [48] their toolpath planning technique, but the authors did not provide any explanations about how to prevent or eliminate them. In the third step, Kiswanto et al.. [49] were needed to carry out an important investigation of the burr-creation processes at the top, bottom, entrance, and exit in addition to the influence of tool wear. This can be seen in Figure 4. The researchers also looked at the average top burr diameters for each cutting parameter. This was done so that they could have a better understanding of the relationship between the cutting parameters and the production of burrs. According to the findings of their study, tool wear was responsible for the appearance of bottom burrs more often than top, entrance, and exit burrs over prolonged machining times. As a direct result of this, it was determined that tool wear, which is caused by prolonged machining, is the most significant factor affecting the growth of burrs. The group also reached the conclusion that up milling should be performed during the micro-milling technique in order to produce a component that is free of burrs. This was another one of the group's findings. In conclusion, it was shown that selecting the appropriate cutting settings might potentially reduce the amount of burr that is produced. Their extensive support provided the requisite knowledge of optimum cutting parameter selection, which was required in order to produce an aluminum alloy 1100 product that was free of burrs.

In a recent study, Medeossi et al. [50] introduced a brand-new approach for quantitatively analyzing burrs that is based on optical microscopy. They accomplished this by coming up with an inventive way to take advantage of the fact that they knew how the manufacturing process worked in advance. Additionally, they used void pixels in a manner that was different from what had been done in the past in order to measure multiple geometrical quantities in a manner that was both quick and non-destructive. They evaluated their recommended procedure on pure titanium grade II for slotting operations in micro-milling. The findings demonstrated that their system possessed the capacity for burr assessment during micro-milling operations to be monitored on-machine, and that burr creation could be decreased or even prevented through the optimization of the process. Both of these outcomes were demonstrated by the findings. The scientists did note, however, that precise modelling of the specific machining method was required to be successful. In addition, online measuring systems that rely on vision have their own inherent limitations. It may be difficult and expensive to measure burr height or burr properties over freeform surfaces, for example, if the online measurement system requires a second rotating axis or right-angle optics. This is because different types of surfaces each have their own unique features.

Burrs on the machined surface of a component all contribute to a reduction in quality, accuracy, function, and performance of the component. This is especially the case with regard to the components that are made up of features and micro parts. As a result of this, it is vital for high-quality micro-milling operations to reduce burrs and, if at all possible, get rid of them altogether. This is attainable by doing in-depth research into various methods of burr prevention in addition to other studies aimed at better comprehending the factors that contribute to the problem. In the future, research will concentrate on a number of significant topics, such as the optimization of cutting parameters, the production of toolpaths, tool shape and material, tool coatings, and lubrication studies.

2.5 Size Effect

When it comes to removing material at a micro scale, the scaling effects that occur during a normal micro milling process create substantial challenges. Another term for this phenomenon is the size effect. As was said before, the size effect causes a change in the conventional procedure for the removal of material during the milling process. Since the characterization of this process and the fundamental cause of it have not yet been uncovered, there is a pressing need for more research on this topic. In addition, it demonstrates that there are a number of factors that influence the formation of chips and the manner in which material is eliminated during a micro size process. To put it another way, the size impact is a phenomenon that changes the process of removing material at the microscale and the manufacturing of chips. Shearing is the predominate removing method used in a conventional milling process. This has previously been stated. It has been observed that the influence of size becomes more noticeable when the scale of the machine is reduced to a micro level, which is the level at which the ploughing mechanism predominates. This behaviour presents a significant technical challenge that needs to be addressed in order to prevent the production of tool chips during the cutting process, which increases cutting force, tool wear, temperature, and friction. In addition, preventing the production of tool chips requires resolving a substantial technical problem. Additionally, this behaviour presents a significant learning opportunity for the individual. As was said before, the scientific community is not yet in agreement over the source of the size effect occurrences, which has prevented them from identifying and accepting that cause. This phenomenon persists although a number of studies have been conducted on the subject. There have been prior discussions and deliberations over this matter. [51]. For example, Qin [52] provided a description of the link that exists between the rake angle of the tool and the specific amount of energy required for cutting. The process of chip removal is influenced in some way by both of these basic physical features. The effective rake angle will increase as the depth of cut decreases, which will have an influence on the specific energy as a result. This, in turn, generates an increase not just in the rake angle but also in the specific energy. This is often considered to be the primary reason why the size effect phenomena occur.

The influence of size may be summed up by using a nonlinear increase in the amount of energy required to make one unit volume less of the material that was removed. This occurrence takes place when the UCT is dropped to the same degree as the cutting tool edge radius or grain size. It's possible that the size effect is caused by the fact that a wide variety of factors might have an influence on the chip production and material removal processes. These processes include the synthesis of chips as well as the removal of material. [53]. The conventional milling equipment is not capable of accurately representing the micro-milling process, as has been shown in a convincing and unequivocal manner. This is because just decreasing the size of the system will not provide the same representational model. [54]. At the nanoscale, the effect of size is substantially more obvious, especially in nanometric cutting, which prioritizes ploughing of material above shearing and chip formation. This is because at this scale, the impact of size is much less. Because of this, a number of variables, such as the properties of the material and its microstructure, the parameters of the micro-milling tool, the machining parameters, and the specifications of the tool, will affect this departure from the typical behavior of the tool and the microstructure of the workpiece while it is being machined. [55]. In the next part, we will investigate the physical mechanisms that are responsible for controlling the size effect. These will cover the most typical procedures for removing material, such as shearing and ploughing, as well as the importance of specific energy and the radius of the tool edge.

2.6 Tool Edge Radius

When doing micro milling, it is very necessary to make use of a tool that has a moderate edge radius as opposed to one that has a pointed tip. When a tool with a moderate edge radius is used, this is done to limit the number of failure spots and fractures that begin at the cutting edge of the tool. On the other hand, because of the size effect, the instantaneous UCT is comparable, on the micro level, to the radius of the cutting tool's edge. Micro milling often results in edge radii that are less than 5 m, even though the heights that may be achieved can reach up to 20 m. It would seem to suggest that the radius of the tool edge and the size of the chip being created are of the same order, which would result in an increase in both the amount of cutting force and the degree of surface roughness [56]. When performing micro milling, the tool edge is purposely kept round in order to bestow strength, lessen the likelihood of plastic deformation, and delay the occurrence of tool breakage. As a direct result of this, even the nominal value is positive, which leads to an effective rake angle that is in the negative. Chips would form on the smooth surface of the rounded face of the instrument. [57] [58].

Lucca et al [59] looked at how the tool edge radius affected the amount of force required and the amount of energy used. They concluded that the specific cutting energy required to produce at exceptionally low chip thickness could not be explained by the energy required for shearing and overcoming friction on the tool's rake face. This was one of the discoveries that they made. Under these conditions, the preponderance of ploughing was considered to be the primary contributor to the increase in specific cutting energy. The function of the effective rake angle was the subject of an experimental enquiry that was carried out by Lucca et al. [60]. Below a particular undeformed chip thickness, it has been shown that the thrust force is a substantial contribution, and the ploughing action is the primary factor in the cutting process. In a separate piece of research, Lucca and his colleagues observed that the tool edge condition has a substantial impact on the pressures that are generated when the ratio of the undeformed chip thickness to the tool edge radius is small. [61].

During the process of micro end milling of Ti-6Al-4V, Vipindas et al. [62] Studied the effect that the cutting-edge radius had on cutting force, coefficient of friction, surface roughness, and chip formation throughout with more feed per tooth. It discovered that the feed per tooth within an adjustment range of one millimeter was the most important component. This figure accounted for about one-third of the cutting-edge radius in its representation. Ploughing is the form of material removal that takes place when the size effect is significant, as it is when it is below this crucial level (as shown in Figure 5). To provide a forecast of cutting force models with accuracy, Mogesi et al [63] created a large and complex mathematical model that takes into consideration the edge-radius of the micro-cutting tool. Due to this, it was required to round the cutting edge of the machinery used for micro-milling; however, doing so would considerably limit the size effect. This is because rounding the cutting edge has an influence on the size effect in a way that is detrimental. This exemplifies how it is possible that a radius will not be required if the cutting edge is sharper in order to prevent fracture onset. As a result, the size effect problem would be alleviated, and the shearing mode of material removal would have a greater chance of becoming the dominant mode. In order to meet the demands of this market, more research into the cutting-edge tool form is required.

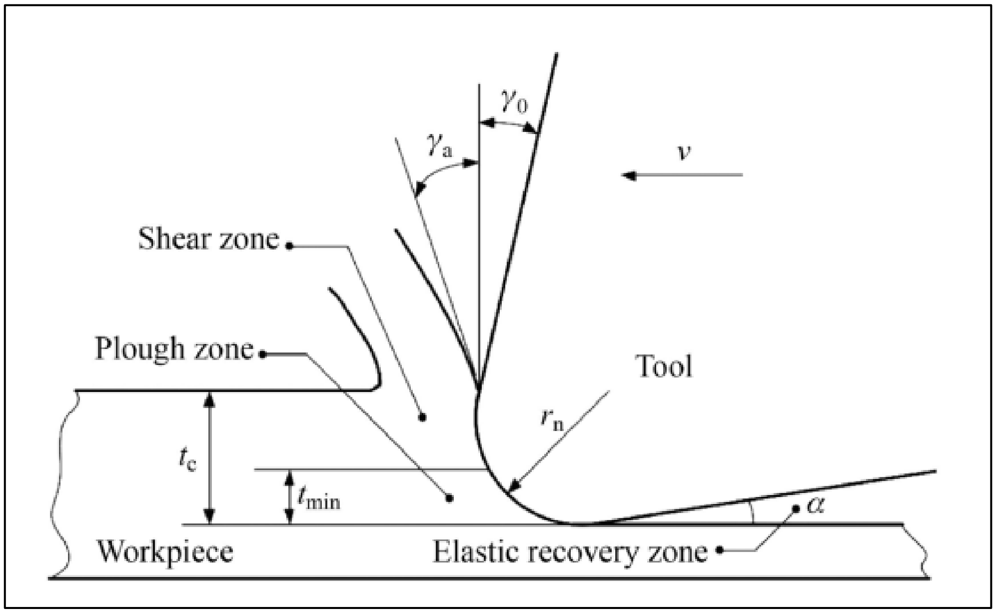


Figure 2: Micro-tool depicting ploughing, shearing, and elastic recovery zones adapted from Gao and Chen [64]

2.7 Tools in Micro Milling

In this section, the characteristics of the cutting tools used in micro milling and their usage will be covered. Although the sizes are geometrically identical, any tool used in Marco scale sizes has a wide range of cutting capabilities. The key dimensions of micro-cutting tools are often on the same scale as the crucial dimensions of chip removal or burr creation techniques, as was already mentioned. Similar to this, the main components of micro-cutting devices often have the same size. Because of its thinness, micro-cutting tools have a short tool life, produce a lot of vibration, and are difficult to check while they operate. Figure 3 displays the many types of micro-milling cutting tools that are often used in a range of settings, including academic and professional ones. [65].

End mills that have the same geometry as end mills designed for macro sizes are often utilized for micro sizes. There are varieties with a single flute (shown in figure 3a), double flutes (shown in figure 3b), and numerous flutes that are all available for purchase. [66] [67]When doing micro-milling, it is essential to keep in mind that the number of cutting edges on the cutting tool should be minimized to the greatest extent possible. This is because increasing the number of cutting edges on a tool makes it less rigid. On the other hand, a device that has a bigger total number of cutting edges may be capable of removing material at a much faster speed (MMR). When it comes to the construction of buildings with sharp edges, these strategies are helpful and advantageous. Because of use, the corner soon begins to round off and lose its sharpness. As a direct result of this, considerable changes are introduced into both the tool geometry and the

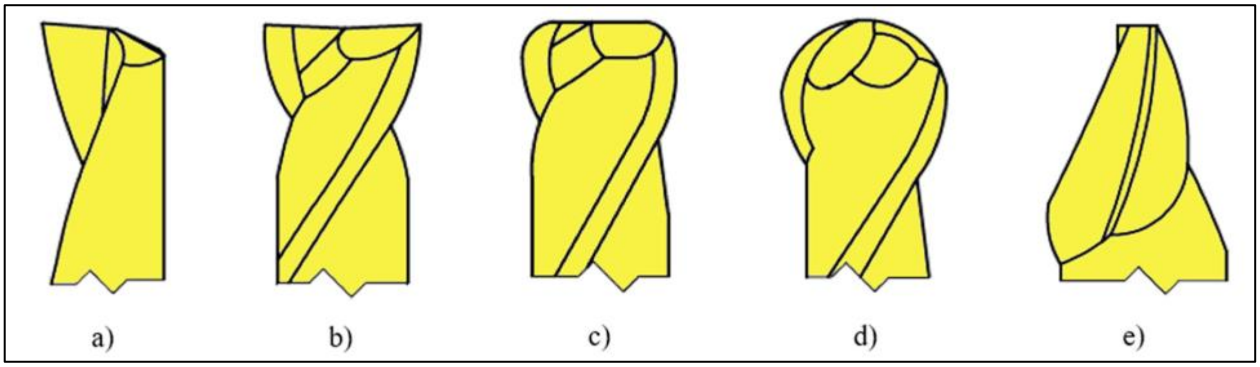


Figure 3: Types of Micro tools used in micro milling adapted from Balázs, Barnabás Zoltán, et al. [172] (a) single-fluted flat end (b) Double-fluted flat end (c) corner radius end mill (d) ball-end (e) tapered micro end

technique, as well as the microstructures that are produced. Additional unfavorable characteristics are associated with this kind [68] [69]The usage of artificial diamond in single-fluted geometries is fairly common, and although this may result in a very sharp cutting edge, it also results in an increase in vibrations. [70] [71].

Figure 3c displays a diagrammatic illustration of a micro flat end mill that has a corner radius. In recent years, this design has seen increasing popularity as a direct result of the enhanced edge stability that it provides. In comparison to prior iterations, the corner radius is very resistant to wear. In addition to that, this milling equipment is able to produce intricately curved surfaces in three dimensions. In addition, the design is adaptable enough to be used with higher feed rates in situations where the depth of cut does not need to be as precise. The primary cutting-edge angle is lowered as a direct result of this circumstance, which results in chip thinning as a side effect. Because of the radius, the axial force component will be much higher in magnitude. When contrasted with the cutting force, this causes the tool to undergo less bending-directional deformation, which, in turn, may contribute to a reduction in vibration. [72].

The diagram depicting a ball-end micro mill that may often be seen in academic literature is shown in figure 3d. Complex three-dimensional geometries may be easily manufactured with this kind of material. Having said that, there are certain constraints. For instance, when milling flat surfaces, the cutting speed is extremely low near to the tool center point (TCP), and the problem of minimal chip thickness emerges as a consequence of the phenomena of chip thinning. This is because the TCP is in the center of the tool. However, these issues may potentially be alleviated to some degree by using the push-milling or pull-milling processing methods, even if doing so would need the use of a more costly and complex (4 or 5-axis) machining center. [73] [74]. Tapered micro-milling tools, shown in Figure 3e, are often used for this process as well because of their ability to decrease burr production. There are also other articles that make use of specialized micro tools to make the process more efficient. [75].

2.8 Cutting Temperature, Tool Wear & Failure

When working with metal, one of the most important considerations to give attention to is the cutting temperature. This is because the cutting temperature has a big impact on the amount of tool wear that happens. On the other hand, in order to get the most usage out of one's tools, each and every machining operation has to take into consideration the amount of tool wear that occurs over the course of the process. When performing tasks such as milling, it is possible that significant heat will be generated as a result of plastic deformation and friction at the point where the tool and the chip come into contact with one another. The temperature, which may reach very high levels, has a considerable impact on the mechanical properties of the material. In 2005, Liu [76] noticed that the strength of a material decreases as the temperature rises, and that the opposite is true when the temperature decreases. When metal crystals are exposed to plastic deformation, it is believed that the mobility of dislocations and their interactions with one another are the primary factors that determine the strength of the material. The theory of dislocation mechanics may accommodate this observation. The temperature influences the thermodynamic chance that dislocations will acquire enough energy to reach the potential peak. This possibility becomes more likely if the temperature continues to climb. As a direct consequence of this, it should come as no surprise that there will be a lessening of the flow stress. Liu [76] discovered that the temperature gradient within the chip is affected by the thickness of the uncut chip.

It is believed that the variable in the machining process that has the greatest influence on the amount of tool wear is the cutting speed. This is due to the fact that higher cutting speeds produce more heat, which in turn quickens the rate at which tools get worn out. Tool wear is the primary contributor to accuracy issues, which may manifest themselves in a number of different ways, including an increase in cutting force, a change in dimensions, or the need for a new tool [77].

2.9 Process Inputs in Micro Milling

In any normal manufacturing process, the outputs, such as cutting force, surface quality, and tool wear, are known to be influenced by variablesisuch as the workpieceimaterial, tool settings, toolipath, and cutting fluid. Other examples of input variables include the workpiece material. These input parameters are known to influence a large number of different outputs, of which various are only a few examples. Due to the fact that the microstructure of both the tool and the workpiece must be taken into consideration, At the microscale, the influence and multifactor effect of process inputs are much more important.. As a direct result of this, they are one of the primary reasons why there is cause for concern regarding the performance of the micro milling process. A quantitative study of the impact of each variable and an understanding of the physics of the process are necessary in order to quickly identify and take into account the input parameters that significantly influence the output quality. This will allow one to quickly identify and account for the input parameters that significantly influence the output quality. To optimize the process for each of the machining parameters can seem like a difficult task, but in theory it shouldn't be.

On the other hand, recent major improvements in prediction models, numerical simulations, statistical analysis, and experimental research have made it possible to accurately study the wide range of factors that affect the results of the process. Because of this, a thorough review of past research on input parameters and how they affect the outputs of the micro-milling process is given.. [78].

2.10 Process Outputs in Micro Milling

To get started, it is necessary to conduct a speedy investigation and analysis of the primary process outputs in order to identify the influence that the process inputs have on those outputs. Taking a closer look into prediction models, in addition to ongoing theoretical and practical work, might be the key to discovering the micro-milling technique that produces the best results for a wide variety of difficult-to-machine materials. It has been shown that the cutting force is not significantly affected by the spindle speed within the range of cutting parameters that are selected but when the feed per tooth is close to the radius of the cutting edge, the cutting force tends to grow at first. This means that the way the material is taken away is more like breaking. As the feed per tooth is increased, it has a tendency to drop in an almost linear fashion, and the shearing technique of material removal begins to take control. [79] [80] [81].

As the cut progresses, the strength of the cut, the temperature of the cut, as well as the depth and width of the cut, all increase. When the feed per tooth is increased in this situation, the cutting temperature first rises but subsequently begins to fall, with the UC serving as the point at which the trend begins to change. However, the temperature of the cut will rise in tandem with an increase in the spindle speed. Surface quality, which is often measured as roughness in the surface, and the left micro-milling tool artefacts on the machined surface, is another important factor that should be taken into consideration when determining how effective the micro-milling process is. Surface roughness is another important factor. [134] [82]. Surface roughness, as well as artefacts or grooves, may be predicted using a comprehensive floor surface model developed by Lu et al [83]. This model was constructed so that it can account for a variety of cutting and tool conditions. This was accomplished successfully by using the model. When the spindle speed was raised, there was an initial drop in the surface roughness, followed by a subsequent rise in the roughness. Regardless, the surface roughness increased as the feed per tooth and depth of cut were increased. According to the authors, more experimental data are needed to figure out how each cutting parameter and how they interact with each other affects the process outputs. Additionally, the authors note that this is necessary in order to evaluate how each cutting parameter affects the process. Lu et al. [84] built on this study by investigating the factors that influence the curved surface roughness. The feed per tooth, the axial cutting depth, the radius of the ball end mill, and the speed of the spindle are some of the factors that may be adjusted. Additionally, a surface roughness prediction model was developed by them in order to improve the accuracy with which cutting parameters for Inconel 718 micro-milling were selected. This was done to ensure that the project's needs were satisfied.

2.11 Microstructure of Workpiece

Because it is no longer possible to represent the structure of the workpiece at the microscale as being homogenous, very in-depth investigations are necessary in order to correctly create trustworthy analytical models. These investigations are required to understand not just how the microstructures of multiphase materials impact things, but also how the micro-milling process affects things. Neither of these aspects can be understood without the other. It is possible to develop more accurate prediction models for the design and machining phases of the process if one uses better models and has a deeper grasp of the microstructure and machinability of the material. This will allow one to construct more accurate models. This will, in addition to increasing the quality of the surface, minimize the amount of wear and tear that is placed on the equipment. When the size effect and chip generation are highly relevant at the microscale, the machining process must take into consideration how multiphase material microstructures operate in an asymmetric fashion. This is because the size effect and chip formation are very important at the microscale. Consider this, since it is among the most essential aspects of the situation. [85].

Fairly early on in the process of modelling, Vogler et al. [86] developed a straightforward mechanical model for micro-milling. This model took into consideration the various phases of the various materials very soon after the modelling process began. An article on this model was written by Vogler and co-authors. This model takes into consideration not only the varying degrees of cutting force but also the various phases and the ways in which each of those phases impacts the overall amount of cutting force that is applied. According to the working idea that the researchers have developed, microstructural effects might be responsible for more than 35 percent of the energy that is included in the cutting force. Attanasio et al. [87] Conducted research on the influence of material microstructures on cutting force by conducting an in-depth analysis of four distinct microstructures of Ti-6Al-4V alloy. These microstructures were described as bimodal, completely equiaxed, fully lamellar, and mill annealed, respectively

The study indicated that totally lamellar microstructures had decrease intensity of cutting forces, and less tool wear than other microstructures. To construct a more precise design of tool-workpiece, it is necessary to have a comprehensive grasp of the ways in which cutting force might vary. This will result in additional improvements to the method for micro-milling as well as new views into the design of microstructures that can be milled using the micro-milling technique. Elkaseer et al. published a model in [88]. that was designed to simulate the process of surface formation that occurs during the micro-milling of multiphase materials in terms of the surface roughness. Using the model that they had developed, they demonstrated how to optimized the process for multiphase materials and predict the surface quality that would be produced after machining in a variety of different machining scenarios. The fact that the model takes into consideration the micro-burrs at the phase borders is an essential component.

CHAPTER 3: METHODOLOGY & EXPERIMENTATION

3.1 Work Piece

Titanium alloy Ti-3Al-2.5V work piece for the experimentation purpose was selected. Workpiece was wire-cut from the 12 mm thickness disc. The dimension of the work piece was 168x12x12 (L x W x H). fig 5 shows the work piece used in the experimentation. Ti-3Al-2.5V is a near two phase α & (α + β) alloy and refers as grade 9 titanium. Conventionally, titanium alloys are divided according to the phases that defined the microstructure of the alloy at room temperature following an annealing process. Thus, the following categories can be used to group titanium alloys: α+β alloys (which contain both and -stabilizers), β-Ti alloys (which are typically divided into stable and metastable), and α-Ti alloys, which are single phase materials. Sometimes, α-Ti alloys have a small number of stabilizers (1-2 wt. percent), allowing for the production of a minor amount of phase. These alloys are referred to as casi-α or super-α alloys, with the Ti-3Al-2.5V alloy serving as an example. Precisely, the aeronautical industry, where it was initially used to produce hydraulic and fuel structures in conventional aero planes, is responsible for the development of the Ti-3Al-2.5V alloy, which has intermediate performances (i.e., mechanical and corrosion resistance) compared to titanium and Ti-6Al-4V. Details of properties of titanium grade-9 are given below.

Figure 4: Work piece used in this research

3.1.1 Mechanical properties:

Mechanical properties of Ti-3Al-2.5V alloy are tabulated below.

Table 1: Mechanical properties of Ti 3Al 2.5V

Tensile Strength (MPa)	Yield Strength (MPa)	Elastic Modulus (GPa)	Shear Modulus (GPa)	Poison's ration	Hardness Brinell (HB) max
620	530	100	44	0.3	256

3.1.2 Chemical properties:

Chemical analysis of the sample was carried out by using metal analyzer and tabulated below are the chemical composition of the sample.

Table 2: Chemical Composition of workpiece of Ti -3Al- 2.5V

Titanium Ti	Aluminum Al	Vanadium V	Iron Fe	Silicon Si	Other
93.76	3.7	2.18	0.048	0.040	Balance

3.1.3 Physical Properties

Following are the physical properties of the grade 9 titanium alloy

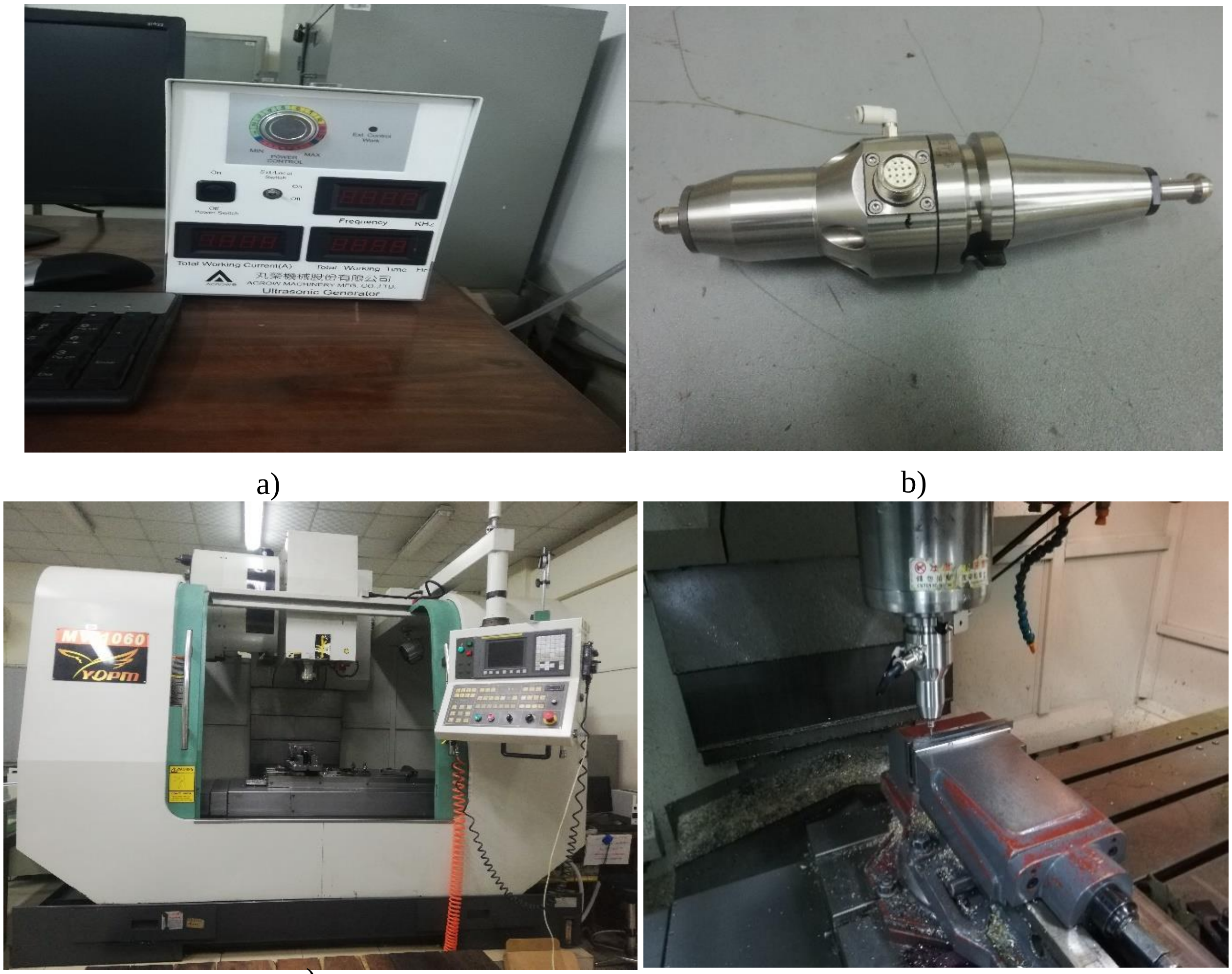
Table 3: Physical properties of Ti -3Al -2.5V

Density (g/cm3)	Melting Point (ºC)	Specific Heat Capacity (J/g°C)	Thermal Conductivity(W/m-K)	Thermal coefficient 20.0 - 540 °C, µm/m-°C
4.48	≤ 1700	0.525	8.30	9.97

3.2 Experimental Setup

Tests were carried out on a FANUC MV-1060 conventional speed machining center. Fig 6 shows the experimental setup which was employed in this investigation. The maximum spindle speed that can be achieved was 800 but the process parameters were selected where machining speed was maximum 48000.

Therefore, an extension ultra-precision high speed spindle with accuracy of 0.1 µm was used for performing experiments to achieve high speed as shown in fig 3d. Maximum 80, 000 rpm can be achieved by this spindle.



a)

b)

c)

d)

Figure 5: Experimental setup (a) RPM Control unit (b) HES810-BT40 Ultra precision high speed spindle (c) FANUC MV-1060 Conventional speed machining center. (d) Experiment being performed

Experiments were conducted based on the L9 array of Taguchi's robust design of experiments approach. Two independent runs with new tool were conducted to check the repeatability of the results.

3.3.1 Process Parameters Selection

Three levels of each parameter of processes have been considered for this research study the detail is given below.

3.3.1.1 Feed

First, tool edge radius was measured for tools which was 5 µm by using Olympus digital microscope. When dealing with miniature products the surface quality requirement is more stringent as compared to macro product. It has been reported in a study that surface roughness is lower when feed rates are below edge radius, therefore, feed below edge radius has been selected in this research study.

3.3.1.2 Cutting Velocity

In literature review it has been observed that cutting speed for titanium alloy (Ti-6Al-4V) has been varied from 10, 000 rpm to 90,000 rpm whereas for titanium grade 9 have not been reported yet. Jafery al has used 25, and 50 Vc therefore, three level i.e., 25, 50 & 75 have been selected in this research to have comparison for grade 9 & grade 5 alloys.

3.3.1.3 Axial Depth of Cut

Niagra tool [89] cutter company has recommended a formula fro the axial depth of cut which is given below:

For Tool Diameters 1/8" and under: ap = D X (min 0.25 & max 0.05.)

Where D = tool diameter, here for this research 5 µm or 0.5 mm tool diameter was used

Therefore, min axial depth = 0.5* 0.05 = 25 µm

Max axial depth of cut = 0.5* 0.25 = 125 µm ,

Based on literature review and this range of axial depth of cuts three level of depth of cut are selected i.e., 30, 60 & 90 µm. Detail of Prosses parameters is tabulated below

Spindle speed (n) and feed velocity Vf was calculated based on following equations:

$$\mathbf{Vc = n . \pi . D} \tag{1}$$

$$\mathbf{Vf = f . n . z} \tag{2}$$

Table 4: Process Parameters for Micro milling of Ti-3Al-2.5V

No of Exp.	Feed Below Edge Radius (fz (µm tooth-1))	Cutting Speed VC (m min-1)	Depth of Cut ap (µm)	n (rpm)	Vf (mm/min)
1	0.25	25	30	16000	8.02
2	0.25	50	60	32000	15.96
3	0.25	75	90	48000	23.95
4	0.45	50	90	32000	28.74
5	0.45	75	30	48000	43.03
6	0.45	25	60	16000	14.40
7	0.65	75	60	32000	62.16
8	0.65	25	90	16000	20.8
9	0.65	50	30	32000	41.47

3.3.2 Experimental Conditions:

Detail of experimental conditions and tool specifications employed in this investigation are tabulated below:

Table 5: Experimental conditions

Condition	Specification
Workpiece	Ti-3Al-2.5V
Cutting Fluid	Dry Cutting
Milling Type	Full Immersion
Cutting Tool	Micro End Mill
Number of Flutes	2
Tool Diameter	500 µm
Helix Angle	30^o
Tool Material	Tungsten carbide
Length of Cut	12 mm

CHAPTER 4: RESULTS AND DISCUSSION

After experimentation phase results were obtained with utmost care. The results of this studies are surface roughness, flank wear of the cutting tool, burr width in down milling. Slots were observed under DSX1000 Digital Microscope and results were compiled. Results are tabulated below. Burrs were quantified by measuring their width. It can be seen in fig 6 that burr width in down milling is greater than up milling, therefore, in this study burr width of down milling was taken into consideration.

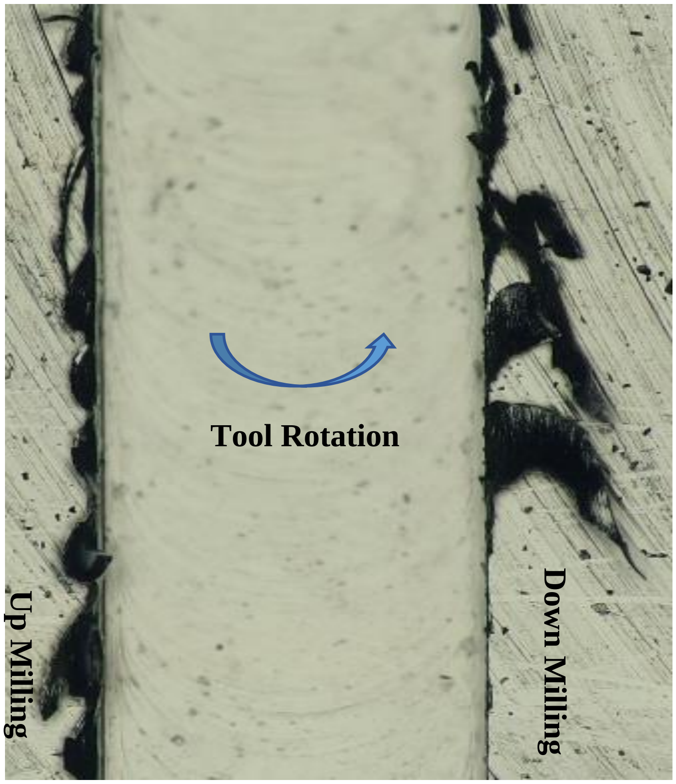
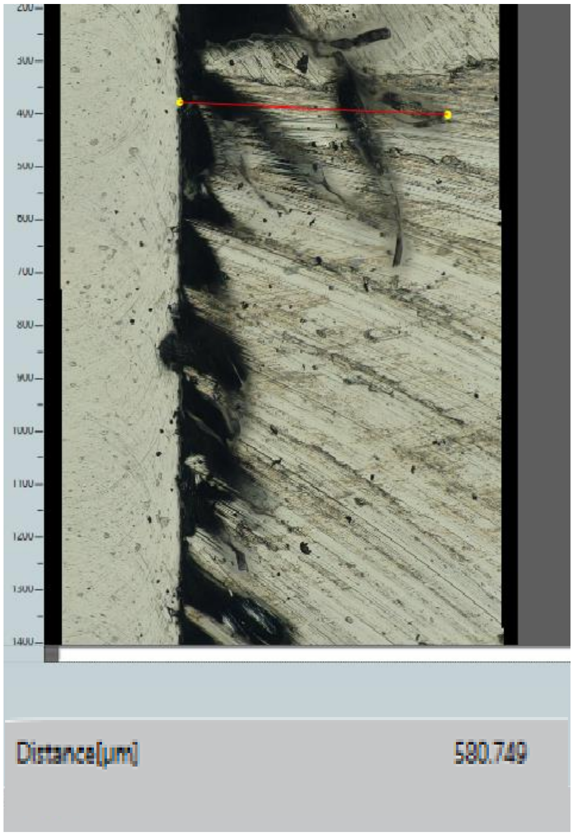


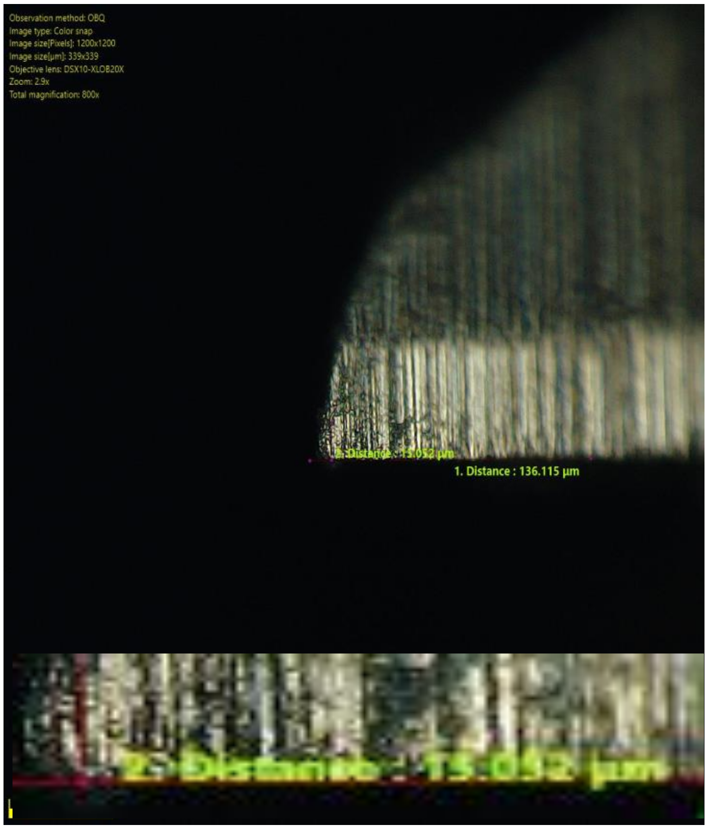
Figure 6: Down & up Milling side burr formation

There are three types of burrs that have been considered in literature review studies viz entry, exist and top burr. Herein only top burr is considered for analysis and only worst case is considered in all the measured burr parameters. Surface roughness is measured at the middle location of the slot and three values were obtained for each slot their average value is used for analysis. Tools were observed before & after experimentation to ensure better quantification of their flank analysis. BUE were observed on tool surface which was removed by cleaning tools by alcohol so that tool edge boundary can be clearly demarked. It has been observed that under the same process parameters the responses were varied. It is mainly due to the combined effect of machine, human errors & variations of tool quality. Variation in surface finish is quite low whereas variation of results in burr width is significant.

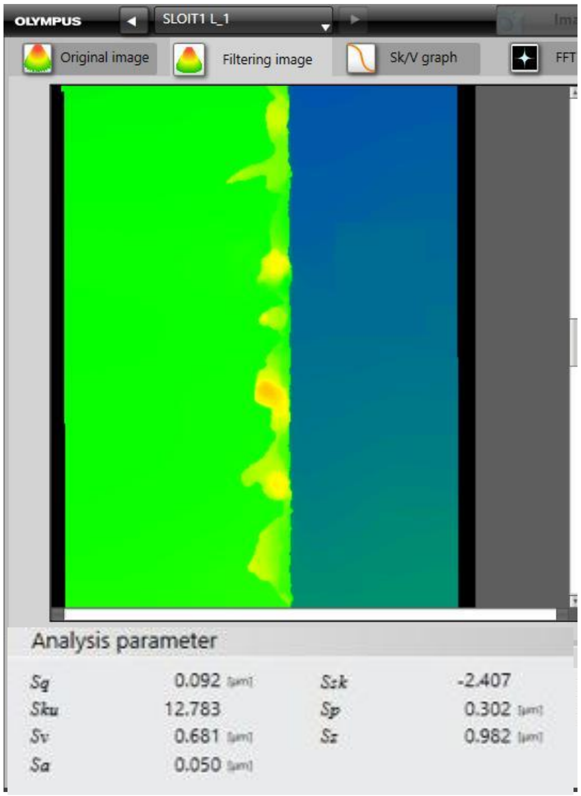
4.1 Olympus Digital Microscope Images



a)



b)



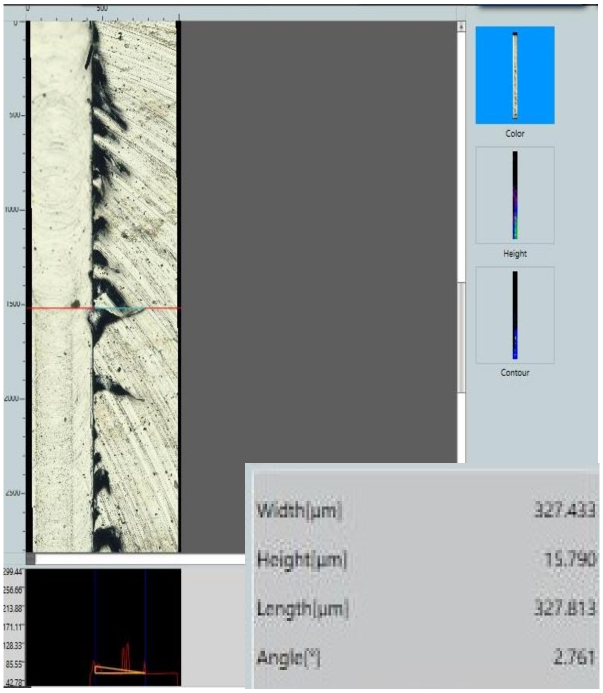
Analysis parameter

Sq	0.092 [µm]	Ssk	-2.407
Sku	12.783	Sp	0.302 [µm]
Sv	0.681 [µm]	Sz	0.982 [µm]
Sa	0.050 [µm]		

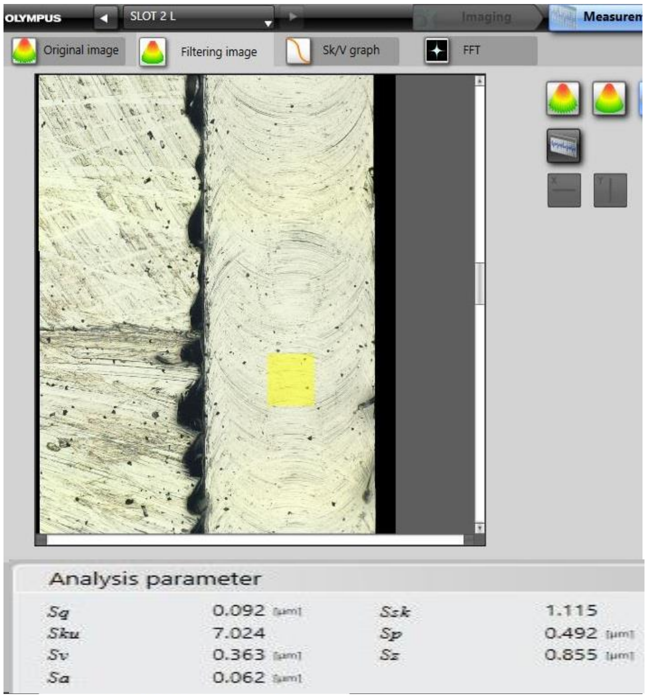
c)

Figure 8: Images of result at fz = 0.25(µm/tooth), Vc = 25(m/min), & ap = 30 µm.

a) Burr width b) Tool wear c) Surface roughness



Width[µm]	327.433
Height[µm]	15.790
Length[µm]	327.813
Angle[°]	2.761

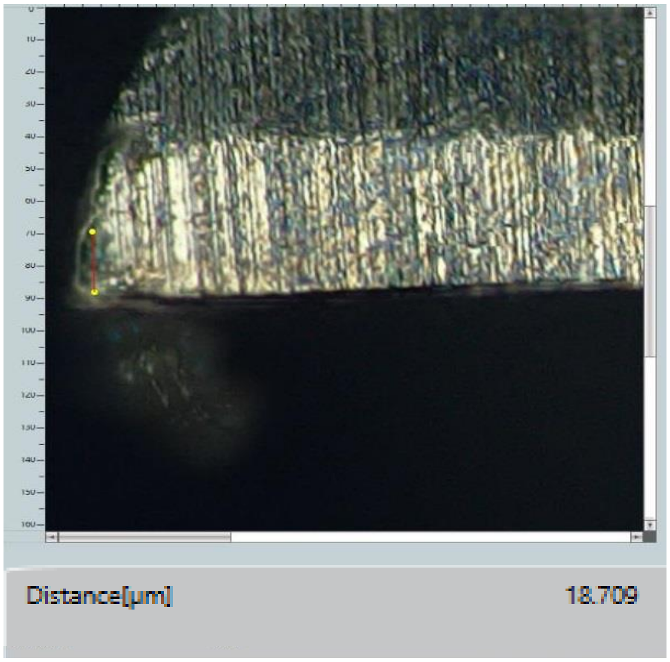


Analysis parameter

Sq	0.092 [µm]	Ssk	1.115
Sku	7.024	Sp	0.492 [µm]
Sv	0.363 [µm]	Sz	0.855 [µm]
Sa	0.062 [µm]		

a)

b)

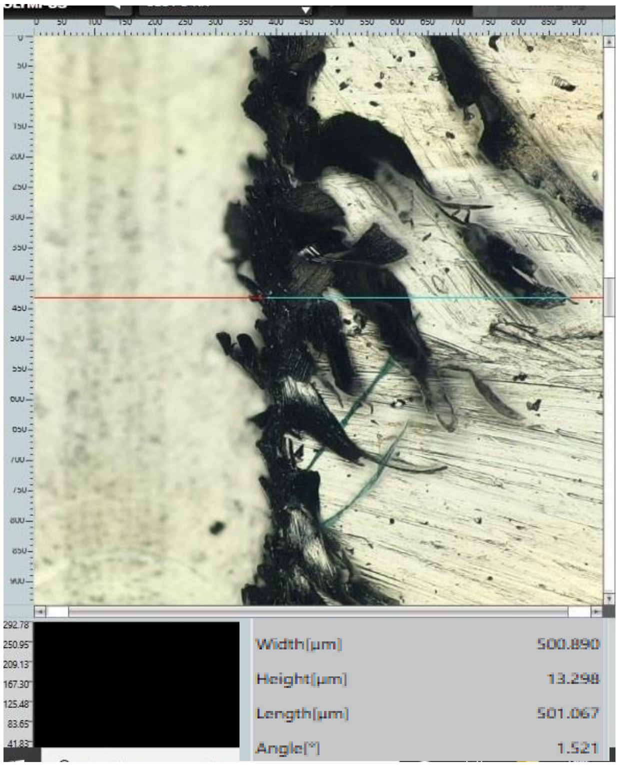


Distance[μm] 18.709

c)

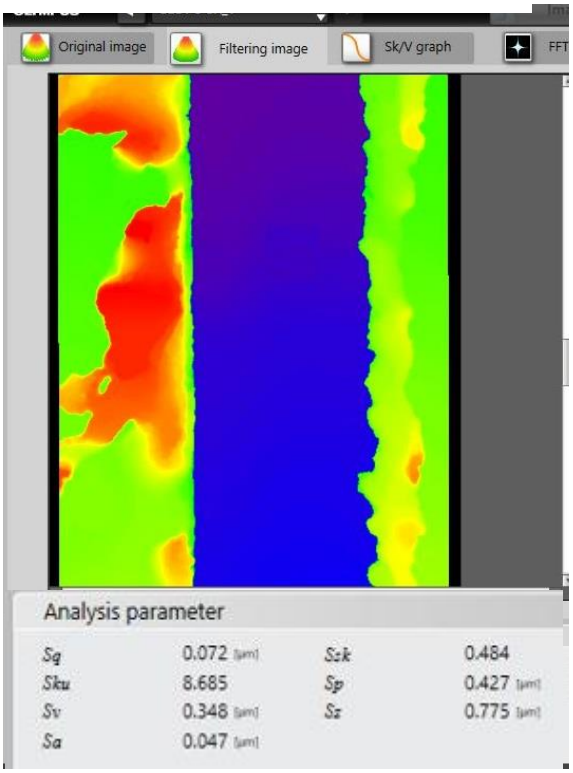
Figure 10: Images of result at f = 0.25(μm/tooth), Vc = 50(m/min), & ap = 60 μm.

a) Burr width *b) Surface finish* *c) Tool wear*



Width[μm]	500.890
Height[μm]	13.298
Length[μm]	501.067
Angle[°]	1.521

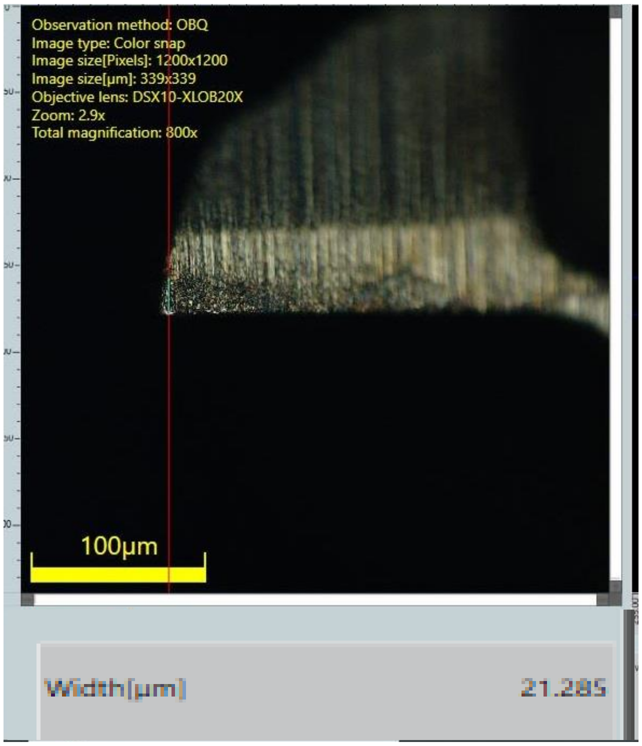
a)



Analysis parameter

Sq	0.072 [μm]	Ssk	0.484
Sku	8.685	Sp	0.427 [μm]
Sv	0.348 [μm]	Sz	0.775 [μm]
Sa	0.047 [μm]		

b)

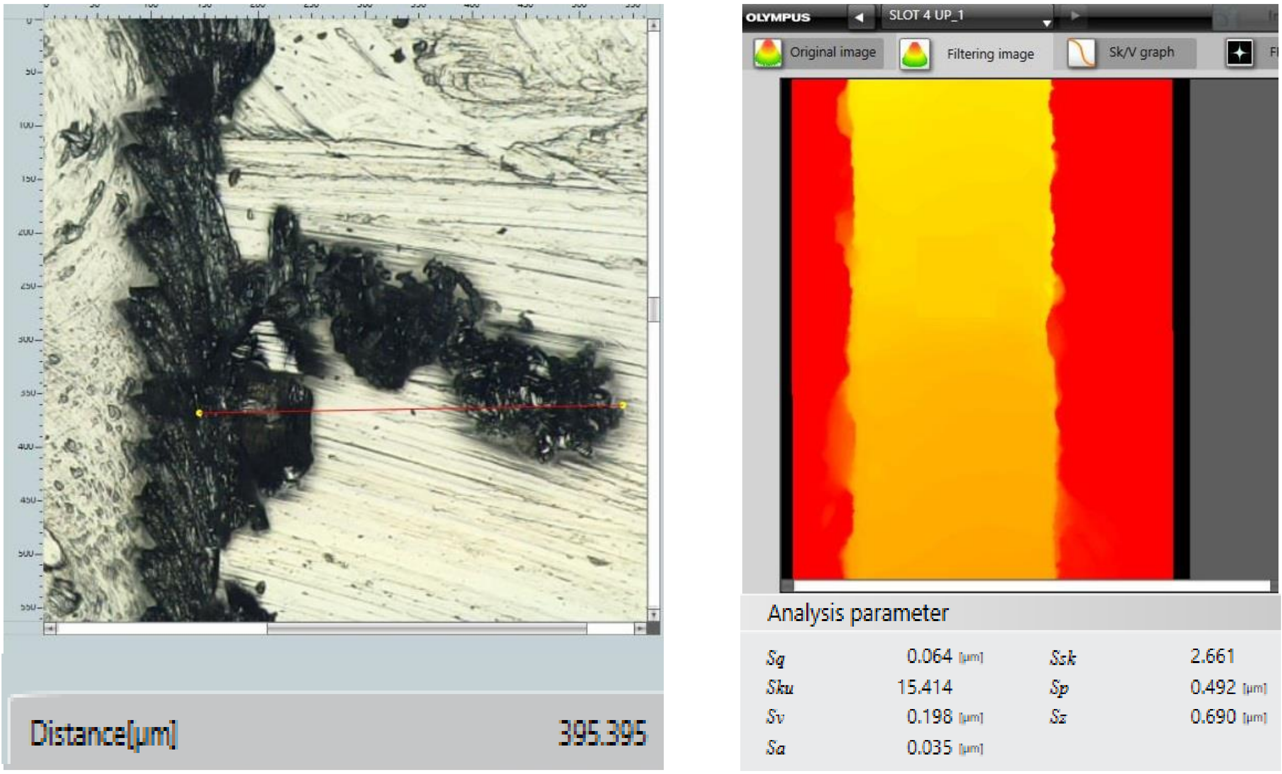

Observation method: OBQ
Image type: Color snap
Image size[Pixels]: 1200x1200
Image size[µm]: 339x339
Objective lens: DSX10-XLOB20X
Zoom: 2.9x
Total magnification: 800x

Width[µm] 21.285

c)

Figure 12: Images of result at fz = 0.25(µm/tooth), Vc = 75 (m/min), & ap = 90 µm.

a) Burr width *b) Surface finish* *c) Tool wear*



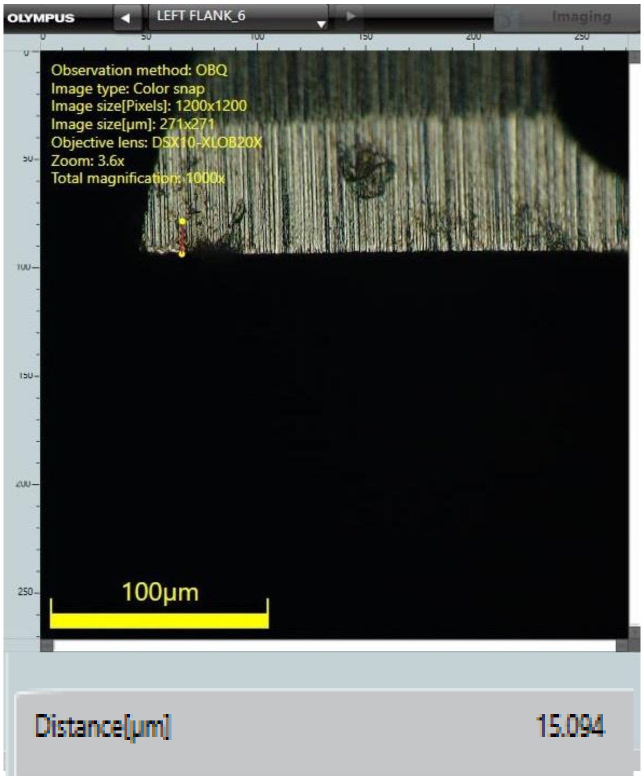
Distance[µm] 395.395

Analysis parameter

Sq	0.064 [µm]	Ssk	2.661
Sku	15.414	Sp	0.492 [µm]
Sv	0.198 [µm]	Sz	0.690 [µm]
Sa	0.035 [µm]		

a)

b)



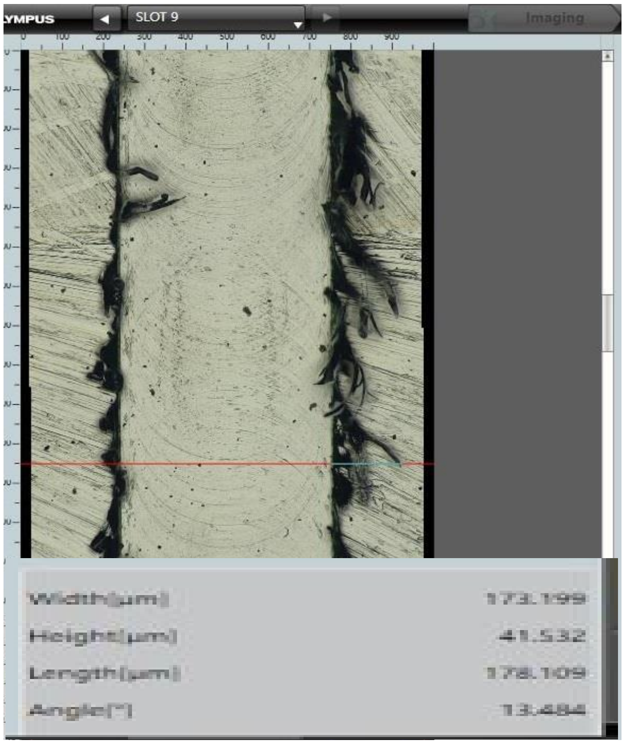
Observation method: OBQ
Image type: Color snap
Image size[Pixels]: 1200x1200
Image size[µm]: 271x271
Objective lens: DSX10-XLOB20X
Zoom: 3.6x
Total magnification: 1000x

Distance[µm]	15.094

c)

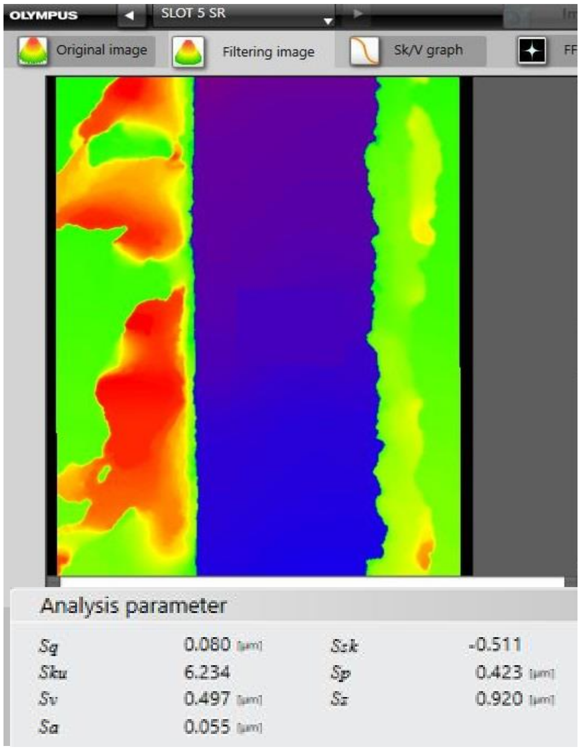
Figure 14: Images of result at fz = 0.45(µm/tooth), Vc = 50 (m/min), & ap = 90 µm.

a) Burr width b) Surface finish c) Tool wear



Width[µm]	173.199
Height[µm]	41.532
Length[µm]	178.109
Angle[°]	13.484

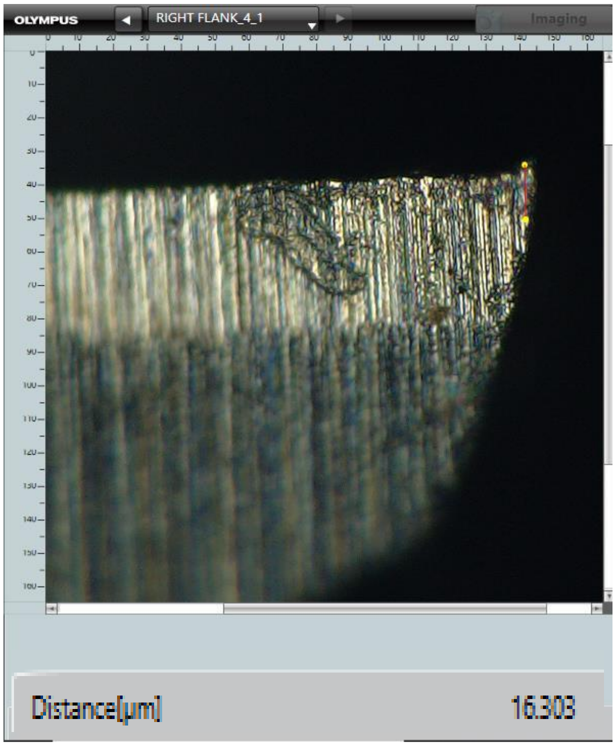
a)



Analysis parameter

Sq	0.080 [µm]	Ssk	-0.511
Sku	6.234	Sp	0.423 [µm]
Sv	0.497 [µm]	Sz	0.920 [µm]
Sa	0.055 [µm]		

b)

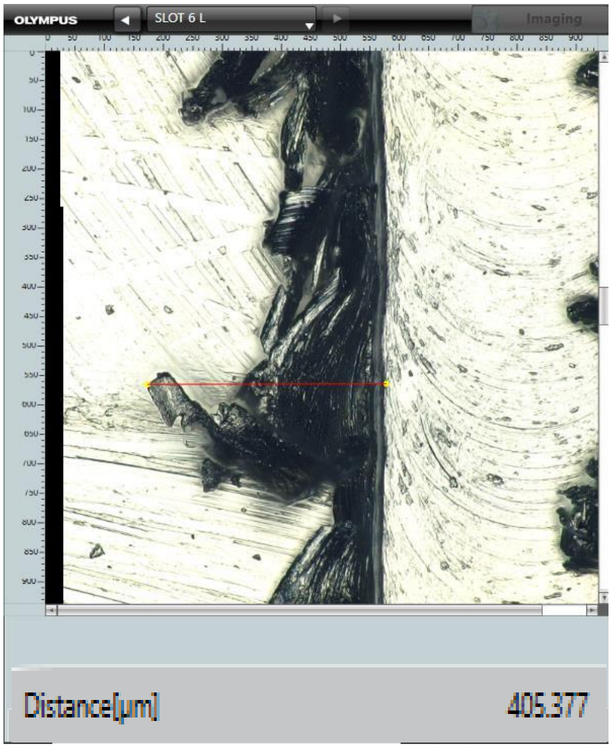


Distance[µm] 16.303

c)

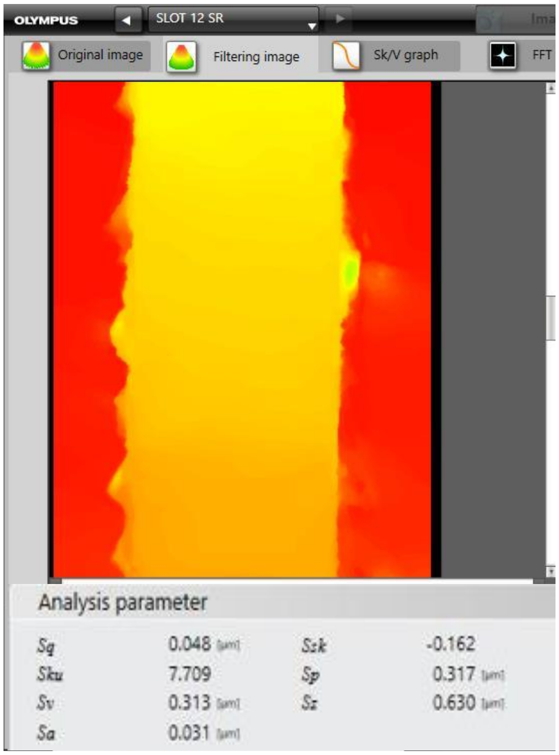
Figure 16: Images of result at fz = 0.45(µm/tooth), Vc = 75 (m/min), & ap = 30 µm.

a) Burr width b) Surface finish c) Tool wear



Distance[µm] 405.377

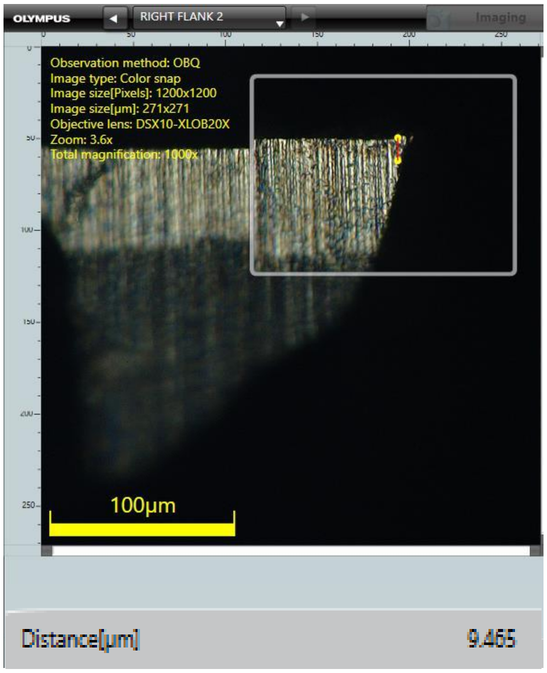
a)



Analysis parameter

Sq	0.048 [µm]	Ssk	-0.162
Sku	7.709	Sp	0.317 [µm]
Sv	0.313 [µm]	Sz	0.630 [µm]
Sa	0.031 [µm]		

b)



Observation method: OBQ
Image type: Color snap
Image size[Pixels]: 1200x1200
Image size[µm]: 271x271
Objective lens: DSX10-XLOB20X
Zoom: 3.6x
Total magnification: 1000x

Distance[µm] 9.465

c)

Figure 18: Images of result at fz = 0.45(µm/tooth), Vc = 25 (m/min), & ap = 60 µm.

a) Burr width b) Surface finish c) Tool wear

Table 6: L9 Array of experimentation with results

Factors			**Surface Roughness**	**Burr Width**	**Burr Length**	**Tool Flank Wear**
Feed (µm/tooth)	Vc (m/min)	ap (µm)	Ra (nm)	Down Milling (µm)		(µm)
0.25	25	30	39.12	580.75	479.702	15.20
			38.65	455.00	572.549	16.63
0.25	50	60	47.34	527.52	342.574	18.57
			45.32	327.43	582.097	18.71
0.25	75	90	41.63	501.04	246.588	21.25
			43.72	440.96	504.984	24.00
0.45	50	90	39.03	358.00	483.26	15.32
			37.55	393.00	289.015	18.31
0.45	75	30	65.09	173.19	259.487	15.00
			63.75	165.00	324.352	16.42
0.45	25	60	37.61	405.37	159.807	9.20
			35.12	375.00	113.971	8.20
0.65	75	60	72.06	165.00	198.456	18.65
			73.11	183.00	323.168	19.32
0.65	50	90	61.08	367.00	310.373	8.65
			59.34	332.00	220.603	10.00
0.65	25	30	66.92	195.00	199.242	12.62
			69.02	205.00	215.474	13.40

4.2 Discussions

After compilation of the results, ANOVA was employed to statistically analyze the results & to assess the significance of each factor.

4.2.1 Surface Roughness

Ti-3Al-4v is mostly used in biomedical applications, owing to this usability of the titanium alloy surface finish requirements are more stringent. ANNOVA was applied for surface finish analysis and results are tabulated below.

Table 7: ANOVA table for surface finish

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value	Significance
F (µm/tooth)	2	2053.67	62.96%	2053.67	1026.84	46.54	0.000	Significant
Vc (m/min)	2	662.83	20.32%	662.83	331.41	15.02	0.001	Significant
ap (µm)	2	302.40	9.27%	302.40	151.20	6.85	0.012	Significant
Error	11	242.72	7.44%	242.72	22.07			
Total	17	3261.62	100.00%					

Feed rate, cutting edge radius, cutting speed, depth of cut and tool coatings are main machining parameters that effect the surface finish during titanium machining (milling) process as reported in the research studies [90] [91]. In this study it is evident from table 6 that all three cutting parameters are significant factors for surface roughness. Feed rate is major contributing factor in surface roughness with contribution ratio of 62 %, whereas, cutting velocity and depth of cut are second and third respectively. These results comport to previous research that was conducted on grade 5 (Ti-6Al-4V) by Jaffery et al. [5] wherein all the three factors were significant.

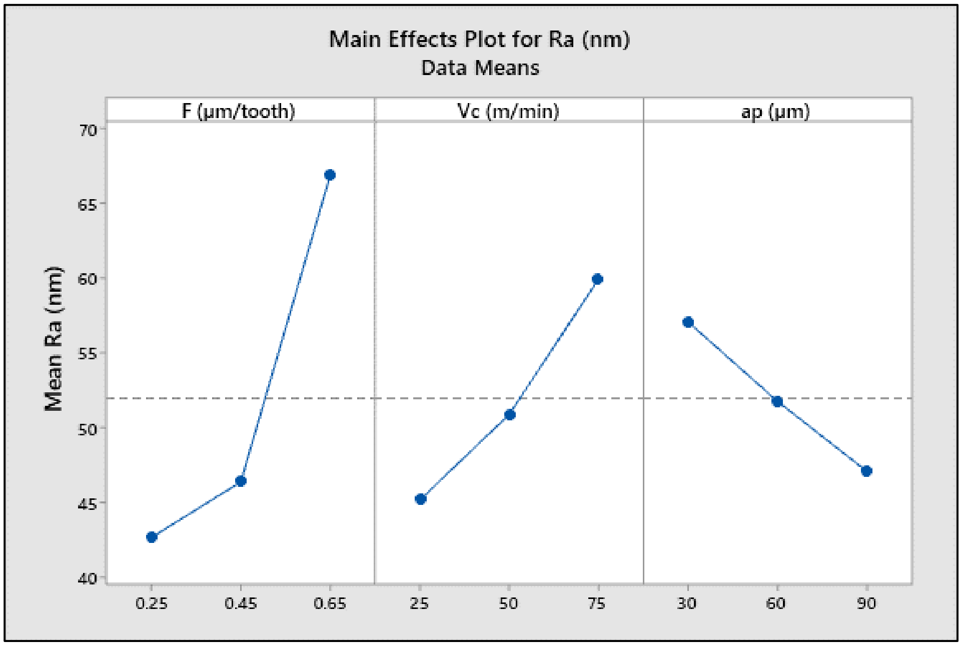
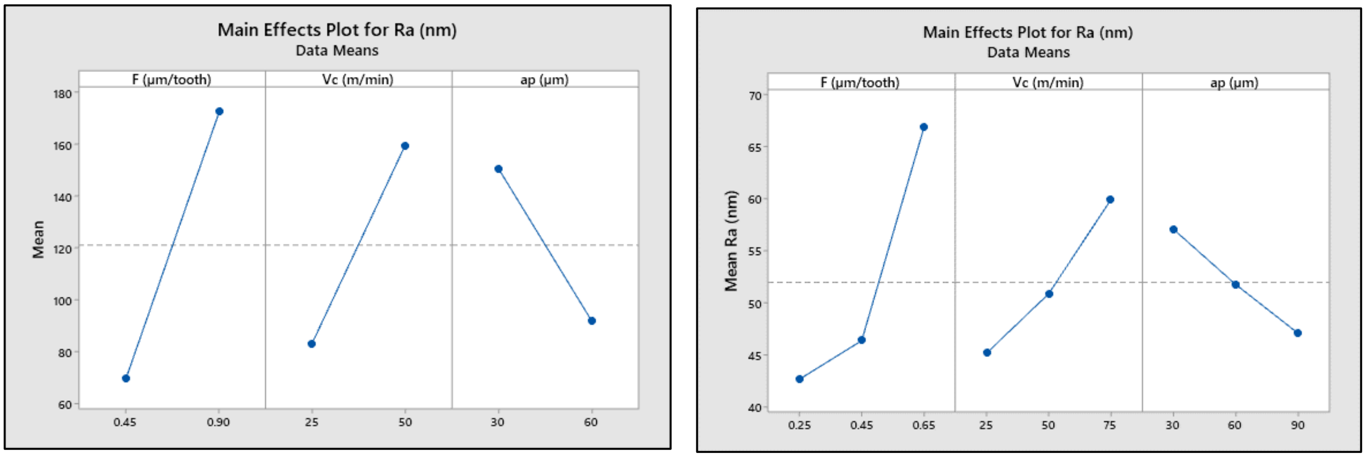


Figure 20: Main effect plot for Surface roughness (Below edge radius)

Figure 20 shows the main effect plots of surface roughness with three main contributing factors. It has been observed that surface roughness increases with the increase of feed rate and cutting velocity. Surface roughness trend decreases with increase of depth of cut. this trend is comparable to the surface roughness trend reported by Jaffery et al. [92]. Comparison of both research is below. It is evident from both the studies that surface roughness increases with the increase of feed and cutting velocity whereas, with increased of depth of cut surface roughness improved.



a) **b)**

Figure 22: Main effect plots; a) adopted from Jaffery et al. [92] b) Main effect plot of this research study

4.2.2 Analysis of Burr Formation:

Burr is characterized by burr height and width and types of burrs in a typical metal machining process. Herein, burr width and length were quantified for down milling. Only worst-case scenario i.e., largest value was taken into consideration for each milling operation. ANOVA was applied for each case and discussed below. There were a large number of burrs with larger width and height was observed in down milling area as compared to up milling area where burrs comparatively smaller in width were observed. These results comport to findings reported in earlier research study [93].

4.2.3 Burr width (Down milling)

It is obvious from table 8 that chip load or feed per tooth is major factor that influence the burr width in down milling area with contribution ratio of 54.05 %. Cutting velocity is also a significant factor with contribution ratio of 21.63 % and depth of cut contributed 10.91 %. CR of this study is comparable to earlier research conducted on grade 5 by by Jaffery et al. [92], wherein all three factors were significant with the contribution ratios of 52 % & 29 % & 17%.

Table 8: Analysis of variance for Burr Width (Down milling)

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value	Significance
F (µm/tooth)	2	164730	54.05%	164730	82365	22.17	0.000	Significant
Vc (m/min)	2	65934	21.63%	65934	32967	8.88	0.005	Significant
ap (µm)	2	33246	10.91%	33246	16623	4.48	0.038	Significant
Error	11	40859	13.41%	40859	3714			
Total	17	304770	100.00%					

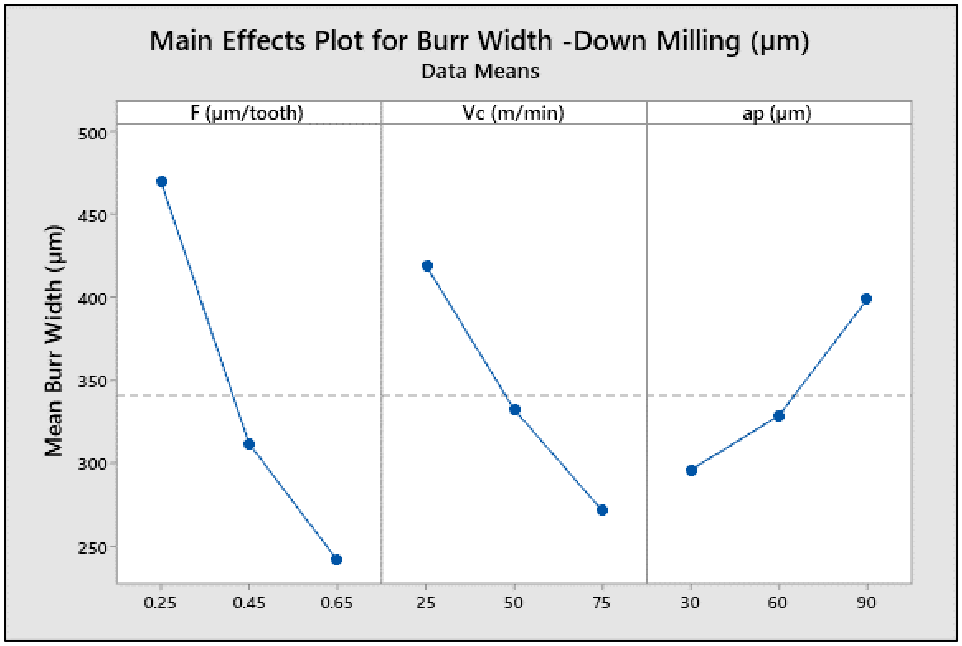
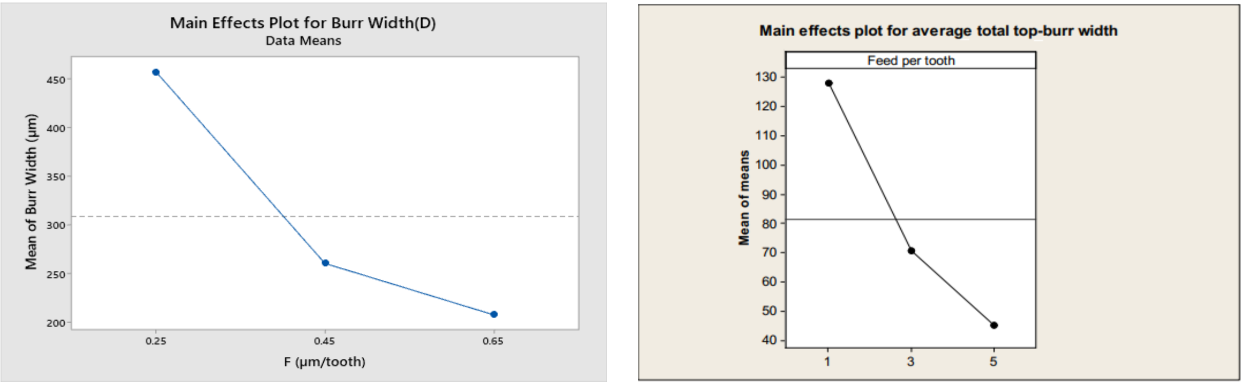


Figure 23: Main effect plot for Burr width (Down milling)

Main effect plot for down milling burr width is given in Fig 23. It is evident from main effect plots that there is inverse relationship between burr width and chip load. When feed per tooth increases burr width decreases. Minimum burrs have been observed at feed rate of 0.65 µm/tooth.

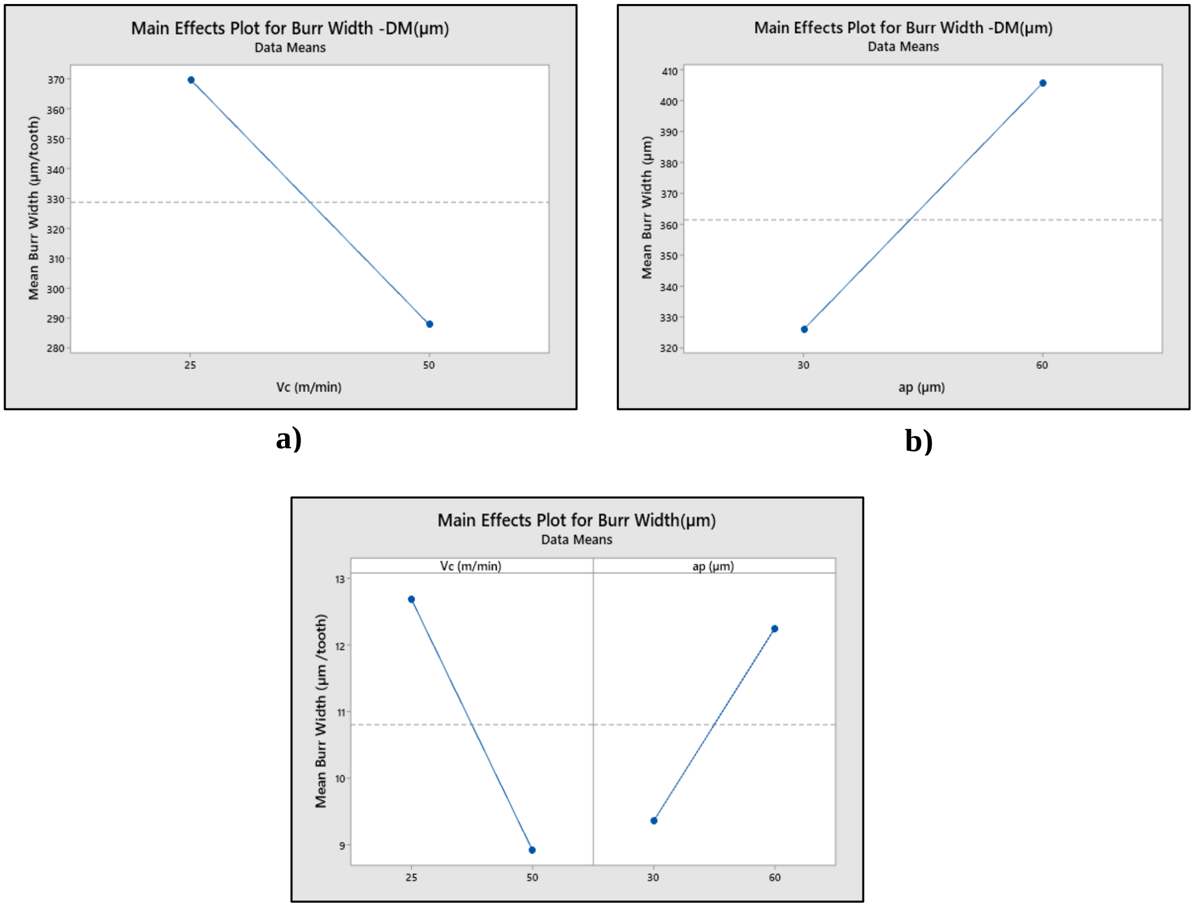
This trend of decrease in burr width with increase of feed rate has been reported in earlier studies conducted on grade 5 (Ti-6Al-4V) in both high-speed micro milling and low speed micro milling. In one of high-speed micro milling conducted by [93] reported that when feed rate is increased then 4-35 % burr width reduction was observed. Another micro-milling study which was conducted on Inconel 718 at low speed by Muhammad, Atif, et al. [94], wherein same trend has been observed. Trend of main effects graph are comparable with earlier study conducted on titanium grade 5at low speed by [95] [95]. Comparison is shown in fig 24. Trend of burr width for both cutting velocity and depth of cut are congruous with earlier research study reported by Jaffery et al. [92]. Comparison is presented in fig 25.



a)

b)

Figure 24: F (µm tooth−1) Comparison a) Feed per tooth of this study b) feed per tooth of study conducted by [95]



a)

b)

c)

Figure 26: Main effect plot comparison of burr width for cutting velocity and depth of cut a) & b) Main effect plot of cutting velocity and depth of cut of this research c) Main effect plot of cutting velocity and depth of cut of rese

4.2.4 Burr Length (Down-Milling)

As discussed earlier, burr is characterized by width, height, and length. In this study burr length was also quantified. Since image of the digital microscope is taken from the top plane of burr where burr width is taken more precisely, whereas length cannot be measured accurately. Burr width and height is easily measured under digital microscope. Therefore, width and height at worst case was measured then by Pythagoras theorem application length was measured.

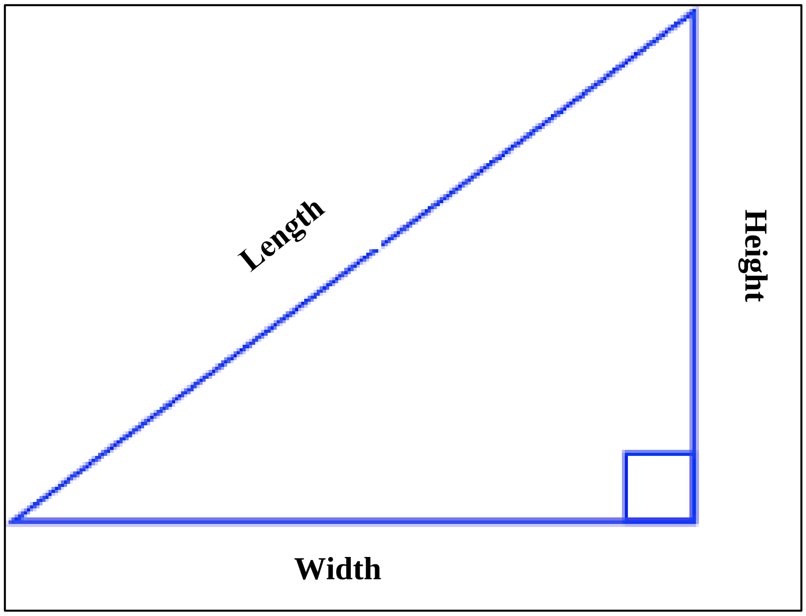


Figure 27: Length measurement

ANOVA table for burr length is tabulated below. From table 9 it is evident that feed rate is most dominant factor that influenced the length of burr, whereas cutting velocity and depth of cut are insignificant factors. Almost 50 % contribution is coming from residual effects.

Table 9: ANOVA table for length

Source	**DF**	**Seq SS**	**Contribution**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**	**Significance**
F (µm/tooth)	2	156885	45.14%	156885	78442	5.04	0.028	Significant
Vc (m/min)	2	7205	2.07%	7205	3602	0.23	0.797	Non-Significant
ap (µm)	2	12303	3.54%	12303	6152	0.40	0.683	Non-Significant
Error	11	171134	49.24%	171134	15558			
Total	17	347527	100.00%					

It can be seen from main effects plot that length of burr is inversely related to feed rate. It is the same trend that has been observed in burr width.

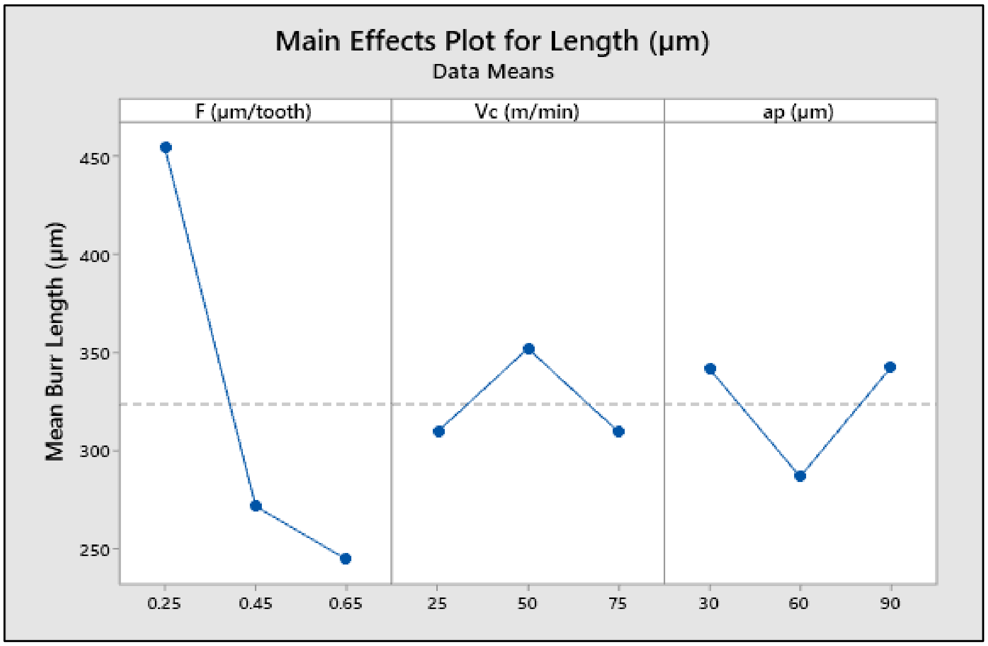


Figure 29: Main Effect Plots for Length of Burr

4.2.5 Tool Wear

ANOVA for tool flank wear is presented in table 10 where it shows that cutting velocity is dominating factor among three factors with CR of 54.02%. Whereas the contribution of tool wear stood at 33.18 %. Depth of cut found insignificant factor for tool flank wear. These results are congruous to earlier findings of Bandapalli, Chakradhar, et al. [96], wherein researcher carried out analysis of tool wear in high speed micro milling on titanium grade-12 (Ti-0.3 Mo-0.8Ni) and noted that feed rate and cutting velocity as major influencing factors for tool flank wear.

Table 10: ANOVA for Tool Wear

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value	Significance
F (µm/tooth)	2	114.315	33.18%	114.315	57.157	16.39	0.001	Significant
Vc (m/min)	2	186.115	54.02%	186.115	93.058	26.68	0.000	Significant
ap (µm)	2	5.712	1.66%	5.712	2.856	0.82	0.466	Non-significant
Error	11	38.371	11.14%	38.371	3.488			
Total	17	344.514	100.00%					

Main effect plot for tool flank wear is shown in Fig -30 where it can be seen that cutting velocity has direct relationship with tool wear where tool flank wear increases with cutting velocity increase.

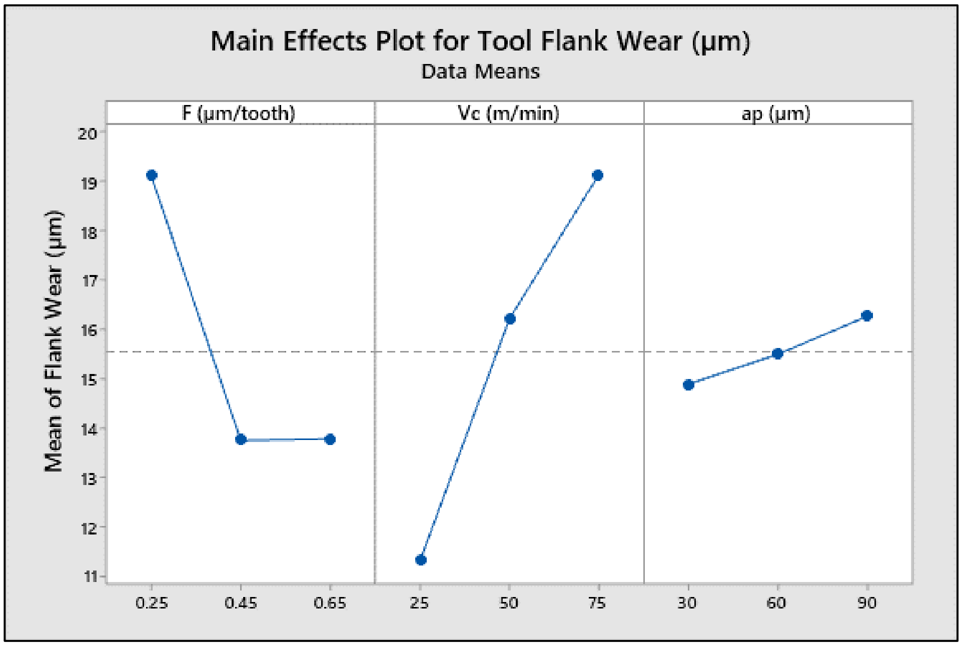


Figure 30: Main Effects Plot for Tool Wear

This result is congruous with research presented earlies, where same trend has been observed by Jaffery et al. [92]. Comparison of both research work at same region of cutting speed is presented in Fig-22

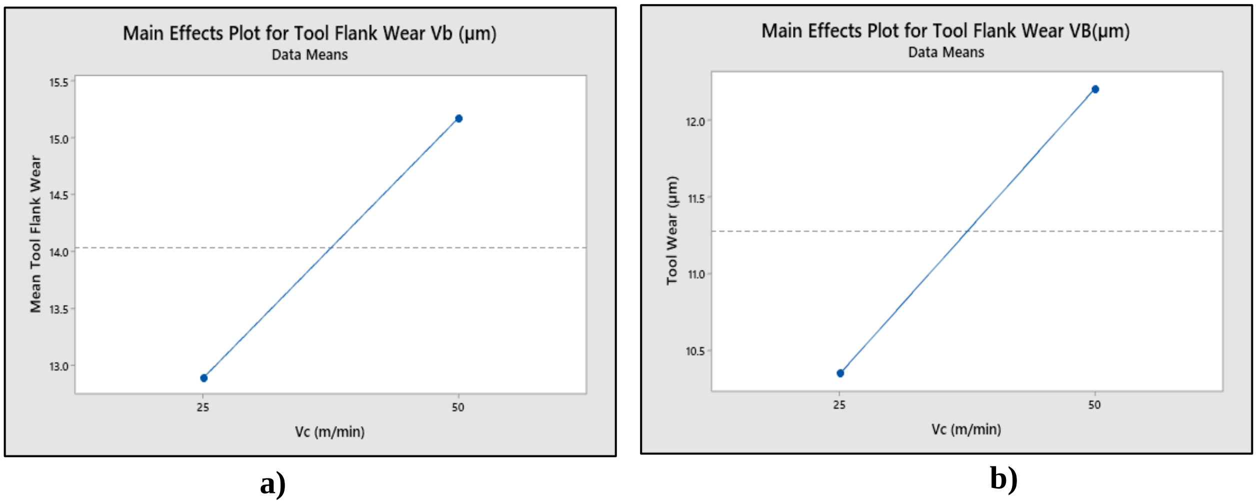
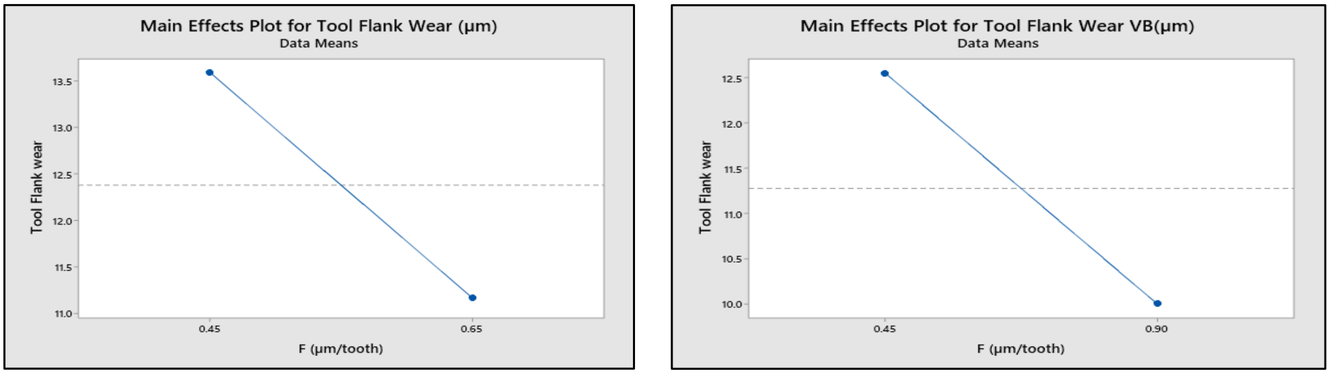


Figure 32: Comparison of main effect plots of cutting speed

a) Main effect plot of this study b) Main effect plot of cutting velocity adopted from Jaffery et al. [92].

Moreover, these findings are congruous to earlier research conducted by Ahsan, Kazi Badrul, et al. [97] , wherein research was conducted on grade 5 (Ti-6Al-4V), it was found that cutting velocity was major influencing factor for tool life. It was noted inverse relationship between tool life and cutting velocity in conventional turning of titanium grade 5. It has also been noted that tool wear decreased when feed rate changed from the 0.25 (µm/tooth) to 0.65 (µm/tooth). Same findings were reported by Jaffery et al. [92]. Wherein tool flank wear decreased when feed rate was changed from 0.45 (µm/tooth) to 0.90 (µm/tooth).



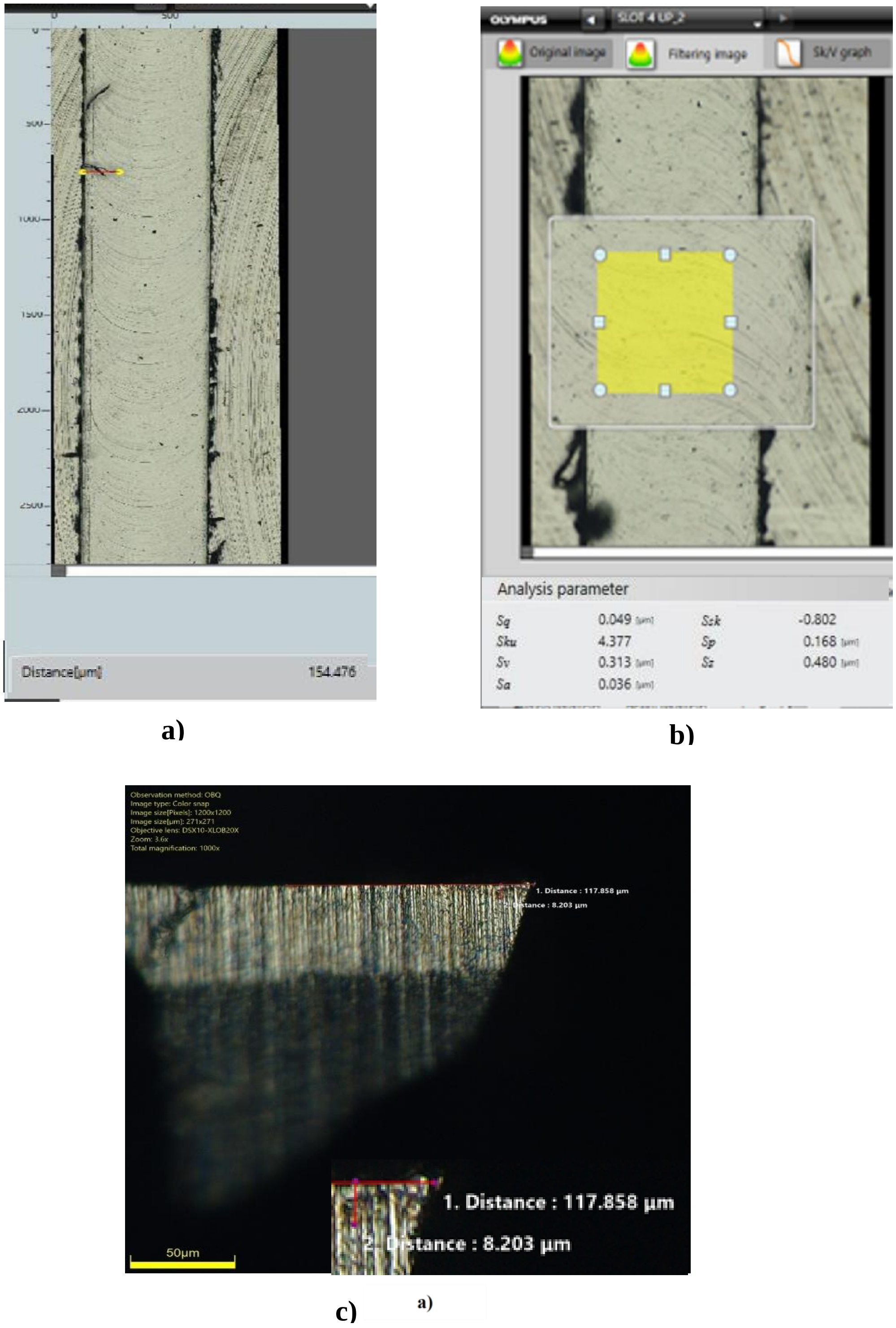
a) **b)**

Figure 34: Tool Flank wear w.r.t feed rate comparison

a) Main effect plot of this study b) Main effect plot of feed rate adopted from Jaffery et al. [92]

4.2.6 Confirmatory Test

ANOVA was applied to minimize the experiments and to find the best optimum condition of process parameters. Therefore, in order to validate the results confirmation test at the best and worst condition was conducted.



Distance[µm] 154.476

Analysis parameter

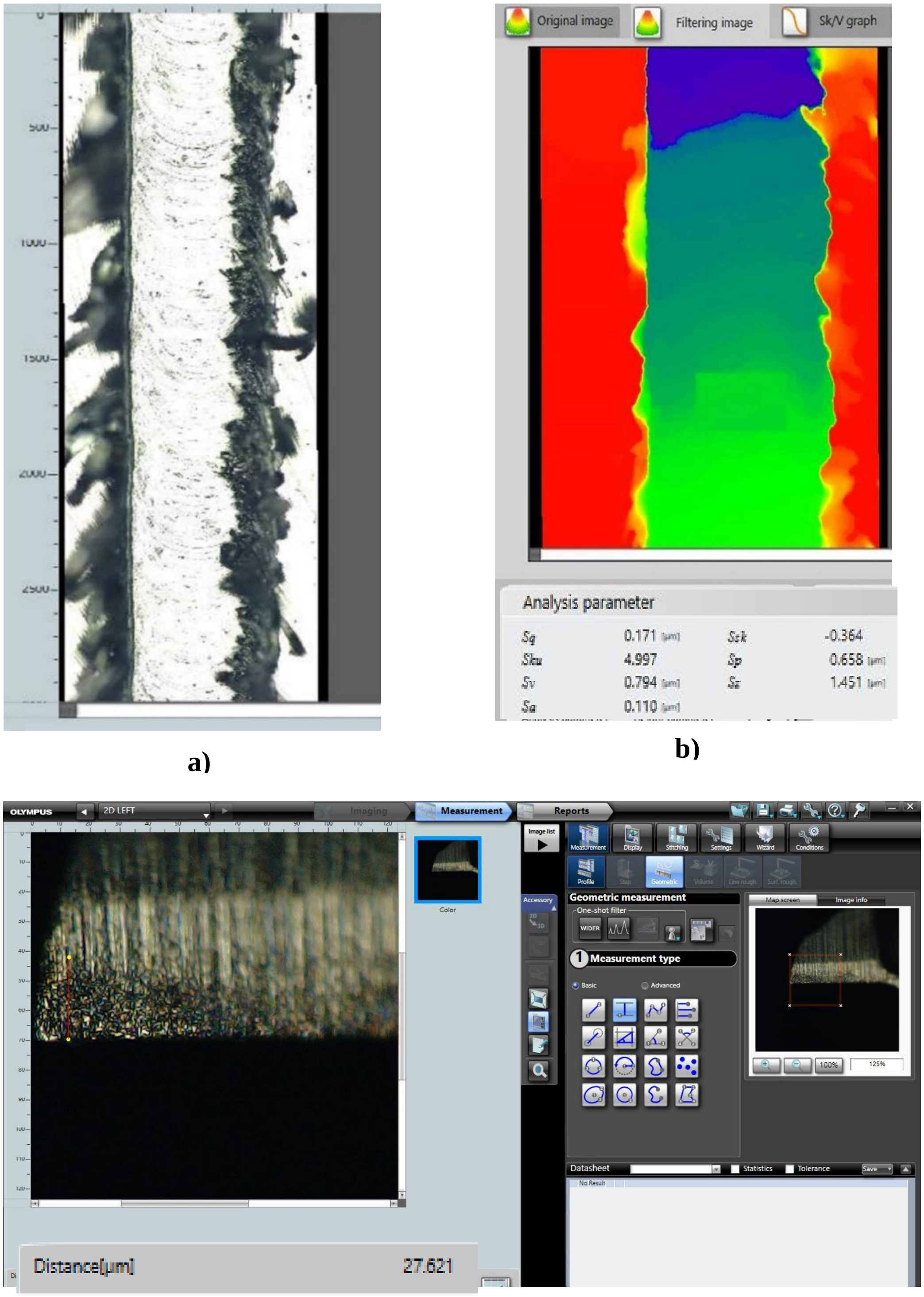
Sq	0.049 [µm]	Ssk	-0.802
Sku	4.377	Sp	0.168 [µm]
Sv	0.313 [µm]	Sz	0.480 [µm]
Sa	0.036 [µm]		

Observation method: OBQ
Image type: Color snap
Image size[Pixels]: 1200x1200
Image size[µm]: 271x271
Objective lens: DSX10-XLOB20X
Zoom: 3.6x
Total magnification: 1000x

1. Distance : 117.858 µm
2. Distance : 8.203 µm

Figure 36: Images of confirmatory test result (Best)

a) Burr width f = 0.65(µm/tooth), Vc = 75 (m/min), & ap = 30 µm. b) Surface finish f = 0.25(µm/tooth), Vc = 25 (m/min), & ap = 90 µm. c) Tool wear f = 0.65(µm/tooth), Vc = 25 (m/min), & ap = 30 µm.



Analysis parameter

Sq	0.171 [µm]	Ssk	-0.364
Sku	4.997	Sp	0.658 [µm]
Sv	0.794 [µm]	Sz	1.451 [µm]
Sa	0.110 [µm]		

Distance[µm] 27.621

a)

b)

c)

Figure 38: Images of confirmatory test results (Worst)

a) Burr width f = 0.25(µm/tooth), Vc = 25 (m/min), & ap = 90 µm. b) Surface finish fz = 0.65(µm/tooth), Vc = 75 (m/min), & ap = 30 µm. c) Tool wear f = 0.25(µm/tooth), Vc = 75 (m/min), & ap = 90 µm.

Table 11: Confirmatory test results

	Factors			**Confirmatory Results**	
Experiment	Feed (µm/tooth)	Vc (m/min)	ap (µm)	Result	
Best	0.25	25	90	Burr Width (µm)	154.47
					148.30
Worst	0.65	75	30		770.79
					590.23
Best	0.65	75	30	Surface Roughness (nm)	36
					28
Worst	0.25	25	90		112
					81
Best	0.65	25	30	Tool wear (µm)	5.02
					8.20
Worst	0.25	75	90		27.67
					25.34
Best	0.65	25	60	Burr Length (µm)	147.99
					134.44
Worst	0.25	50	30		769.70
					590.24

CHAPTER 5: CONCLUSIONS

For production cost reduction and improvement of product quality identification of KPVs for a process are very important. Herein three main process parameters of micro milling of titanium grade 9 were investigated. Most of the literature is abounds by the application and investigation of titanium grade 5, whereas no study has been reported on micro machining parameters optimization of titanium grade-9 yet. There are some applications where titanium grade 9 is used, therefore, this research has been conducted to find the key process parameters for this titanium grade.

- Surface roughness trends of grade 9 (Ti-6Al-4V) are similar as reported for titanium grade 5 (Ti-3Al-2.5V). Moreover, better surface finish is achieved below edge radius for titanium grade 9 as well.
- Feed rate was dominating factor that influenced the surface finish with contribution ratio of almost 63 % at 95 % confidence level. Cutting speed and depth of cut were also significant factors for surface roughness. These results are comparable with titanium grade 5.
- Feed rate was major contributing factor with CR of 54 % for burr width as well and inverse relationship with burr width has been observed. Lower burr width has been observed at higher feed rates. CR of cutting velocity and depth of cut was stood at 21.63 % and almost 11 5 respectively. All the factors were significant for burr width.
- Burr size on down milling side was more as compared to up milling side.
- Cutting velocity and feed rate were found to be dominating factors for tool wear with contribution ratio of 54.02 % & 33.18 %, which is almost 90 % of total variability.
- Minimum values of burr width, length, surface roughness and tool flank wear were obtained at optimum parameters.
- Feed rate found to be influential factor for almost all the results

5.1 Recommendations

- Analysis of coated and uncoated tool on surface finish, tool wear and burr formation in micro milling of titanium grade 9.
- Study of MQL (minimum quantity lubricant) and wet conditions in micro milling of titanium grade 9
- Comparison of macro and micro-milling of titanium grade 9.

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