Analysis of Cutting Forces and Tool Wear during Micro milling of Ti-6Al-4V at low machining speed

By

Ammir Rashid

Supervisor

Dr Mushtaq Khan

Design and Manufacturing Engineering
SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING
NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY
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Analysis of Cutting Forces and Tool Wear during Micro milling of Ti-6Al-4V at low machining speed

Author

Ammir Rashid

00000204505

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Thesis Supervisor:

Dr Mushtaq Khan

Thesis Supervisor's Signature: ____

Design and Manufacturing Engineering
SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING
NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY
ISLAMABAD

May 2021

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I certify that this research work titled "Analysis of Cutting Forces and Tool Wear during Micro milling of Ti-6Al-4V at low machining speed

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Ammir Rashid

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Examination Committee Members

1 Name: Dr. Shahid Ikramullah Butt Signature: _______________

2 Name: Dr. Najam ul Qadir Signature: _______________

3 Name: Dr.Syed Hussain Imran Signature: _______________

Supervisor's name: Dr. Mushtaq Khan Signature: _______________

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Abstract

In this research milling tests were carried out in order to analyze the influence of different parameters of machining such as feed rate, cutting speed, depth of cut and type of tool being used on cutting forces and wear of cutting inserts while micro milling the Ti-alloy (Ti-6Al-4V) using uncoated, AlTiN coated and multi coated (AlTiN and SiN coating) tungsten carbide end mill cutters. The results were analyzed through Statistical technique ANOVA in order to govern the key process variables. Consequences show that depth of cut is most leading factor in cutting forces (44.45% contribution ratio) and cutting speed is most substantial factor in wear of cutting inserts (67.59%) Feed rate and depth of cut had slight influence upon wear of the tool with the contribution of 5.29% and 3.85% respectively. It is observed that multi coated tool undergoes least cutting forces and wear in comparison to other two cutting inserts while micro milling Ti-alloy at low-speed machining setup.

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Chapter1

1.1 Introduction

Micromachining is an advanced technology which includes micro-scale milling, turning and drilling where materials are detached in the form of chips within the dimensions of 0.1 µm to 10µm. With the passage of time there exists an increase in demand of small-scale components so manufacturing operations and techniques are shifting their focus on small scale components and research needs to be done at the micro and nano scale level of machining. Micromachining requires certain level of precision that isn’t easily attainable. Micromachining processes are classified as traditional and advanced micromachining whose further classification is shown in Fig.1 [1].

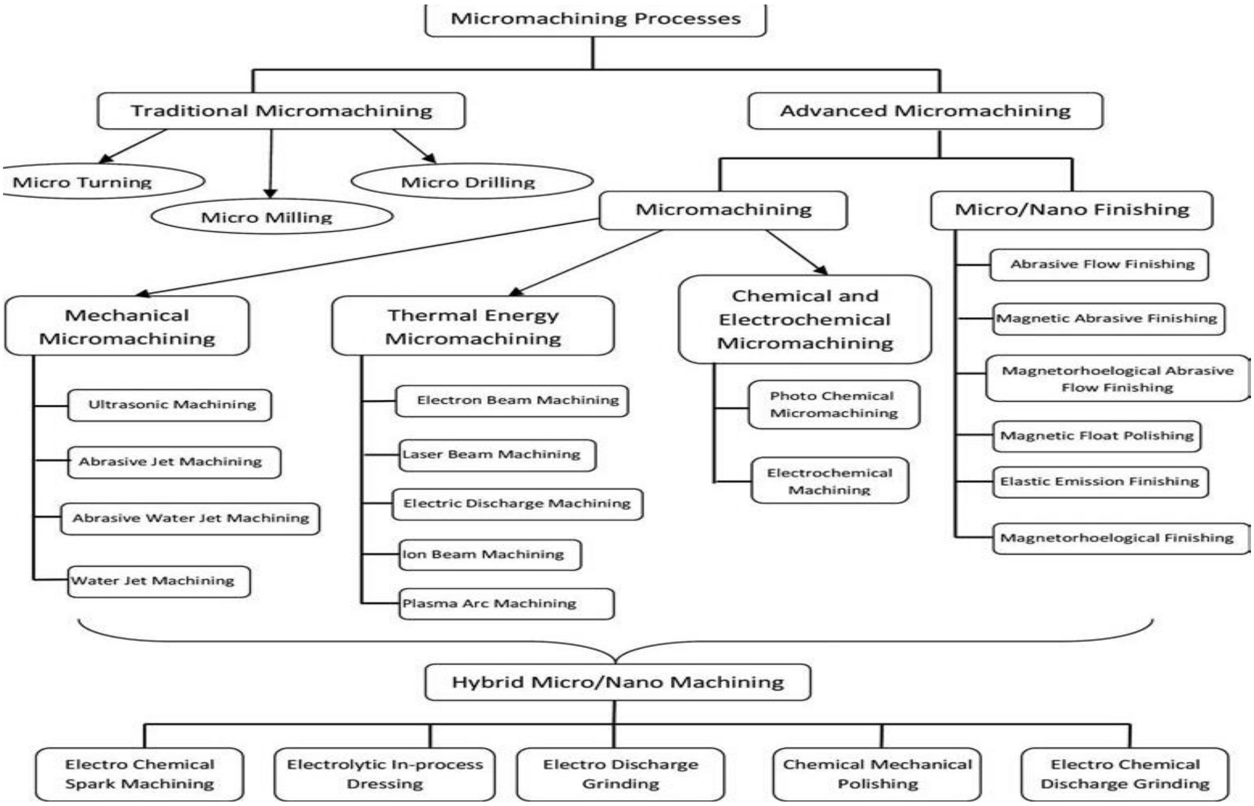


Figure 1Classification of micromachine and nano finishing processes

In order to achieve appropriate accuracy of small-scale components the right tooling and work holding, finishing processes and inspection and quality control must all work together relevantly. It is very difficult to attain required precision and accuracy in micro component so in order to achieve these parameters this research is the major driving force.

1.2 Micro milling

For massive manufacturing of small parts micro milling is one of the most dominating and new existing technologies with sub-micron tolerance and tools tip being used that can hardly be seen with naked eye. In micro milling sharp tool undergoes mechanical contact with the job under process, which lead to rupture of cutting inserts inside the material along defined paths, and finally results in removal of the undesired part of the work piece in the form of chips.To achieve the desired accuracy and excellence in micro milling and to overcome economic and commercial constraints the whole manufacturing chain must be advanced and harmonized.

There exist various factors which are responsible for causing machining errors such as accuracy and thermal deformation of milling machines, errors in work setup, tool exhausting and deflection of tool during the machining process.

In comparison to the milling on macroscale, microscale milling has several challenges that must be addressed wisely. Rapid wear and fracture of the tool, severe burr formation and poor surface finish are major problems faced in micro milling process so this research is a major driving force to overcome some of these problems.

1.3 Comparison between Micro and Macro Machining

Mechanical contact of sharp cutting inserts with job being used eventually removing unnecessary part of job under operation in the form of chips. Micro milling is usually for manufacturing components with micro structures such as complex three-dimensional surfaces at micro scale. While material removing process using power driven tools in order to attain the desired profile of workpiece is said to macro machining.

Table 1The differences between micro machining and macro aching operations are shown in table.

Parameters	Micro Machining	Macro Machining
Diameter of cutting tool	Less than 1mm	Greater than 1mm
Chip Thickness	0.1µm-100µm	Usually greater
Tool Wear	Quickly	Gradually
Burr formation	Smaller in size	Bigger in size

1.4 Research Motivation

In metal cutting processes Productivity and Profitability are widely affected by tool wear so in to achieve more productivity it is beneficial to minimize wear of cutting insert being used.

Tool wear depends upon many parameters such as cutting forces, cutting speed and machining processes (turning, milling, drilling) etc. Tool wear ultimately results in poor finishing of surface, diminished finished part accuracy, cutting forces increment and enough temperature of cutting might lead to tool breakage. So, measurement of cutting insert being used is very important in order to predict the life of tool inserted as there is a remnant effect of these tool wear parameters on producing jobs with appropriate quality[2, 3].

As cutting speed has great impact upon tool wear and much of the work has been done to investigate tool wear between 16m/min to 141m/min i.e., 16m/min is minimum cutting speed so far reported in the literature [4]. The cutting forces are also dominant at low cutting speeds so they also adversely affect the tool. It was analyzed that instead of using high speed machining setup, burr formation can be reduced using low speed machining setup varying feed per tooth [5]. So, to investigate wear of cutting inserts during machining of TC4 low speed machining setup could be preferred to observe the affect of low cutting speed and high cutting forces on tool.

1.5 Research Aim and objectives

The objective of this research is to investigate the effect of critical machining parameters such as low speed cutting, cutting forces, rate of feed and depth of cut on wear of cutting inserts using Solid Carbide Tools (without and with coatings) for micro milling of TC4 [6]. Cutting procedure is interrupted when there exists the need for tool replacement or grinding which ultimately leads to an increase in time for replacement and adjustment of machine tool results in increasing the cost and reducing productivity.

The main objectives of research are

- Analysis of coated and uncoated tool wear while micro milling of TC4 at low cutting speeds
- At 95% confidence level investigating most significant factor contributing towards cutting forces and wear of cutting inserts
- Analysis of cutting forces at low cutting speed and their impact on tool wear
- Find out the influence of each parameter using ANOVA
- To investigate the appropriate tool (with or without coating) at low cutting speed

1.6 Research Scope

The limitation of this research is micro end milling of TC4 using coated (AlTiN coated and multi coated) and uncoated end mill cutters at low machining speed of less than 8000rpm.

Chapter2

2.1 LITERATURE REVIEW

The requirement for high exactness in manufacturing was handled by manufacturers universally to advance quality control, interchangeability of mechanisms and longer wear/fatigue life [7]. The demand of highly accurate and precise micro components is increasing widely in automotive, aerospace, electronics, optical switches used in display devices and optical communications, biomedical industries. In Micromachining the size of the parts created is in the order of 10^{-6}m. As regards micromachining product quality and dimension are the best indicator of the levels of technology and request. In different manufacturing aspects there exists several environmental (reduce noise, vibration, waste and pollution control), economical (small apparatus with reduction in capital investment and running cost) and technical advantages (inertia reduction). On other hand micromachining is sometimes proved to be challenging during machining of hard parts such as Titanium alloys. Ti-alloys are expensive when considered to other metals due to its extraction process and difficulties in melting and fabrication process. They are characterized by poor machinability because of high chemical responsiveness and low thermal acuteness, excess cutting temperature and limited tool life because 80% of the generated heat during their machining has adverse effect on cutting insert so It is quite problematic to achieve better quality along with cost effectiveness during micro machining of Ti-alloys.Ti-6Al-4V (also sometimes called Ti64) is an alpha beta titanium alloy with high strength to weight ratio and brilliant corrosion resistance is one of the most commonly used titanium alloys with a wide range of applications such as gas turbines, marine applications, aerospace industry and biomechanical applications. As TC4 has poor thermal conduction along with high chemical reactivity so there exist many machining challenges in its machining so it is very necessary to investigate these problems and determine their appropriate solutions.

The finishing of surface, cutting forces and wear of cutting inserts are associated to heat engendered at cutting zone and abrasion between tool and work interface while in order to get better surface finish and minimum wear, effective lubrication method must be introduced during machining [8]. Cutting speed has a major impact (72.3%) for minimizing roughness of surface while feed rate has second leading impact (17.49%). To attain better surface finish PCD insert was recommended for machining of Ti-6Al-4V. The optimal experimental conditions for cutting forces and roughness of surface were attained when speed of cutting is maintained to 180m/min. The resultant cutting force has an inverse relation to the cutting speed while directly related to the feed rate.

In machining Ti-6Al-4V the dominant wear modes observed so far are non-uniform flank wear and coarse wear. The wear of the cutting insert experimentally observed can be reduced by high cutting speed and low feed rate sacrificing quality of surface with dominant ploughing effect on cutting zone leading to premature tool failure and burr formation because of low feed rate [9]. The analysis indicated that 110m/min results in longest tool life (91min) with the increase of 83% in material removal rate and productivity. As there exist rapid chipping and fracture of cutting edge, Cubic Boron Nitride (CBN) and super abrasives like ceramics are not helpful for machining of Ti-alloy. Very low surface integrity status of machined surface has been achieved using ceramic tools [10].

The higher speed of cutting led to higher cutting forces, specific cutting power and energy inducing higher mechanical and thermal stresses ultimately results in rapid tool wear. The wear mechanisms were the collaboration of thermal wear and mechanical wear. The low feed rate along with the combination of high cutting speed is most favorable for cutting forces. At several cutting conditions with the variation in cutting parameters coated inserts performs far better than uncoated tools while as compared to flooded and dry scenario it is quite favorable to perform machining at minimum quality lubrication. In faster machining less tool wear was observed during dry machining using coated tools as compared to that of without coating. Smoother surface finish with lower surface roughness was achieved while using carbide tool with coating of AlTiN, hence coated tools are proved to be more effective for machining of TC4. In dry machining the surface roughness and machining time were found to be lower compared to flood coolant machining. Small spherical defects on machined surface of Ti-6Al-4V were observed in both high and conventional speed machining processes. With the usage of flood coolant, the orientation and grain size are not affected by both high speed and conventional machining processes as temperature was in control to avoid the transformation of phases. An efficient cutting tool not only enhances productivity but also helps in minimizing the reconditioning tool cost.

The optimum values of rake and clearance angles are -50 to +100 and -50 to +80 respectively [11]. Feed rate is inversely related to tool life as feed into the work piece increases, it leads to the high temperature build up on the cutting insert resulting in its wear and reducing its life [12]. Similarly, with the increase in speed of cutting tool life is affected adversely and require regrinding or replacement. Flank wear of cutting tool is most preferably considered as tool life criteria as it determines the appropriate machining accuracy, reliability and stability.

2.2 Machining of Titanium Alloys (Ti-6Al-4V)

Commercially pure titanium has alpha structure and exhibits more corrosion resistance but titanium alloys have better mechanical properties than titanium itself. In comparison to beta alloys of titanium, alpha alloys have higher heat resistance and easy to weld but lower strength and workability. The chemical reactivity and low thermal conductivity of Ti-alloys are most degrading factors for Titanium alloys machining. α−β TC4 alloy is the most prevalent (60%) of all Ti-based alloys being used. Ti-6Al-4V comprises of maximum contents of Titanium (90%) along with aluminum and vanadium in small proportions as publicized in table below.

Table 2 Composition of Ti-6Al-4V

Constituent	Wt.%
Ti	90
Al	06
V	04
Fe	0.25 (max)

The low thermal conductivity of Ti-alloys lead to rise the temperature of cutting tool edge during machining which ultimately results in rapid tool wear due to high temperature and strong adhesion among the material of tool and workpiece. Although lot of work has been done to investigate and analyze the tool condition while machining Ti-alloys but still there is room to study tool behavior while machining at low cutting speed with single, mufti and uncoated tools and selecting the appropriate tool with minimum tool wear among these while machining Ti-alloys and also investigate the impact of cutting forces at low cutting speed upon these tools. The physical and mechanical properties of Ti-6Al-4V are shown in table 2 and 3 respectively.

Table 3 Physical Properties of Ti-6Al-4V

Material	Density (g/cm3)	Melting Point (°C)	Thermal Conductivity (W/m.K)	Specific Heat Capacity (J/g.°C)	Co-eff of Thermal Expansion 0-500°C (µm/m.°C)
Ti-6Al-4V	4.43	1674	6.7	0.5263	9.7

Table 4 Mechanical Properties of Ti-6Al-4V

Material	Tensile Strength (MPa)	Yield Strength (MPa)	Poisson’s Ratio	Elastic Modulus (GPa)	Shear Modulus (GPa)	Hardness Brinell (HB max)
Titanium 6Al-4V	≥895	≥828	0.31	105-120	41-45	334

2.3 Tool Wear Mechanism

Cutting inserts are actually exposed to a severe rubbing process as they face metal to metal contact while machining any job. The original shape of the tool changes because of gradual loss of tool material during cutting. Tool wear is actually defined as “Steady loss of material of cutting inserts at tool work piece interface resulting the cutting insert to reach its life limit. The time duration up to which tool can machine the parts properly without any requirement of regrinding or replacement is said to be tool’s life. Tool life actually depends upon the nature of material of which tool is made as well as with cutting conditions. The cutting tool wear depends upon following parameters

- Material of cutting insert being used and work piece under process
- Tool shape
- Machining Parameters such as speed of cutting, feed, depth of cut

The wear of the tool ultimately results in increase in cutting forces and cutting temperatures while on the other hand accuracy of machined parts and tool life is decreased Which ultimately lead to poor surface finish.

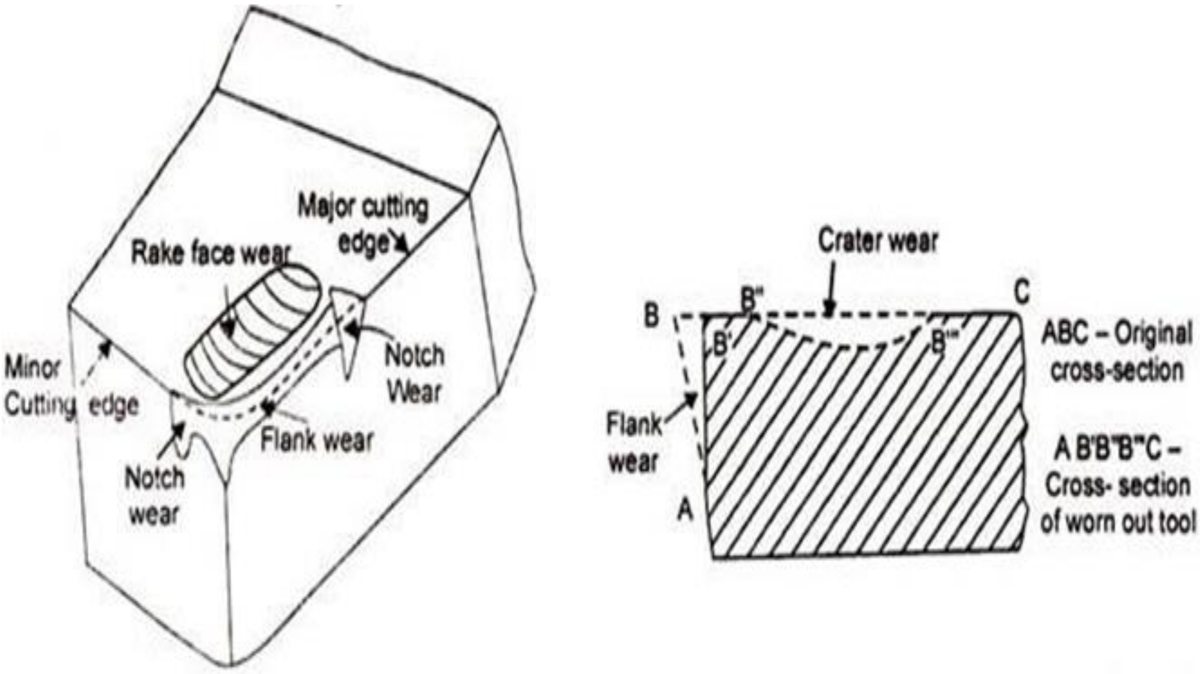


Figure 2 Tool Wear and Flank Wear Phenomenon

2.4 Types of Tool Wear

1. Flank Wear
2. Crater Wear

2.4.1 Flank Wear:

Wear on the flank face (relief or clearance face) of the tool is called flank wear. During machining there exists friction between tool’s flank face and machined surface of work piece which lead to adhering the tool particles upon surface of work piece and sheared off periodically [13].

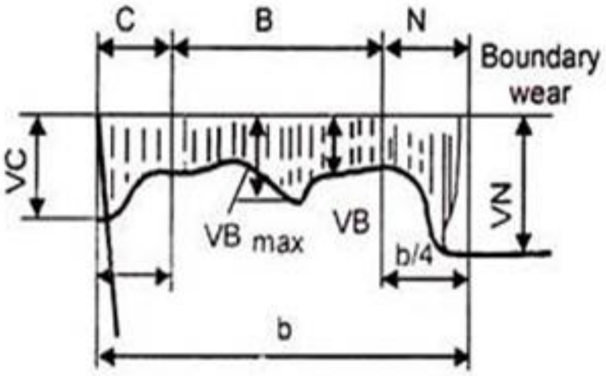
Flank wear of cutting tools is often selected as tool life criteria as it determines the appropriate machining accuracy and stability.

2.5 Characteristics of Flank Wear

- It usually appears on the flank surface parallel to the cutting edge.
- Abrasive or adhesive wear of cutting edge against the machined surface is actually a major cause of flank wear.
- High temperature is also one of its major impacts of flank wear which adversely affects the tool and work material properties.
- It leads to the wear of land formation.

2.5.1 Severe Flank Wear Effects

- Cutting Force Increases
- Component Surface Roughness Increases
- Adversely affect the dimensional accuracy of component
- Change the geometry of component being produced



(a)

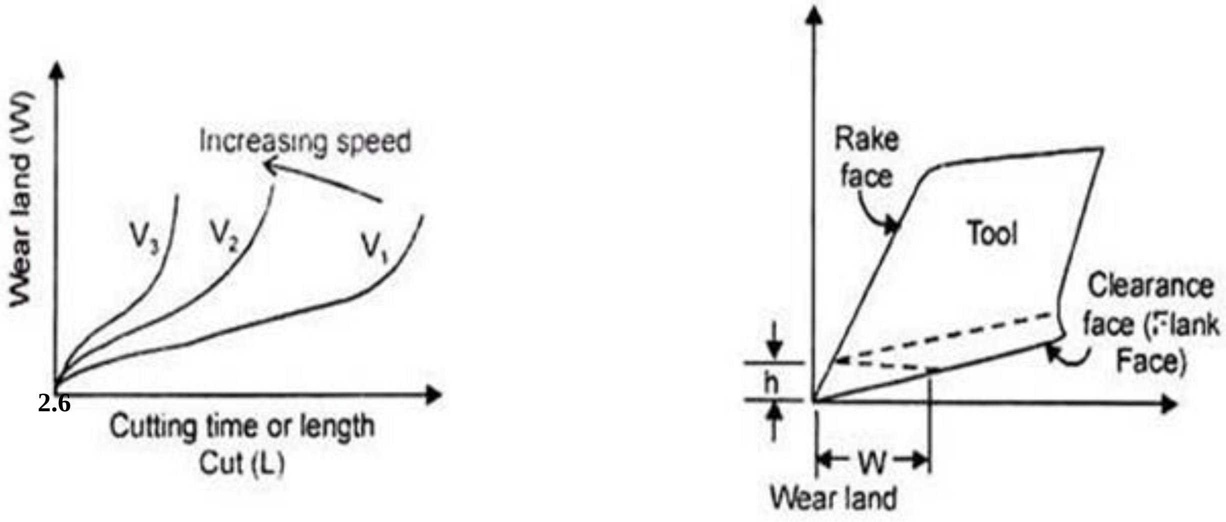


Figure 3a) Maximum and Average Flank Wear (b) Effect of cutting time on Flank wear (c) Flank Wear

2.7 Crater Wear

When supporting part of cutting tool moves forward with velocity than metal is removed from shearing plane by shearing action and chips flows from rake face causing friction between the chips and tool face, heat is generated due to friction, which results in changing the tool geometry [14]. This wear is said to be Crater Wear as shown in fig below.

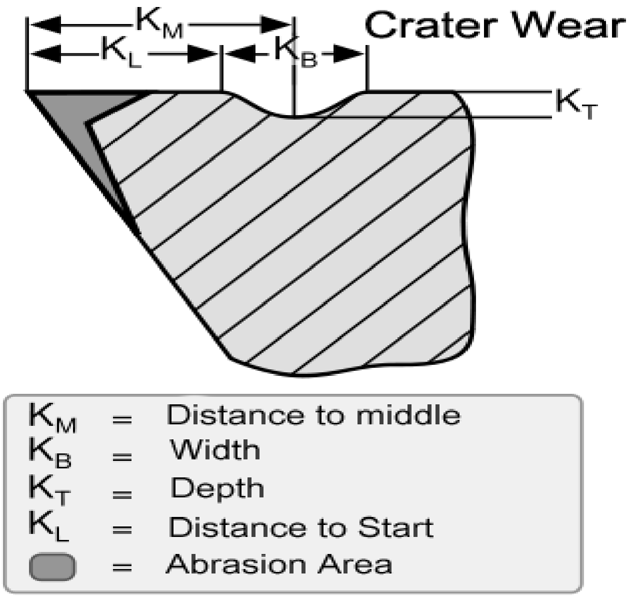


Figure 4 Crater Wear

2.7.1 Characteristics of Crater Wear

- Crater wear actually damages the rake face of the tool..
- Crater wear results in weakening of cutting edge
- Crater wear is more common in ductile materials which are capable of producing long continuous chips like steels.
- Crater wear occurs usually at high temperature zones (near 700°C)

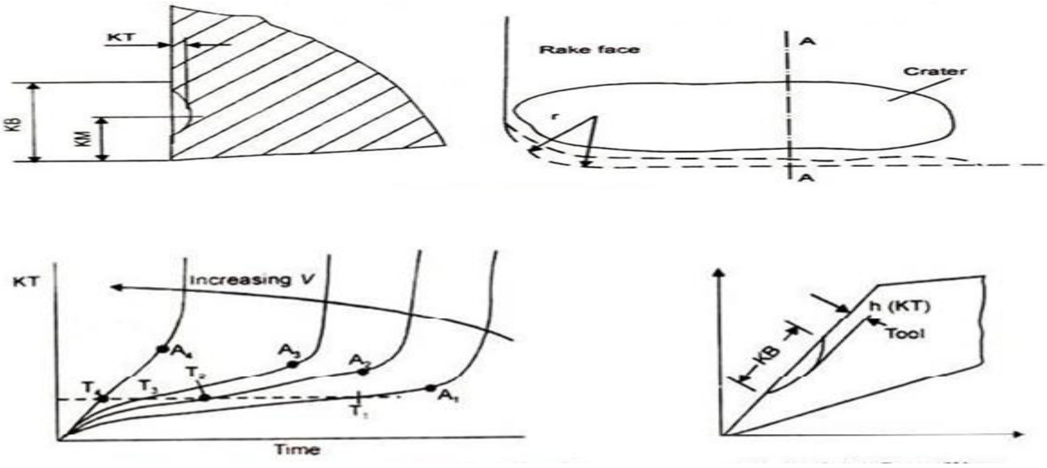


Figure 5 Effect of cutting speed V and cutting time on crater wear depth

2.7.2 Growth of Tool Wear

There are different stages of tool wear during machining. The tool wear eroded with the passage of time and ultimately lead to failure or breakage of tool.

2.7.3 Initial, Preliminary or Rapid Wear Zone

The growth of wear is rapid for new cutting edge. The major causes of this rapid wear are oxidation, micro cracking, and carbon loss layer. Micro-roughness of tool tip grinding.

2.7.4 Steady Wear Zone

The rate of wear becomes constant after the initial wear. In this stage wear rate is actually proportional to the time of cutting.

2.7.5 Severe/Ultimate/Catastrophic Wear Zone

Finally, the growth of wear is much faster in this zone and leads to the disastrous failure of the cutting edge. When the wear size increases to the critical value cutting forces and temperature increases rapidly and wear rate increases too.

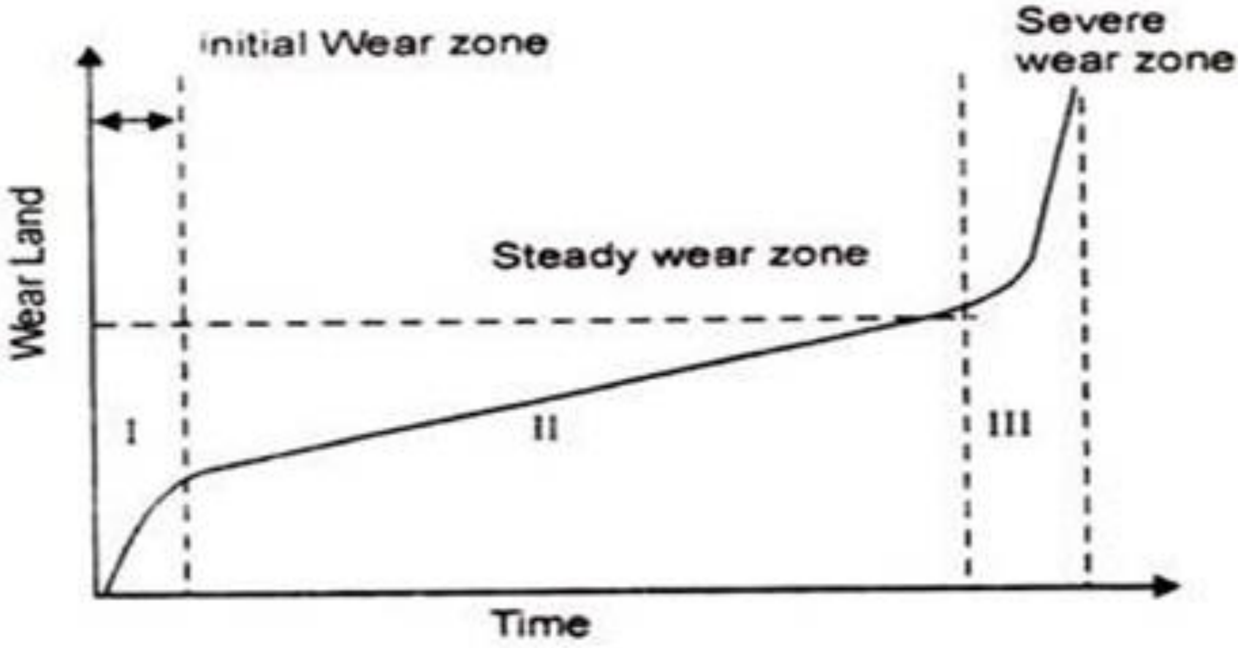


Figure 6.The Growth of Tool Wear

There exists specific range of width wear land for specific operations being performed and specific type of tool being used (H.S.S tools or Carbide tools) as shown in tables below. While exceeding these limits leads to poor surface finish, un even cutting forces and sudden breakage of cutting inserts being used.

Table 5 Allowable width of wear land VB for various operations and cutting tools

Operations	Allowable Width Wear Land (VB)
Precision Turning	Below 0.2 mm
Finish Turning	0.3mm to 0.4 mm
Rough Turning	0.6 t0 1.2 mm
Wheel Set Turning	1.2 to 1.5 mm
Roll Turning	1 to 1.5 mm
Precision milling	Below 0.2 mm
Finish milling	0.3 to 0.4 mm

Operations	H.S.S Tools	Carbide Tools
Turning	1.5mm	0.4mm
Face milling	1.5mm	0.4mm
End milling	0.3mm	0.3mm
Drilling	0.4mm	0.4mm
Reaming	0.15mm	0.15mm

Chapter3

3.1 Materials and Method

The tests for machining were carried out on CNC milling center, in which TC4 was used as material of the workpiece. The cutting inserts used for micro milling experiments of TC4 were ultrafine Tungsten Carbide Solid End Mill cutters (with and without coatings).The tools used were flat end mill cutters, with two flutes and diameter of 500 μm ,helix angle of 35° while length of tool was 50mm as shown in fig below

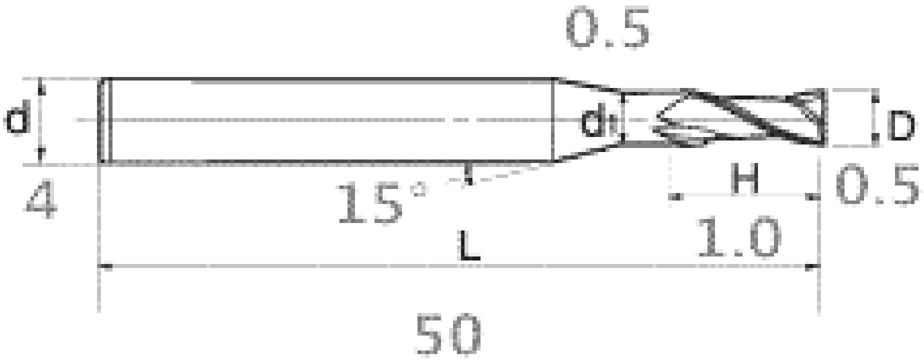


Figure 7 Solid Carbide End Mill Cutter

The block dimensions mounted on the fixture were 10 x 20 x 10 mm, undergoing full immersion milling. Slots of 10 mm (length wise) were machined in each trial. For each experiment three independent runs using three different inserts of same type (uncoated, single layered and multi layered coating) under the same cutting conditions were carried out in order to estimate error variance. Taguchi method is preferred in order to examine the results as it is considered to be robust design techniques widely used in industries. It actually led to minimization of variation the process maintains and promoting the stability of quality, limiting the experiments numbering followed by improvement in processing quality. Taguchi recommended the specially intended arrangement called orthogonal array to study the several constraint space with least number of trials to be carried out.

3.1.1 Orthogonal Array Selection

I selected 9 experiments to be performed for my experimental work taking three readings for each individual experiment and then compiling their mean values as experiments to be conducted are fixed as per following formula

DOF = P*(L – 1)

Where

DOF = Degree of Freedom

P = Number of Factors = 4

L = Number of Levels = 3

(DOF) = 4(3 – 1) = 8

The total Degree of freedom of the orthogonal array should be equal or greater than total degree of freedom required for experiment. Thus, in order to perform experiment with 4 factors and 3 levels L9 Orthogonal Array is selected.

Basic steps that are involved in Taguchi DOE technique are:

Step 1: Determination of characteristic of quality which have to be optimized.

Step 2: Identifying the control features and their alternative levels.

Step 3: Identifying the noise factors and test conditions.

Step 4: Designing of experimental matrix and defining the procedure for data analysis

Step 1

Determination of the **quality characteristic** and **Objective function**

- Cutting Forces (N)
- Tool Wear

Step 2

Identifying the **control factors** and their alternative levels

• Cutting Speed (m/min)	5	7.5	10
• Cutting Feed (µm)	8	10	12
• Depth of cut (µm)	50	75	100
• Tool being used	uncoated	AlTiN coated	nACo coated

Step 3

Identifying the **noise factors** and test conditions

- Experimentation Condition
- Operator skill

Step 4

Orthogonal array selection

- L9

Step 5

Conduct **Experimentation**

- Perform experiments as per orthogonal array

3.2 Parameters Selection

The levels of prescribed factors shown in table 5 were selected according to the following criteria.

3.2.1 Cutting Speed

The reported speed of cutting in literature varies between 16m/min (10,000rpm) and 141 m/min (90,000rpm) [15] .The focus of this study is to investigate the machining effect upon cutting inserts below reported cutting speed hence cutting speed was selected below 16m/min (10,000 rpm).

3.2.2 Feed per Tooth

Simple Electron Microscope was used to determine the edge radius of cutting inserts and their average value was calculated that was measured for uncoated tool to be 4.04 µm while for AlTiN coated tool it was 3.37 µm and for multi coated tool it was 2.78 µm.

Jeffery et al in his research work concluded that if feed/tooth was selected below edge radius than residual effects were more dominant and significant [16], hence in order to reduce the residual effects, the feed rate was considered above the edge radius. So feed rate selected for this research work held between 8 and 12 µm tooth−1.

3.2.3 Depth of Cut

According the tool diameter being used there exists recommended depth of cut to be considered. For tool diameter 3.18 mm and under

Depth of cut = tool diameter x (0.05 to 0.25)

Minimum a_p = 0.5 x 0.05 = 0.025mm = 25 µm

Maximum a_p = 0.5 x 0.25 = 0.125 = 125 µm

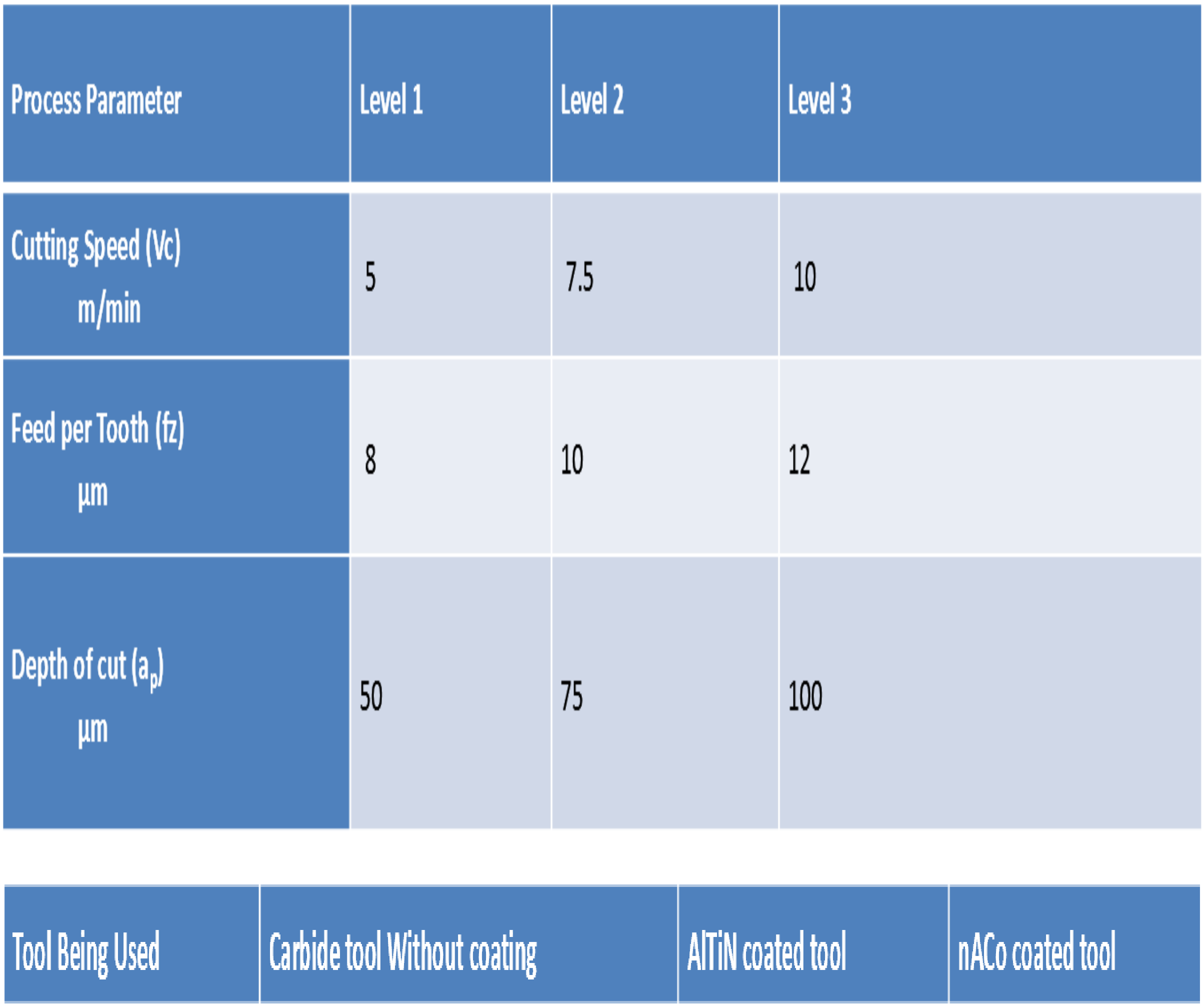
Hence cutting depth was nominated between 25 µm and 125 µm. The revolution (per minute) of the spindle (N) and feed speed ($\boldsymbol{Vf}$) can be determined using the equations (1) and (2) respectively.

$N= Vc\pi\ x\ D$ (1)

$Vf=f\ x\ N\ x\ z$ (2)

The details of parameters and level design are shown in table 8

Table 6 Process Parameters



Process Parameter	Level 1	Level 2	Level 3
Cutting Speed (Vc) m/min	5	7.5	10
Feed per Tooth (fz) µm	8	10	12
Depth of cut (a_p) µm	50	75	100

Tool Being Used	Carbide tool Without coating	AlTiN coated tool	nACo coated tool

3.3 Experimental Design and Setup

Experimental Design was based on Taguchi's L9 orthogonal array with 3-Levels and 4-factors. Four independent factors of speed of cutting, feed/tooth, depth of cut and tool being used were considered. The conditions of experiment are reported in table 7.

Table 7 Experimental Conditions

f_z (µm/tooth)	V_c (m/min)	a_p (µm)	Tool bein Used	N (rpm)	Vf (mm/min)
8	5	50	Uncoated	3183	50.93
8	7.5	75	AlTiN	4775	76.39
8	10	100	nACo	6366	101.85
10	5	75	nACo	3183	63.66
10	7.5	100	Uncoated	4775	95.5
10	10	50	AlTiN	6366	127.3
12	5	100	AlTiN	3183	76.39
12	7.5	50	nACo	4775	114.6
12	10	75	Uncoated	6366	152.78

Table 8 Experimental Conditions

Work piece	TC4 (Grade 5)
Milling Tools	2- Flute Tungsten Carbide Micro End mill 500µm (with and witho coatings)
Fluid for cutting	Dry Cutting
Length of cutting	10mm
Type of Milling	Full immersion

The experiments were performed using a FANUC MV-1060. Figure 8 shows experimental setup. After presetting of cutting insert it was introduced in tool holder and load cells connected to Arduino were introduced beneath the workpiece holder plate which was further connected to computer for conversion of analogue signals to digital signals as shown in fig. 8.

Figure 8 Magnified View of Experimental setup

Solid Carbide end mill cutter was used for micromilling of Ti-6Al-4V and load cell based dynamometer connected with computer through aordiano was used in order to convert analouge signals to digital for determining the resultant cutting forces for three different types of tools i.e. coated and uncoated tools for different cutting conditions respectively.

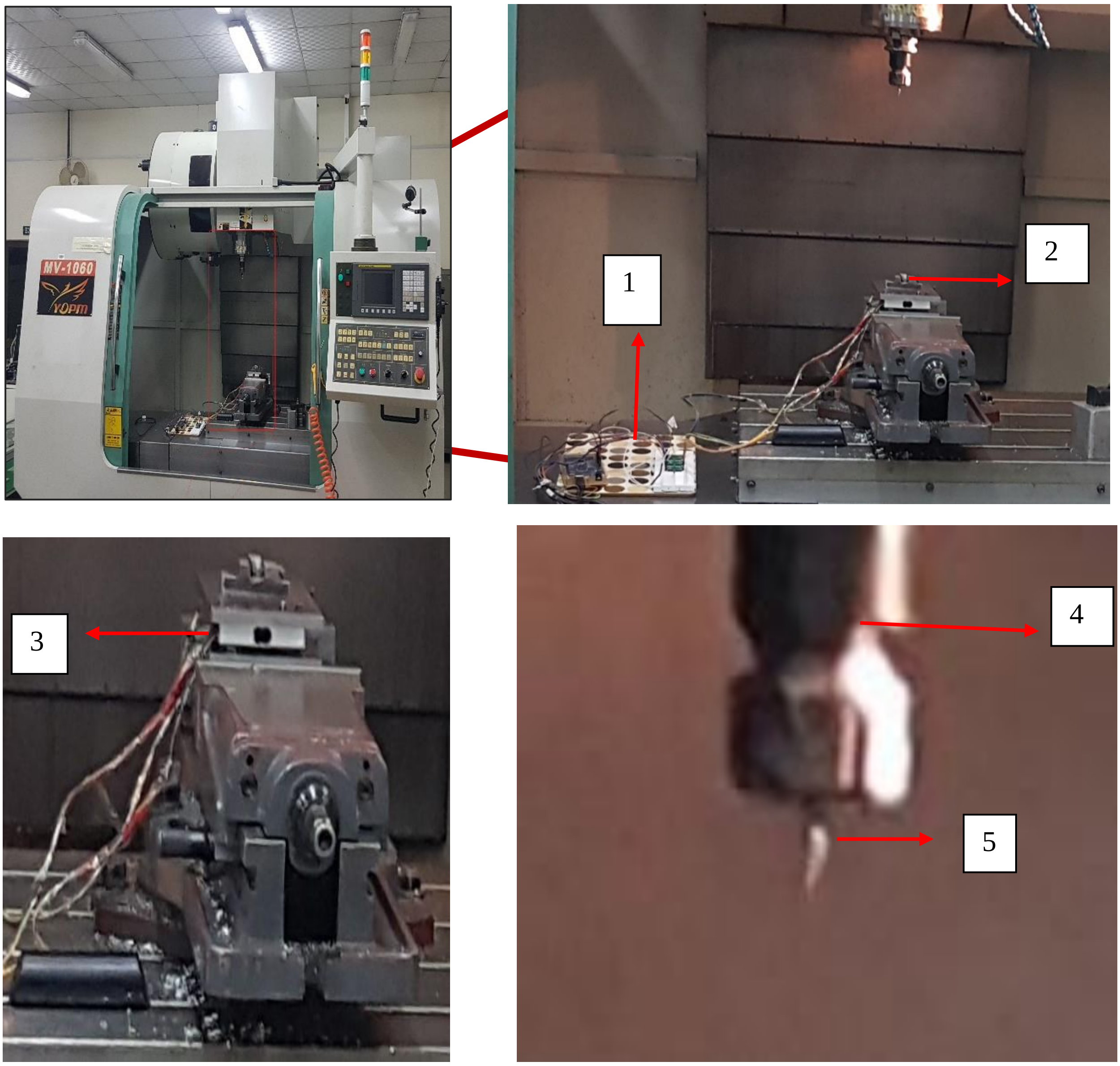


Figure 9 (1) Arduino (2) Workpiece (Ti-6Al-4V) (3) Load Cell Dynamometer (4) Spindle (5) Carbide End Mill cutter

3.4 Solid Carbide End Mill Cutters

Solid Carbide end mill cutters were used for micro milling of Ti-6Al-4V. Carbide cutting maintain their cutting-edge hardness at extreme temperatures generated by high cutting feed and speed which lead to the reduction of machining cycle time results in better quality and improved surface finish. Three Cutting inserts uncoated and coated carbide end mill cutters were used as shown in fig 10.

Figure 10 Solid carbide End Mill Cutters

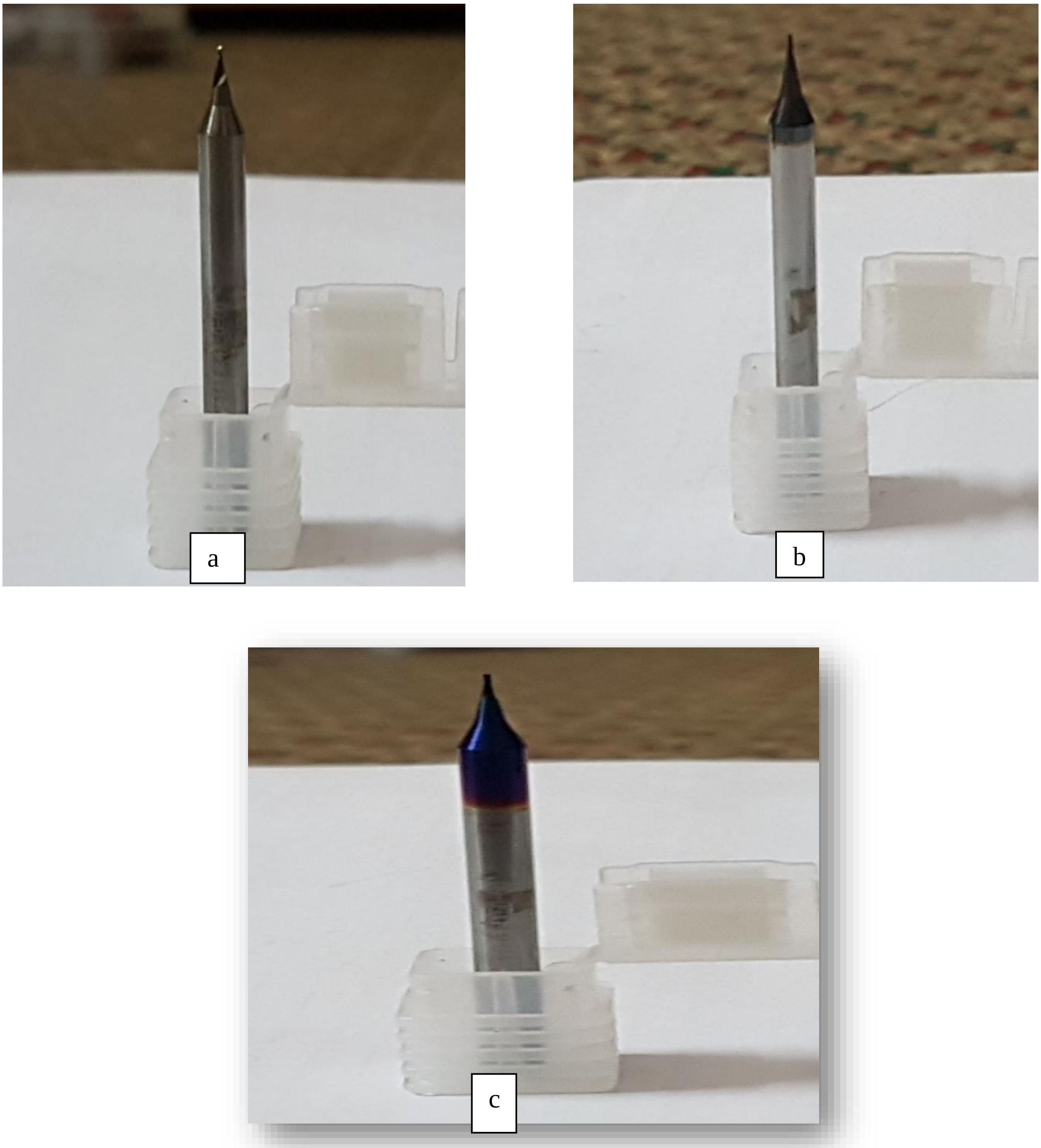


Figure 11.(a) Uncoated Carbide Tool (b) AlTiN Coated (c) nACO Coated

Simple Electron microscope with prescribed specifications was used to determine edge radius of each used tool prior to the experiment being performed. The edge radius of uncoated tool was calculated to be 4.04 µm and that of AlTiN and nACo (AlTiN and SiN coating) were 3.367 µm and 2.78 µm respectively.

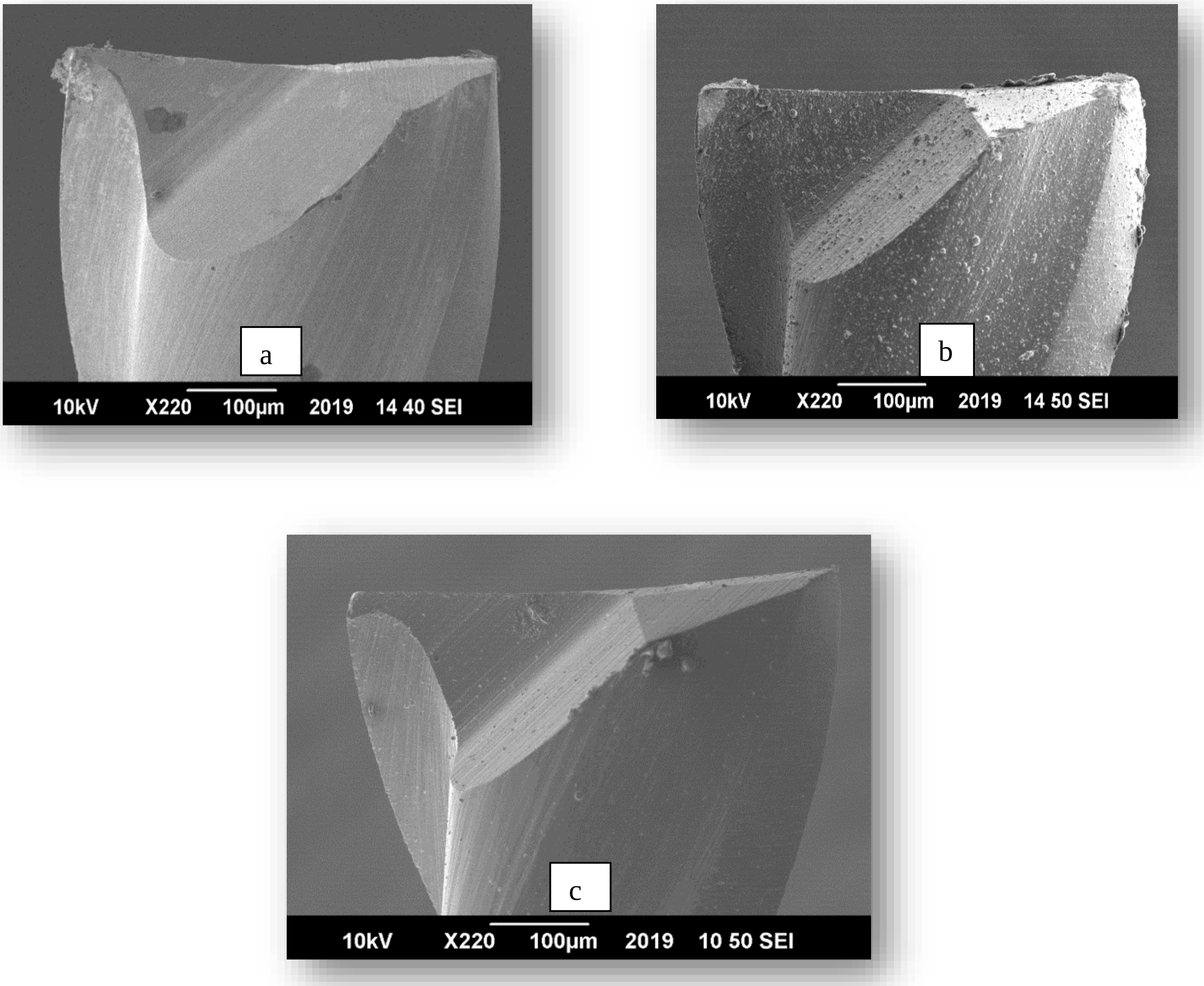


Figure 12 SEM Front view of (a) Uncoated Tool (b) AlTiN Coated Tool (c) nACo (AlTiN and SiN) Coated Tool

3.5 Micro Tool Presetting

Three different cutting inserts were used. Solid Carbide end mill cutters without coating AlTiN coated and multi coated tool. Away from machine tool the tools are being set in advance in special holders is known as tool presetting. A presetting device called tool presetor is used in order to preset axial and radial position of tool tip on tool holder.

Figure 13 Tool Presetor

Table 9. Tool Presetor Specifications

Tool Presetor Specifications	
Model	410V
Tool Diameter	180MM
Tool Length	300MM
Accuracy	0.001/100

It allows to kit up our jobs and change our machine being used in much more effective and quick manner. Tool offsets needed for accurate machining were entered in CNC. The specifications of tools such as diameter, length angles and cutting-edge radius are crucial for precision in machining process. The magnified view of tool being preset is shown below.

Figure 14 Magnified View of Tool Presetting

3.6 Load Cell based Dynamometer

Load Cell based Dynamometer is used in order to investigate the cutting forces. Load cells were interfaced with Mega2560, initially each load cell with a dedicated Mega2560 boards. Subsequently, 03 x load cells were interfaced with one Mega2560 by combining following wires in output wires of HX-711 with each other thus enabling them to share similar ports on Arduino Mega2560:

- PWR wires
- GND wires
- SCK Wires

The load cell installation and fitting assembly are shown in figure below

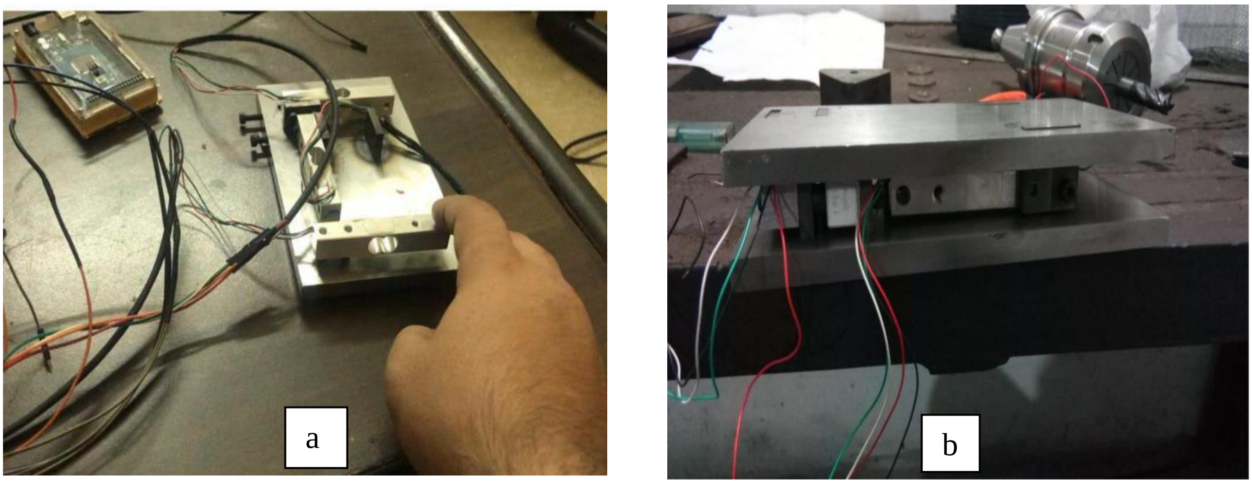


Figure 15 (a) Load Cell Installation *(b) Assembly Fitting*

Following circuit diagram illustrates interfacing of 01 x Load cell and 03 Load Cells with Arduino Mega2560 respectively:

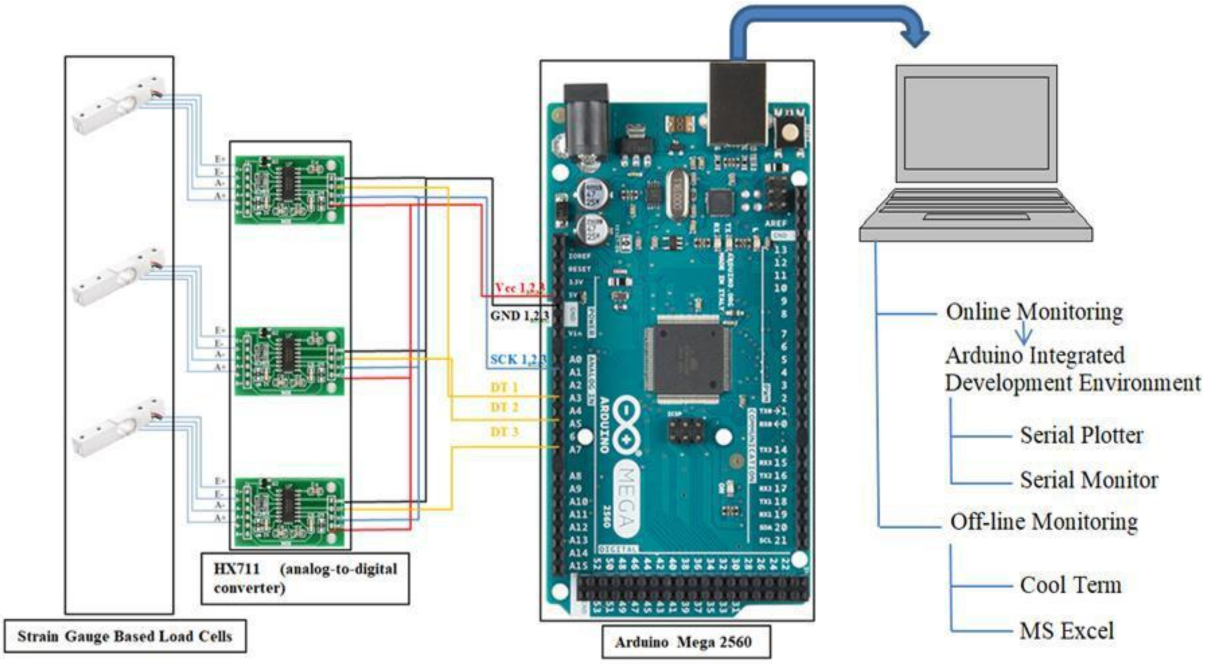


Figure 16 Interfacing Load Cells with Arduino Mega2560

Chapter4

4.1 Results and Discussions

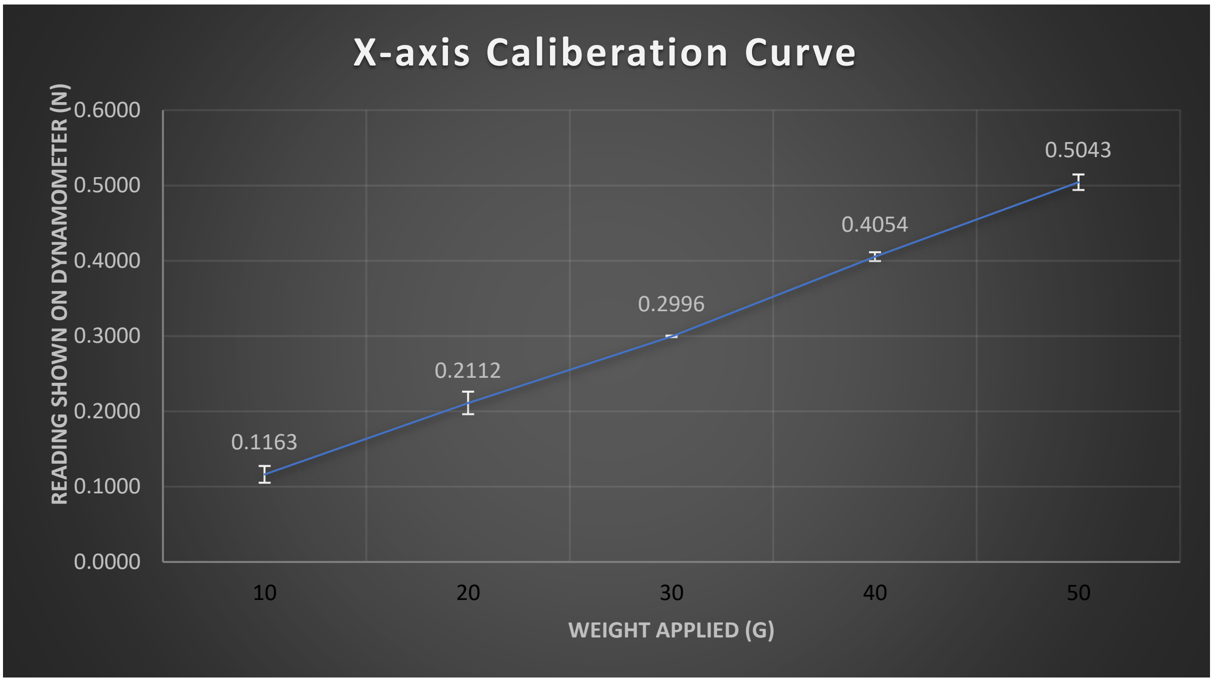
ANOVA technique was used for analysis of cutting forces and wear of cutting inserts during micro milling of TC4 using Taguchi Method L9 Orthogonal Array and results were compiled graphically and analytically and at 95% confidence level the effect of most significant factor upon cutting forces and tool wear were studied.

4.2 Analysis of Cutting Forces

The micro end milling is carried out to investigate the cutting forces at low cutting speeds and their ultimate effect on cutting inserts. Three cutting inserts uncoated, AlTiN coated and multi coated tool were investigated and then respective cutting forces on each tool was calculated. The structure of machine tools and work pieces is mainly deformed by forces of cutting in Micro-end milling which results in forming error and tolerance violation. The cutting forces are produced at restricted area of work tool contact. Load cell-based dynamometer was used in order to measure cutting forces in three directions of Fx, F_y and F_z respectively than forces were interrupted into the computer from signal analyzer. The resultant cutting forces were than calculated by Eq.1.

$$FR=\sqrt{Fx2+Fy2+Fz2}$$

Dynamometer was calibrated in X, Y and Z axis by Calibrating the load cells. Calibration curves were plotted, and illustrated below, as relation between applied load and subsequent readings in newtons along with functional testing of dynamometer in all respective axis. This attempt ensure us the proper working condition of dynamometer being used.



. *Figure 17 X-axis Calibration*

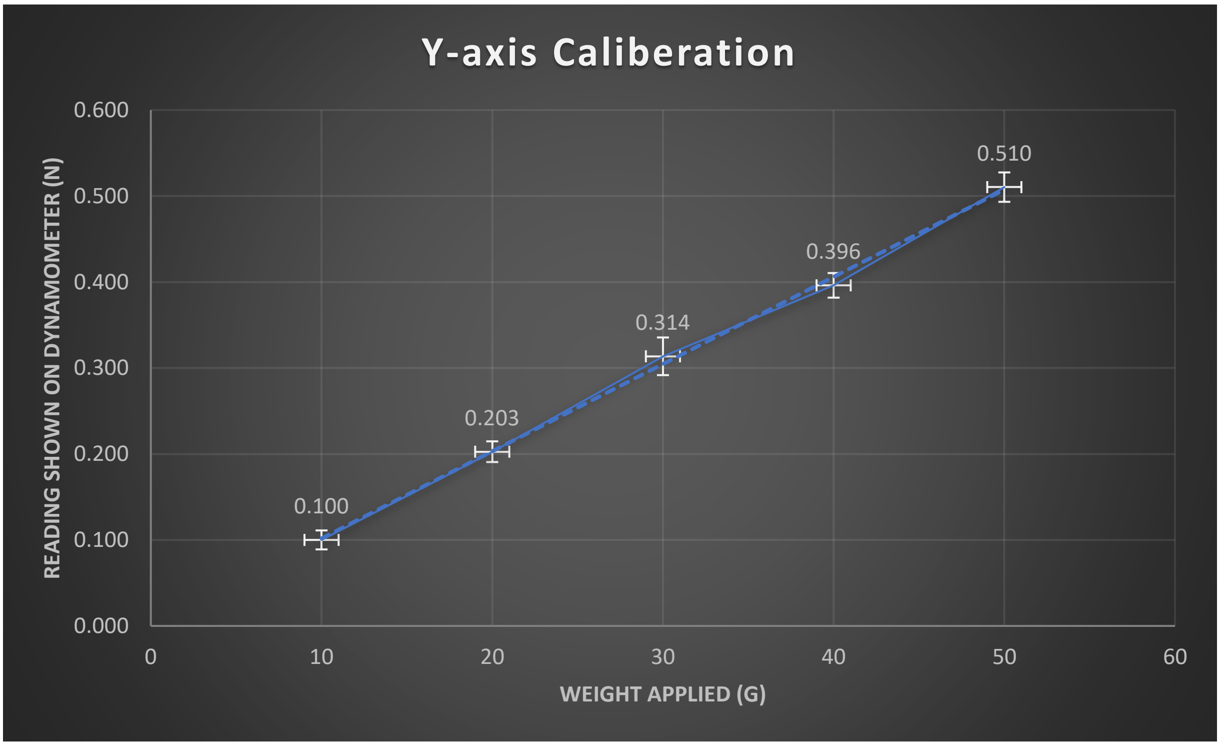


Figure 18 Y-axis Calibration

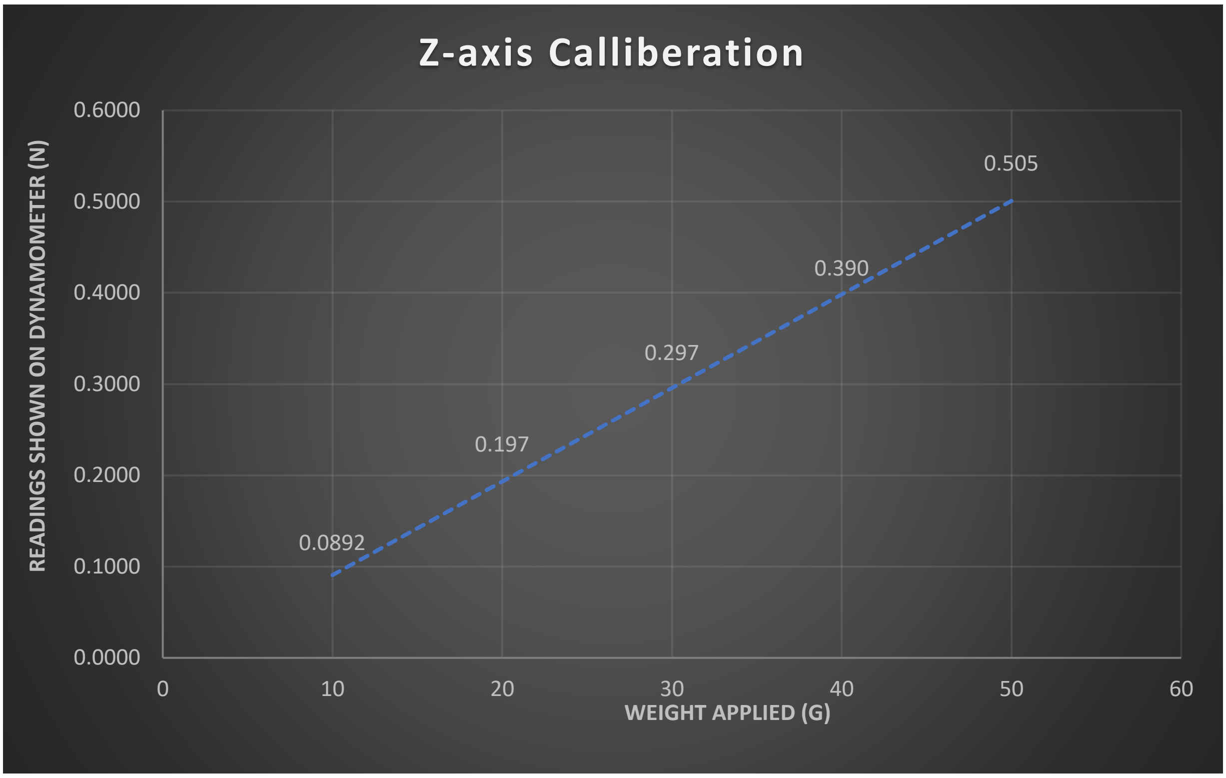


Figure 19 Z-axis Calibration

4.3 Micro milling with uncoated tools

From the results of experimentation, it was observed that cutting forces were more significantly affected by the cutting depth followed by feed rate and speed of cutting. The cutting forces for uncoated tools increased initially with the increment in feed rate as at low cutting speed led to extreme chances of vibration at tool work piece interface hence micro milling at low cutting speed led to increase in cutting forces with the increase in feed per tooth initially which ultimately results in slight reduction of forces with further increase in feed because of reduction in vibration. For uncoated tools with the rise in speed of cutting. Cutting forces decreases. Initially at very low cutting speed as the machining proceeds cutting forces increases but at certain level the vibration at tool work interface becomes less significant and lead to reduce in cutting forces with the increase in cutting speed. Cutting Depth have significant affect upon cutting forces at low-speed cutting, with the increase in cutting depth the cutting forces increases and vice versa.

It was observed that at low feed, speed and depth of cut, least cutting forces are produced while micro milling of Ti-alloys as in level 1. At level 2 the cutting depth was supposed to be at its extreme value which leads to cutting forces increment followed by increase in feed and cutting speed. At level 3 although there is significant increment in feed and speed of cutting but cutting forces decreases because of reduction in cutting depth. Hence it was concluded that for uncoated tools cutting depth has supreme effect on cutting forces. With the increase in cutting depth, cutting forces increases and vice versa.

4.3.1 Micro milling with AlTiN Coated Tool and multi coated tool

Micro milling with coated tools lead to better results as compare to that of uncoated solid carbide end mill cutter as friction can be reduced using coatings for cutting inserts, create enough grip and increase resistance to wear and cracking also coatings help in reduction of temperature which increases with the machining. AlTiN proved to be performed better at low machining speed as compared to uncoated tool but multicoated tool was observed far better than both uncoated and AlTiN coated tool as very low cutting forces were observed using multicoated tool. It resists the work material adhesion to the tool edge. Hence with the increment in depth of cut there exist prominent rise in cutting forces for all the cutting inserts being used i.e. coated and uncoated tools but as it is evident from the graph that there is very less increment in cutting forces for multicoated tools while machining at low cutting speed which lead to better finishing of machined part and increase the life of tool being used. Graphical representation showed that multi coated tool performed far better than uncoated and AlTiN coated tool in concern of cutting forces while machining at low cutting speed. AliN proved to be less good than that of multi coated tool but it is better as compare to uncoated tool as shown in graph.

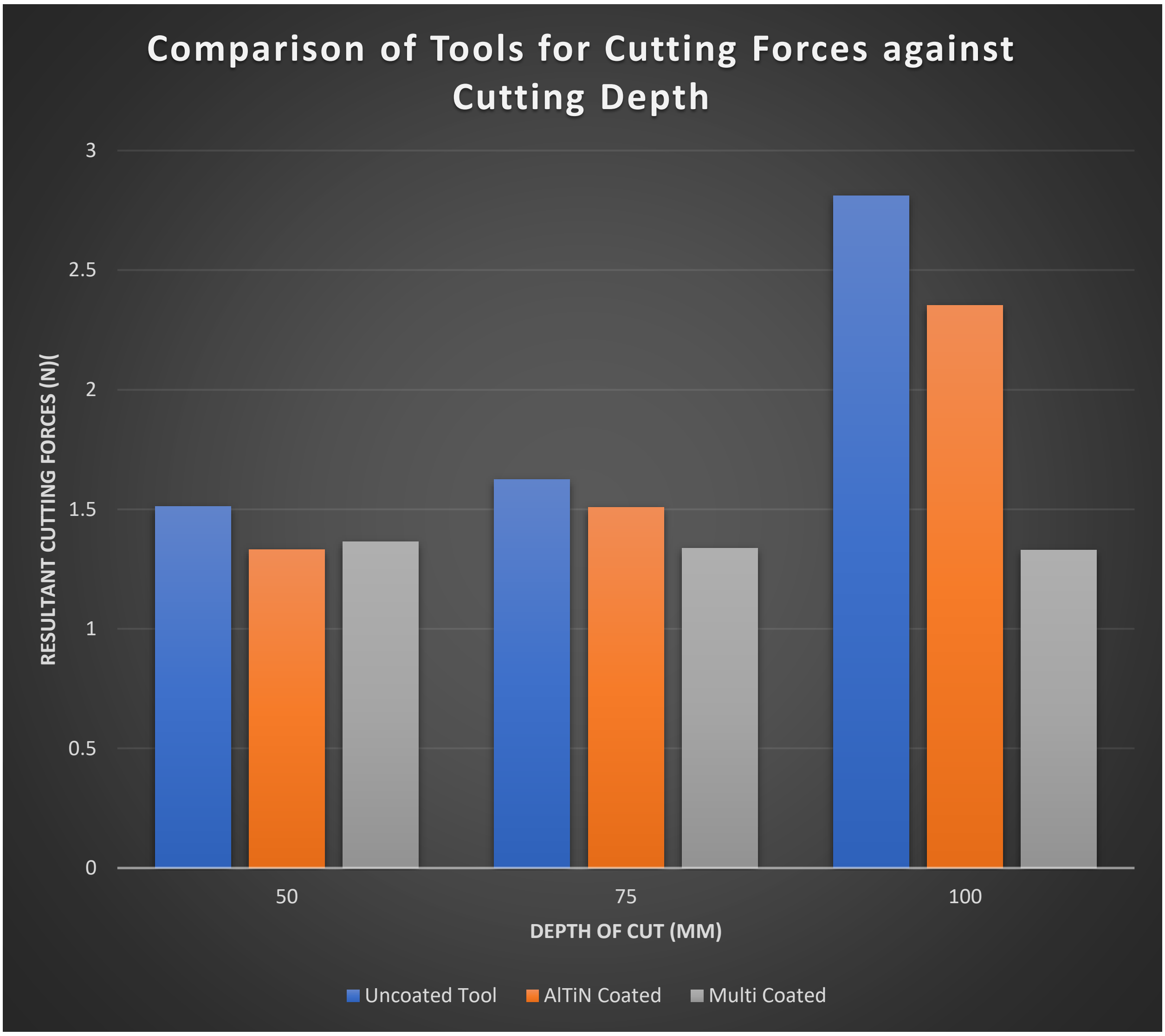


Figure 20 Assessment of (a) uncoated, (b) coated TiAlN and (c) multi coated tools for resultant cutting force (N) different Depth of cuts

With the significant increase in feed/tooth resultant cutting forces for multicoated tool is less as compare to both uncoated and AlTiN coated tool. While comparing uncoated and AlTiN coated tool initially with the increase in feed resultant cutting forces using AlTiN coated tool reduces but with the further increase in feed uncoated tool lead to perform better as compare AlTiN coated tool as with the increase in the feed coating of the tool cause resistance in machining which lead to increase in resultant cutting forces of coated tool as compare to that of uncoated tool. While same is the case with the variation in cutting speed but in all the cases the performance of multi coated tool is far better than both uncoated and AlTiN coated tool.

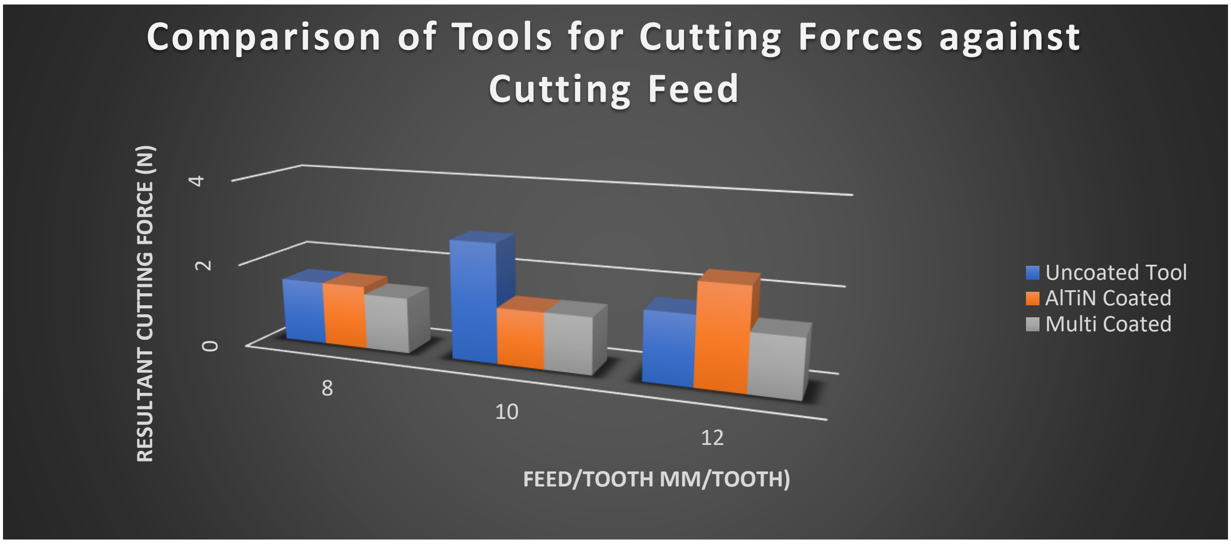


Figure 21 . Assessment of (a) uncoated, (b) coated TiAlN and (c) multi coated tools for resultant cutting force (N) different Feed

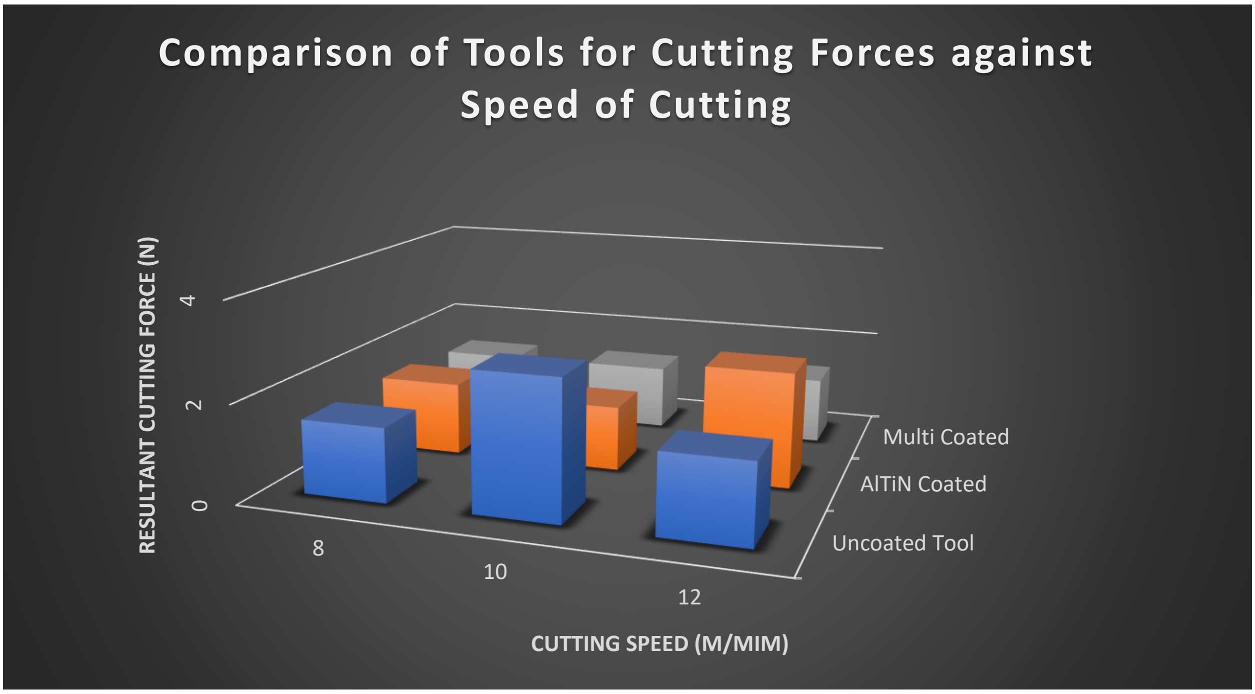


Figure 22 Assessment of (a) uncoated, (b) coated TiAlN and (c) multi coated tools for Resultant cutting forces (N) different cutting speeds

While micro milling at low-speed cutting depth has substantial affect with major influence of 44.45% followed by type of tool being used (uncoated, AlTiN coated, multi coated)26.46%, cutting speed 14.33% and feed rate 10.81%. Taughi Method was used for analysis of Resultant Cutting Force that comprises of three levels and four factors L9 Orthogonal Array. Response table for means and signal to noise ratio is shown below along with graphical representation.

Table 10 Experimental results of resultant cutting forces at different cutting conditions

f_z (µm/tooth	V_c (m/min	a_p (µm)	Tool being used	N (rpm)	Vf (mm/min)	Cutting Forces (N)		
8	5	50	Uncoated	3183	50.93	1.489	1.509	1.539
8	7.5	75	AlTiN	4775	76.39	1.398	1.438	1.690
8	10	100	nACo	6366	101.85	1.461	1.183	1.346
10	5	75	nACo	3183	63.66	1.293	1.316	1.406
10	7.5	100	Uncoated	4775	95.5	3.032	2.689	2.714
10	10	50	AlTiN	6366	127.3	1.219	1.438	1.339
12	5	100	AlTiN	3183	76.39	2.412	2.419	2.231
12	7.5	50	nACo	4775	114.6	1.303	1.413	1.379
12	10	75	Uncoated	6366	152.78	1.438	1.694	1.743

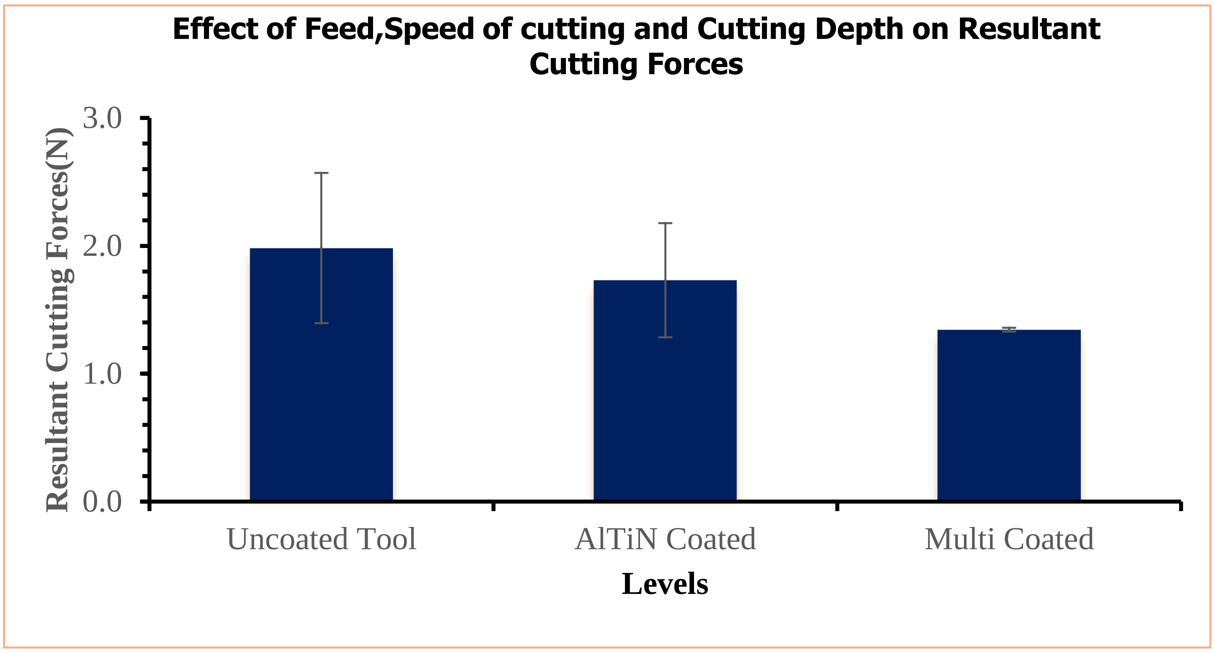


Figure 23 Effect of Feed, Cuttinfg speed and cutting Depth on Resultant Cutting Forces

Cutting Depth has important effect on cutting forces followed type of tool being used, Speed of cutting and feed. The mean effect plot for SN ratios for analysis of Taugchi Design is selected to be smaller the better. As it is evident the least will be the cutting forces while machining better will be the performance of cutting tool and workpiece being used. There will be less chances of instant tool breakage and rough finishing of workpiece.

Response Table for Signal to Noise Ratios

Level	fz (µm/tooth)	Vc (m/min	ap (µm)	Tools Used
1	-3.246	-4.524	-2.936	-5.611
2	-4.679	-5.101	-3.462	-4.518
3	-4.799	-3.098	-6.325	-2.595
Delta	1.552	2.003	3.389	3.015
Rank	4	3	1	2

Response Table for Means

Level	fz (µm/tooth)	Vc (m/min)	ap (µm)	Tools Used
1	1.452	1.735	1.403	1.983
2	1.827	1.895	1.491	1.731
3	1.781	1.431	2.167	1.346
Delta	0.375	0.465	0.764	0.637
Rank	4	3	1	2

As it is clear from the graphical representation that as the machining starts at low speed and feed tool has to bear excess vibration and resistance which ultimately lead to rise in cutting forces to a certain limit that with further increment in speed of cutting and feed the motion of the tool became smooth and lead to reduction of cutting forces. On other hand cutting depth has important effect on cutting forces as it increases the cutting forces increases and vice versa.

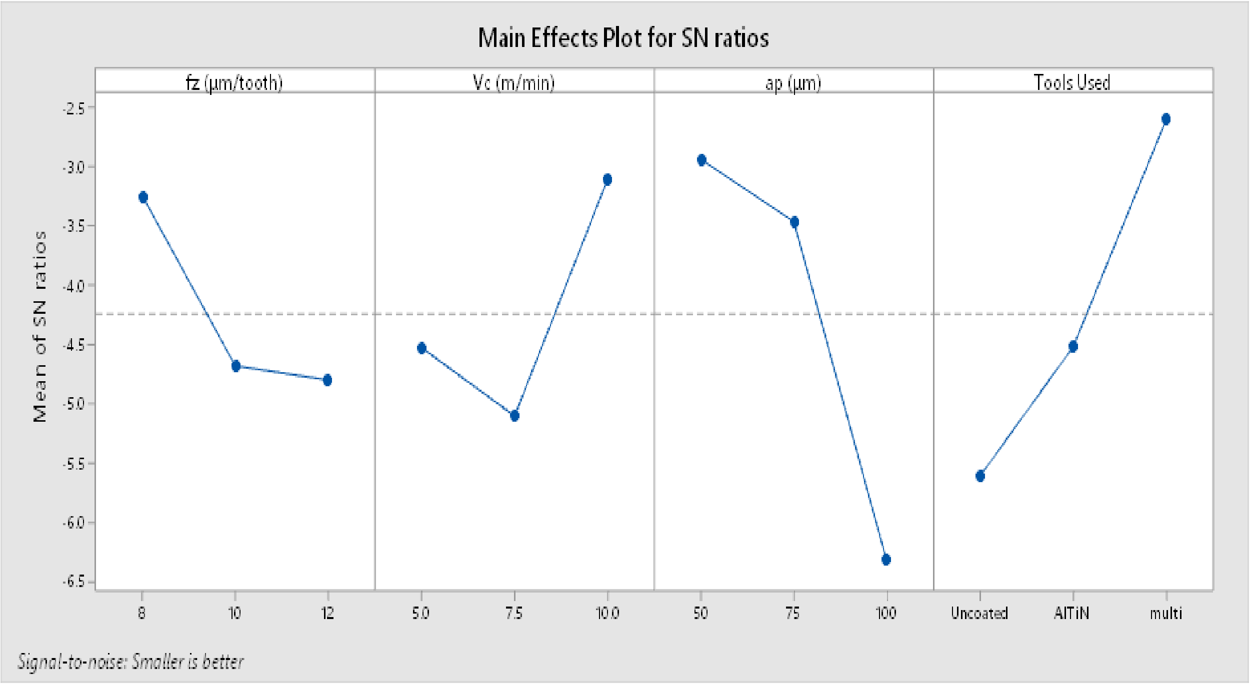


Figure 24 Signal to Noise Ratio (Smaller the better)

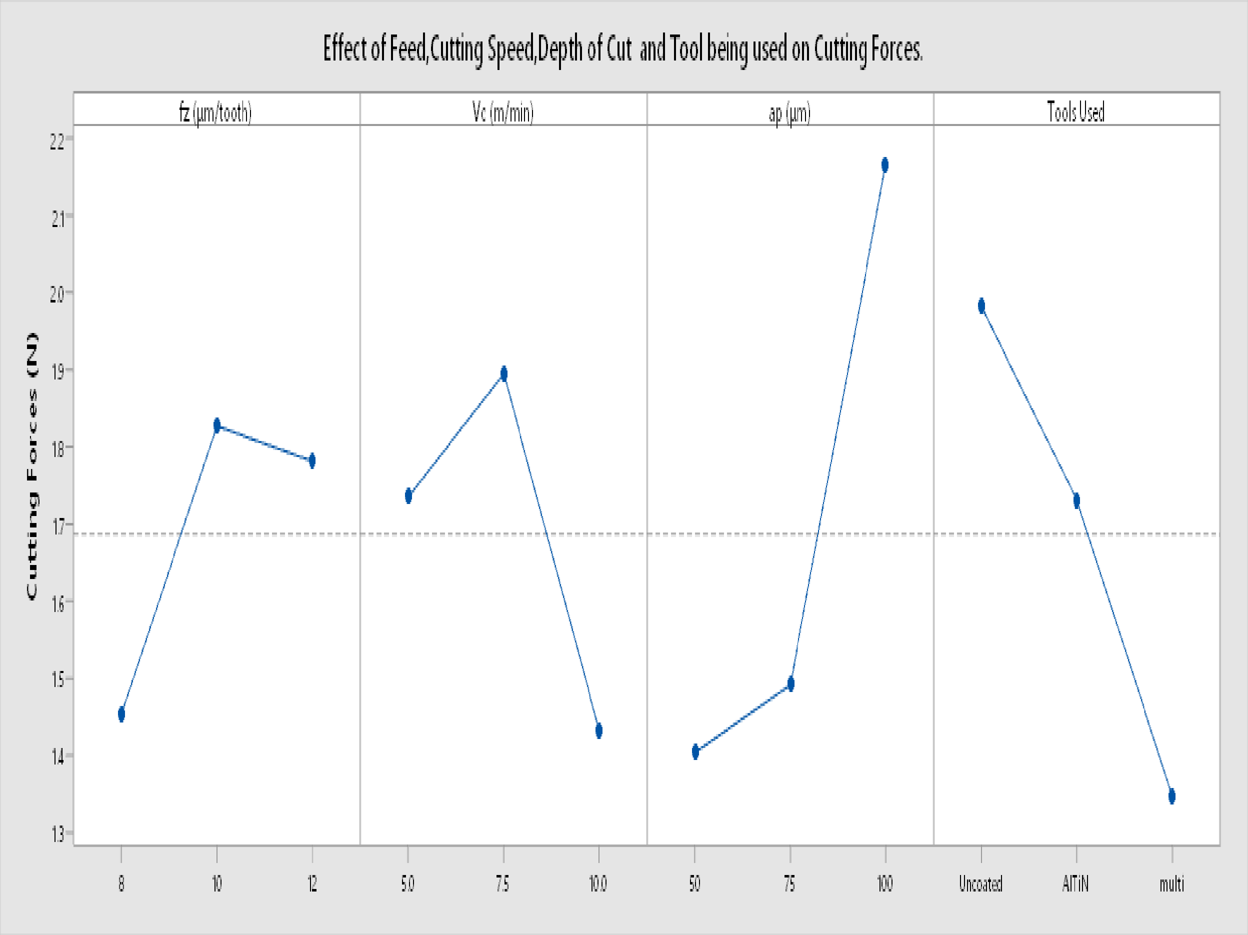


Figure 25 Effect of feed, cutting speed, Depth of cut and Tool being used on Cutting Forces

. While from whole experimentation it was observed that least forces are considered for multicoated (AlTiN and SiN coating) cutting insert as it resists the adhesion of work material at tool work interface and tip of the tool secondly coatings can lesser friction create enough grip and increase hinderance to wear and cracking. AlTiN coated tool also performed better than uncoated tool but they are not as good as multi coated tool.

4.3.2 Analysis of tool wear

The top view of solid carbide end mill cutters after micro milling of Ti-6Al-4V are shown in fig. below. Three tools of each category i.e., uncoated and both AlTiN and multi coated tools were mounted vertically in optical microscope and top view of each tool was observed to analyze the wear of cutting insert. Then average of the tool wear of each cutting insert were calculated and results for all three levels and four factors for each respective tool was collected in Minitab using Taguchi method (ANOVA) L9 Orthogonal Array.

Tool wear were analyzed in Optical micro scope at 20x magnification. Three tools of each coated and uncoated category were analyzed by holding the tool vertically inside the microscope in order to detect the top damaged or wear part of the cutting insert and ultimately their average wear was calculated.

Figure 26 Optical Microscope to analyze tool wear of cutting inserts

Results from ANOVA shows that tool wear was suggestively affected by speed of cutting with major influence of 67.59% followed by type of tool being used 18.96%. Feed rate and cutting depth also had slight affect upon wear of the tool with the contribution of 5.29% and 3.85% respectively. The complete detail of factors and levels Analysis of Variance are shown in table below.

Table 11.Analysis of Variance

Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Fz (µm/tooth)	2	7.156	5.29%	7.156	3.5782	11.04	0.001
Vc (m/min)	2	91.422	67.59%	91.422	45.7109	140.99	0.000
ap (µm)	2	5.204	3.85%	5.204	2.6018	8.03	0.003
Tools Used	2	25.648	18.96%	25.648	12.8242	39.56	0.000
Error	18	5.836	4.31%	5.836	0.3242		
Total	26	135.266	100.00%				

Three readings for three different slots on workpiece for each tool were taken and ultimately average tool wear for each cutting insert was calculated and results are compiled using Taguchi Method for Analysis of Variance It was detected that multicoated cutting insert showed least wear as compare to other two cutting inserts. With the increment in speed of cutting tool wear increases and vice versa.

Table 12 Tool Wear Analysis During Micro Milling of Ti-6Al-4V

f_z (µm/tooth)	V_c (m/min)	a_p (µm)	Tool used	N (rpm)	Vf (mm/min)	Tool Wear (µm)		
8	5	50	Uncoated	3183	50.93	7.098	6..987	7.434
8	7.5	75	AlTiN	4775	76.39	7.66	7.215	6.879
8	10	100	nACo	6366	101.85	9.5	10.55	9.03
10	5	75	nACo	3183	63.66	5.4	4.3	6.01
10	7.5	100	Uncoated	4775	95.5	11.51	12.13	10.6
10	10	50	AlTiN	6366	127.3	10.45	10.9	11.8
12	5	100	AlTiN	3183	76.39	6.6	6..645	7.03
12	7.5	50	nACo	4775	114.6	7.314	8.34	7.99
12	10	75	Uncoated	6366	152.78	12.21	11.83	11.01

Tool wear of all respective tools was observed under optical microscope as shown in fig below.

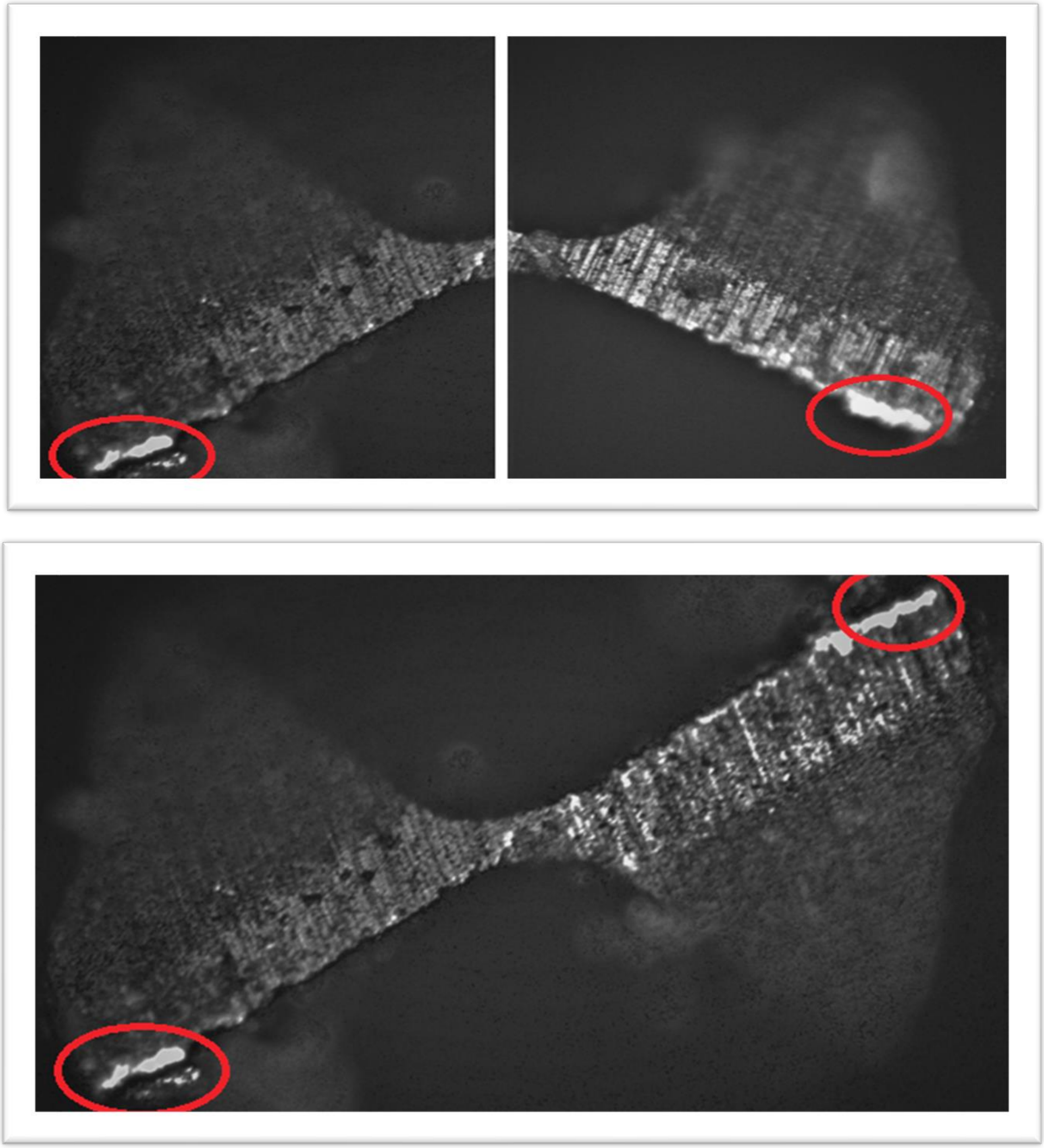


Figure 27 Tool Wear of Uncoated cutting inserts

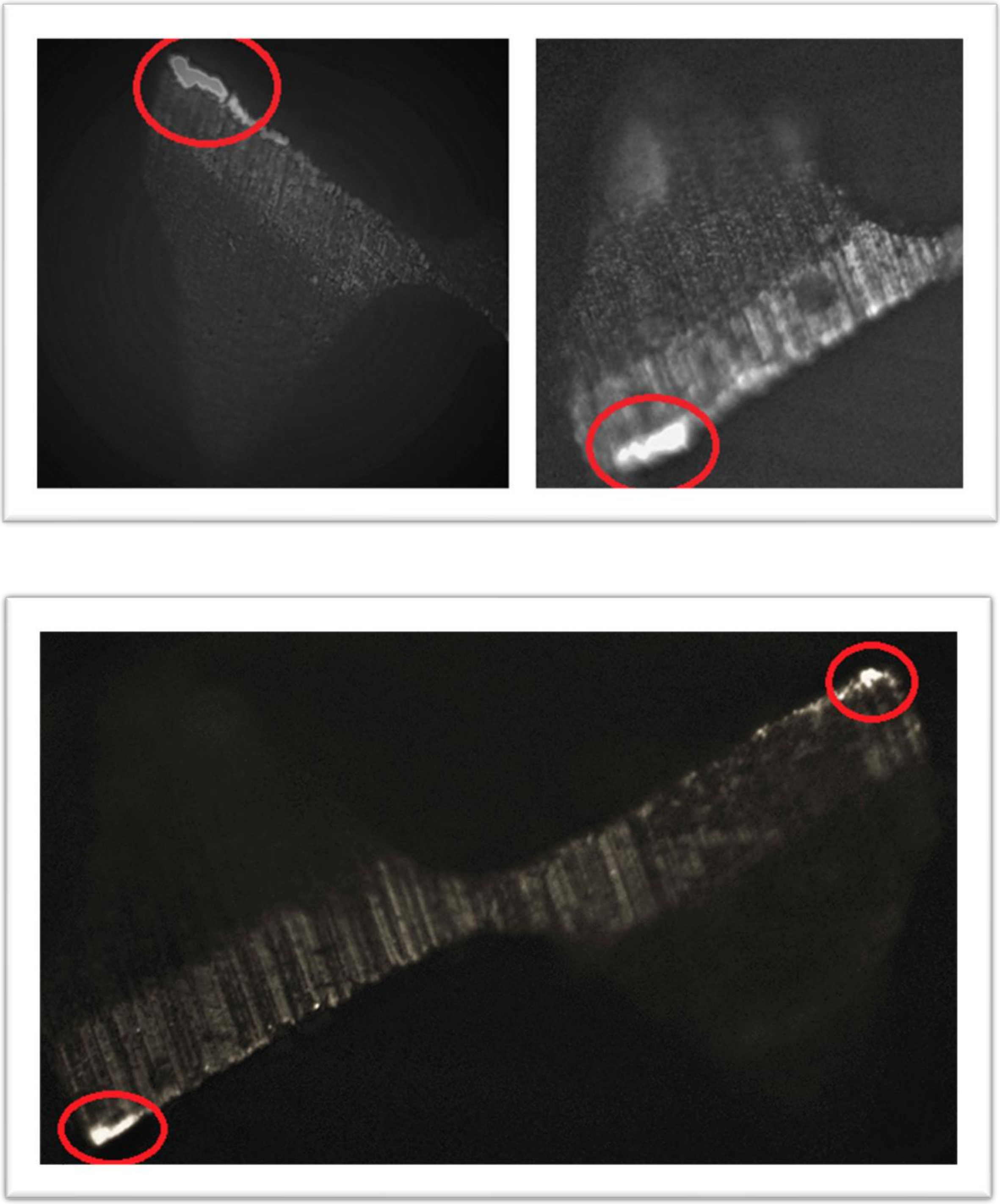


Figure 28Tool wear of AlTiN Coated Cutting Inserts

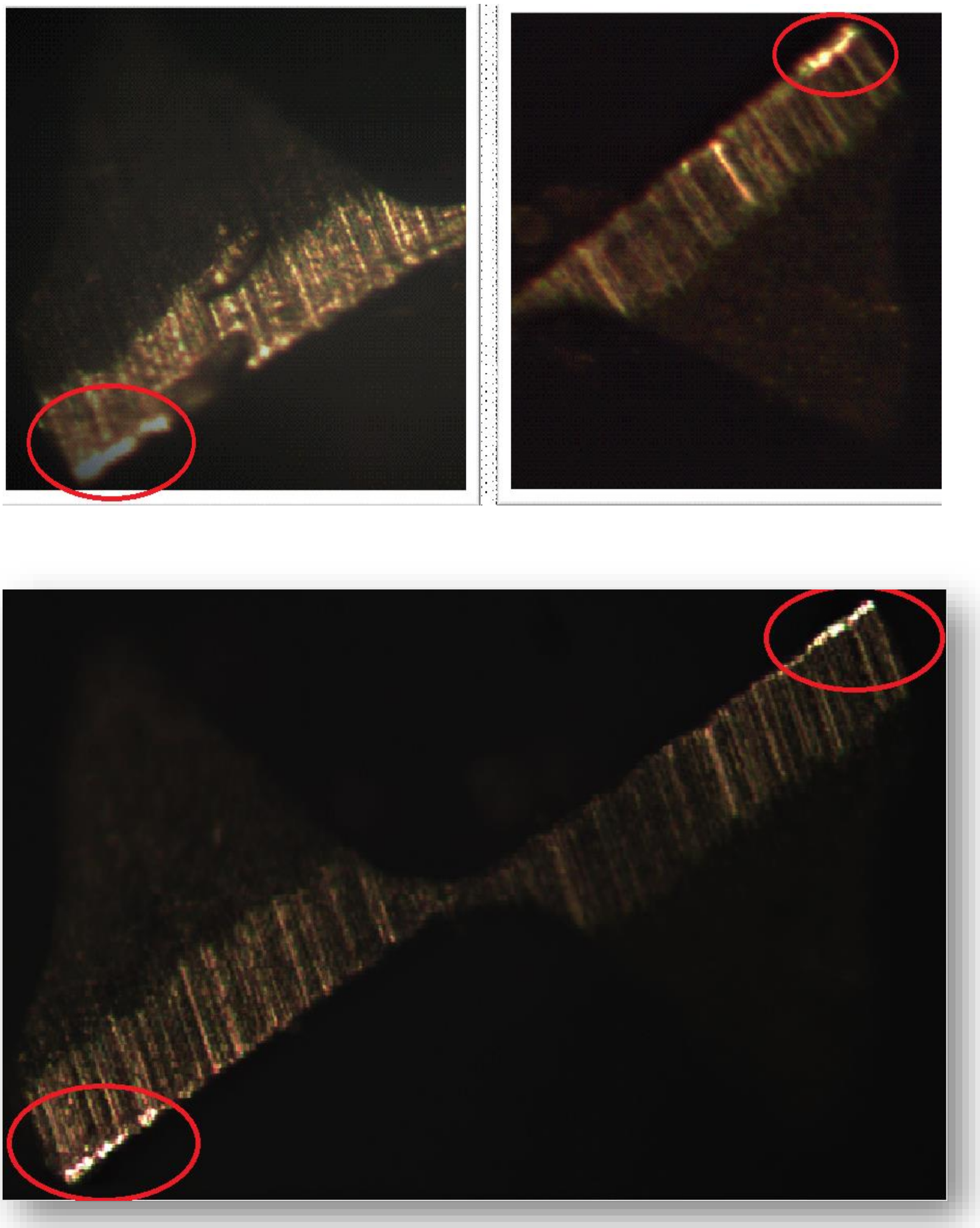


Figure 29 Tool wear of multi Coated Cutting Inserts

The main effect plots between wear of cutting inserts and cutting factors using ANOVA were analyzed and investigated most significant factor contributing towards tool wear.

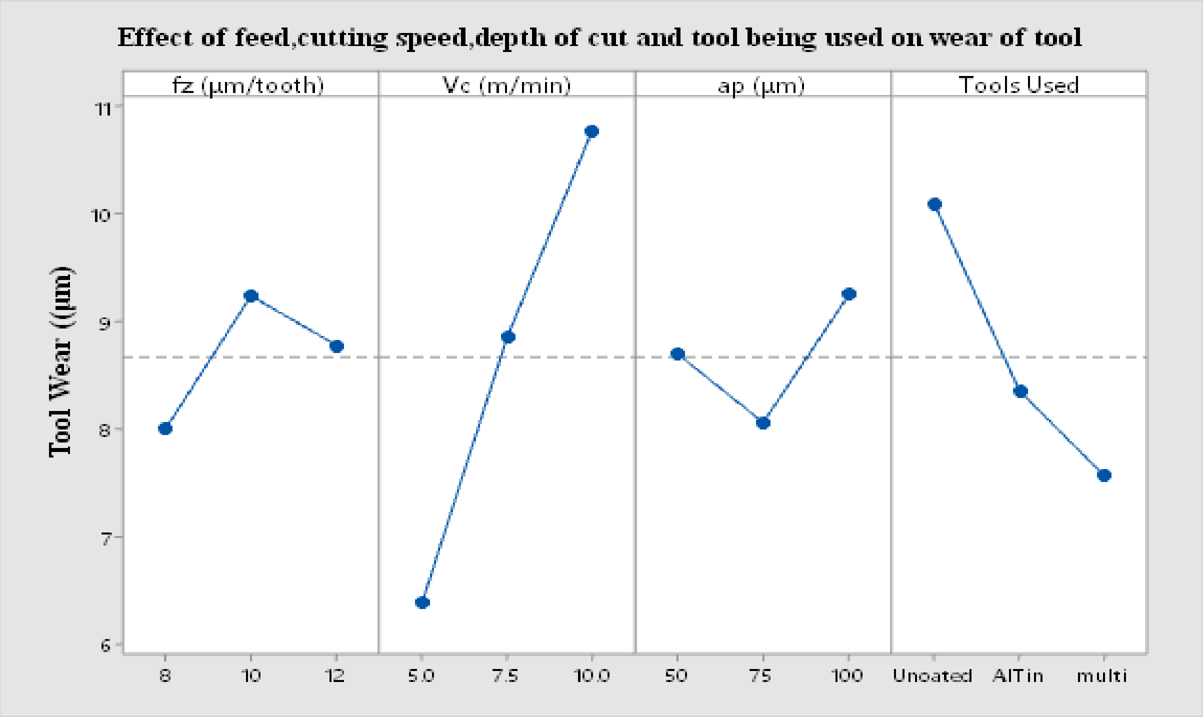


Figure 30 Effect of feed, cutting speed, Depth of cut and Tool being used on Tool Wear

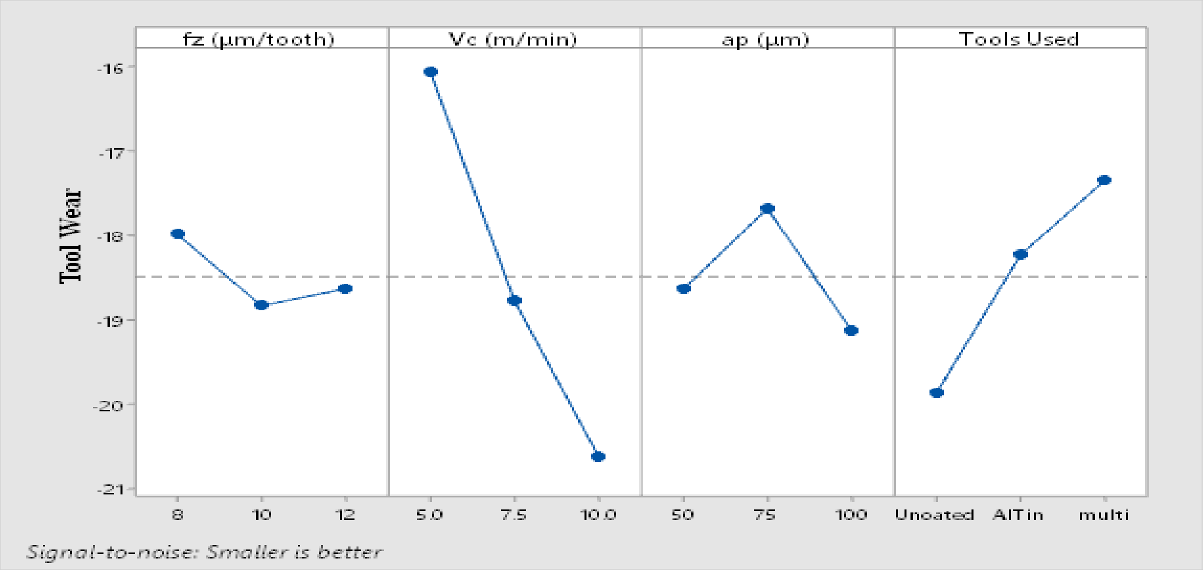


Figure 31Signal-to-noise ratio (smaller is better)

The effect of four factors at 3 different levels on cutting inserts were observed and detailed results are shown graphically along with signal to noise ratio. It was detected that at low speed machining all the tools showed least wear which rises with the increment in speed of cutting and uncoated solid end mill cutter undergoes maximum wear while multi coated tool shows minimum wear as it is clear from graphs above.

4.3.3 Cutting Speed effect on Wear of Cutting Inserts for Uncoated Tool and Coated tools

With the increment in speed of cutting the wear of cutting insert increases. Cutting speed had significant effect on wear of tool as compare to other three factors followed by type of tool being used feed and cutting depth. The graph shows linear relation for wear of the tool against cutting speed for all three cutting inserts respectively.

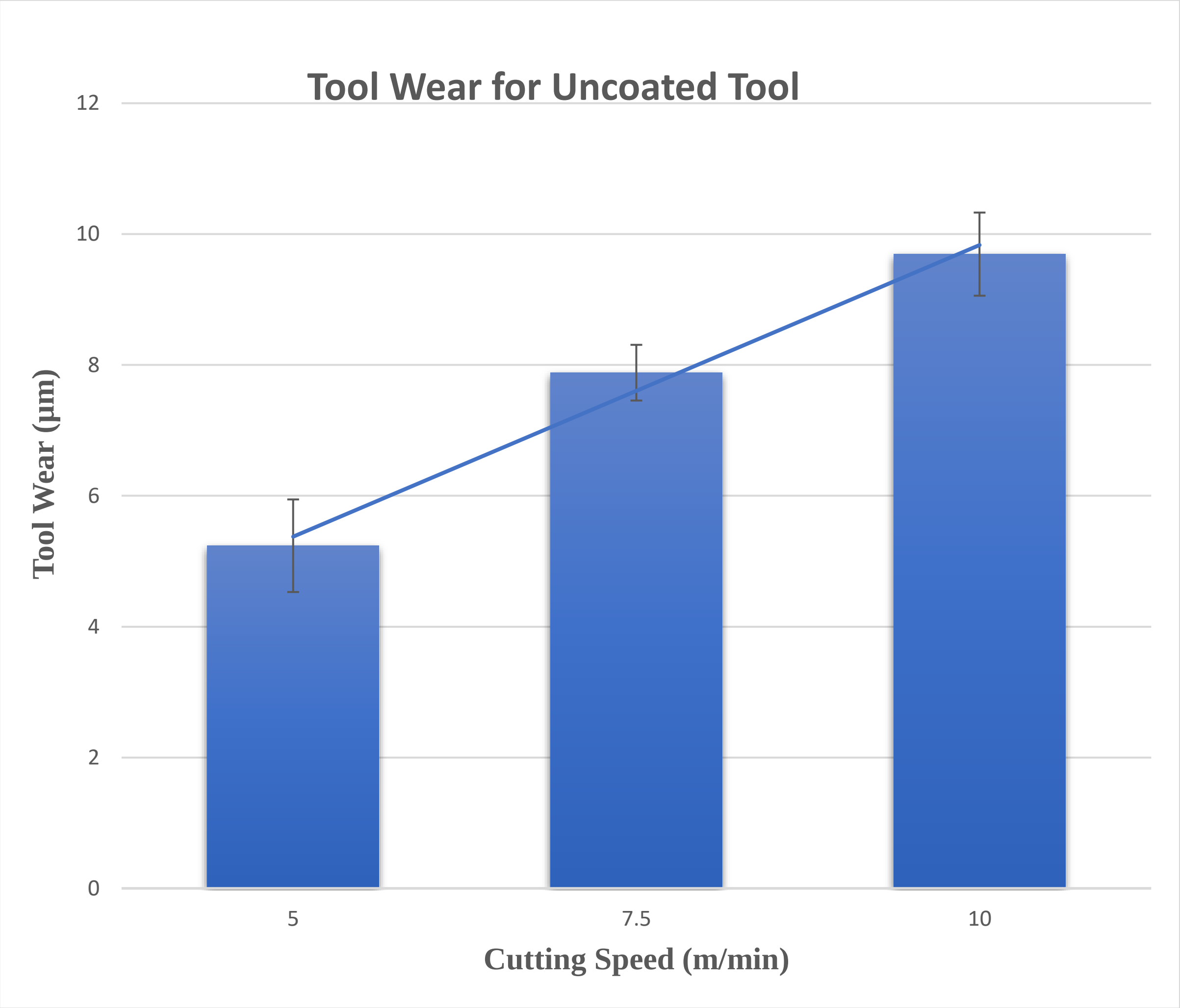


Figure 32 cutting speed effect on wear of uncoated tool

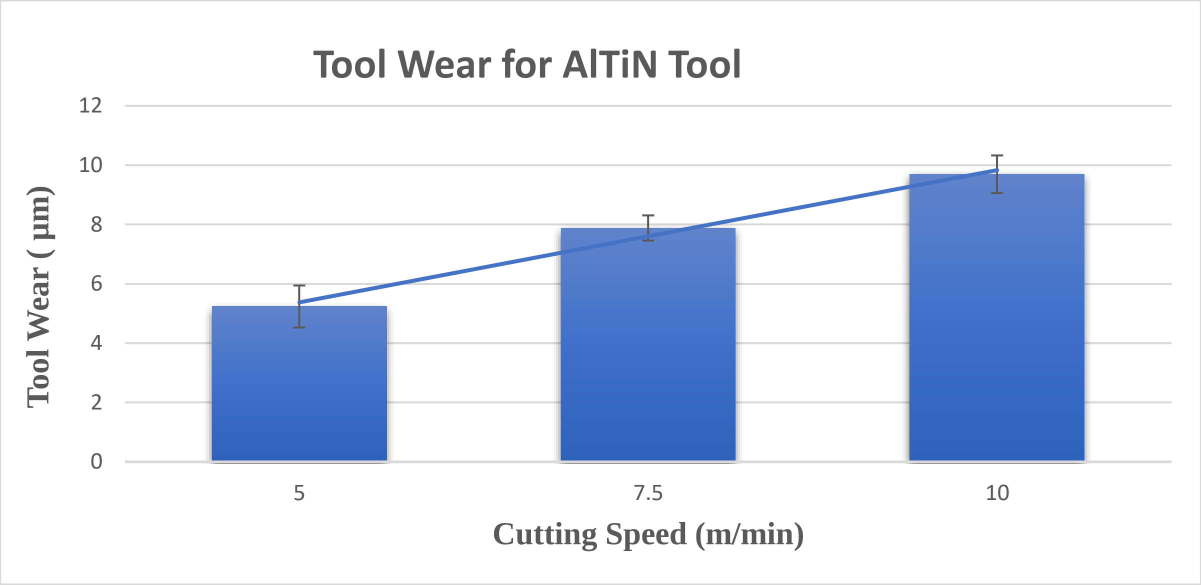


Figure 33 Cutting speed effect on wear of AlTiN coated tool

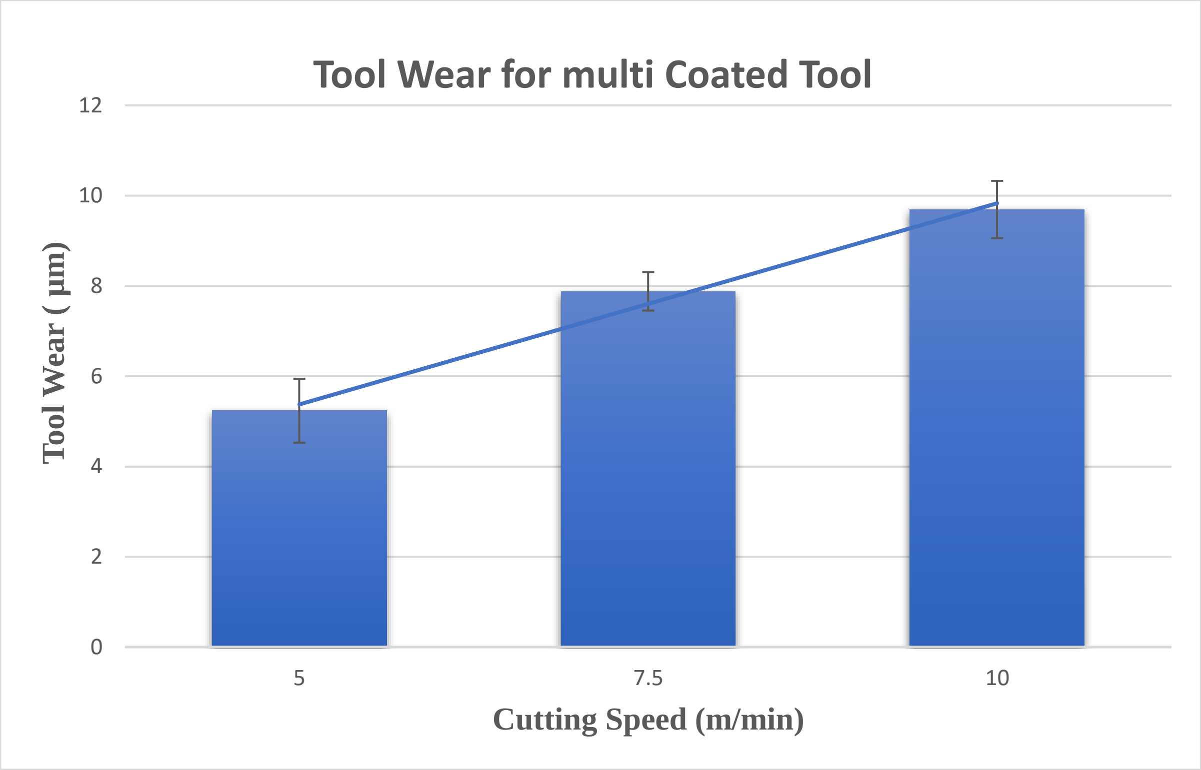


Figure 48 Cutting speed effect on wear of multi coated tool

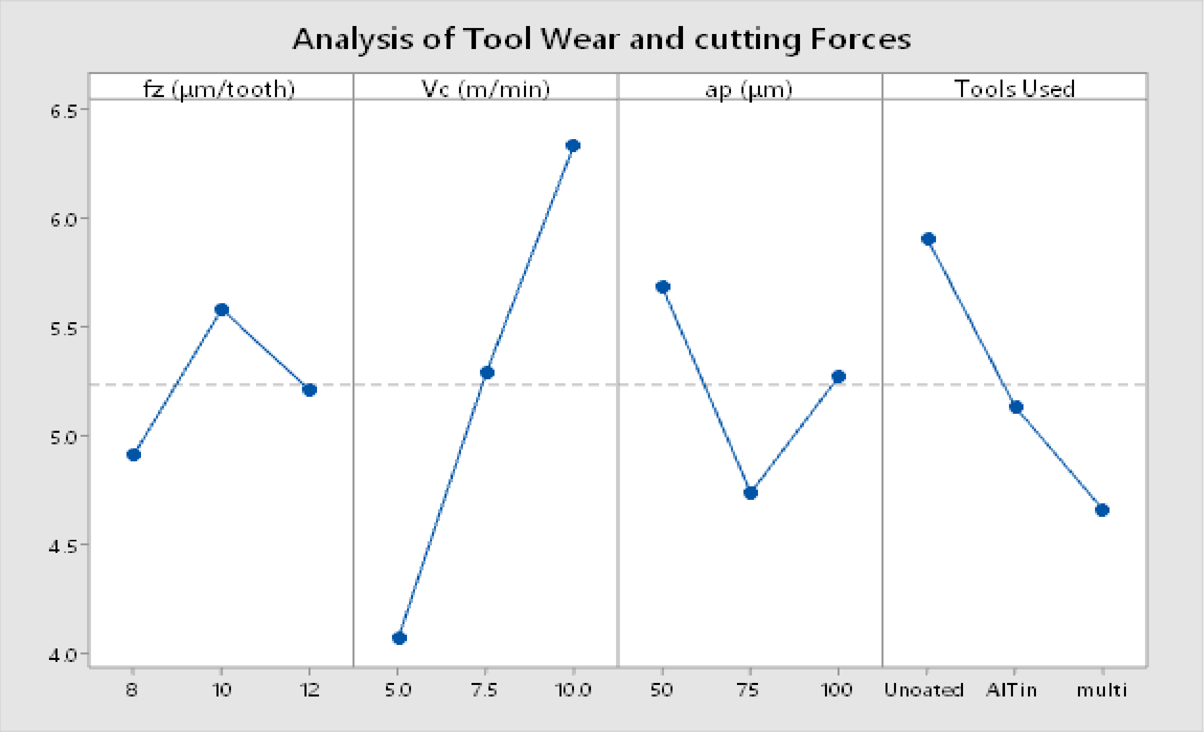


Figure 51 Tool Wear, Cutting Force(N) versus fz (µm/tooth),Vc(m/min), ap((µm)),tool used

From all the observations and experimentations Taguchi Analysis showed that multi coated tools are considered to be best solid carbide end mill cutter while machining of TC4 at low cutting speed. Multi Coated insert performed much better as compare to that of AlTiN coated and uncoated tool. While considering AlTiN and uncoated tool AltiN showed least cutting forces and wear of the tool. Multi Coated Tool led to superior surface finishing of job reducing cycle time because using this tool it is not necessary to change tool while machining at regular intervals as it possesses higher strength accumulating least wear and cutting forces so this tool is preferred while machining hard Titanium alloys at low machining speed where there are extreme chances of vibration, tool wear and tool breakage.

4.3.4 Confirmation Test

Optimal Process parameters both for resultant cutting forces and wear of cutting inserts were given below. It is evident from the confirmation test that optimal conditions produce better results compared to initial and final results reported in table 10 and 12 respectively.

Table 13 Optimum process parameters for Cutting Forces

f_z (µm/tooth)	V_c (m/min)	a_p (µ)	Tool used	Cutting Forces (N)		
8	10	50	nACo coated	1.0132	0.79641	1.201

Table 14 Optimum process parameters for wear of cutting inserts

f_z (µm/tooth)	V_c (m/min)	a_p (µm)	Tool used	Tool wear (minimum)		
`8	5	75	nACo coated	4.721	5.114	5.325

Table 15 Optimum process parameters for wear of cutting inserts

f_z (µm/tooth)	V_c (m/min)	a_p (µm)	Tool used	Tool wear (maximum)		
10	10	100	Uncoated Tool	13.124	11.893	12.746

Chapter5

5.1 Conclusion

The impact of machining constraints (feed, speed of cutting, cutting depth and type of cutting insert being used) is quite different in micro milling as compared to that of macro machining. In this research influence of these constraints on cutting forces and wear of cutting inserts are studied in detail and ANOVA technique is used to examine the influence of machining parameters on wear of cutting inserts and cutting forces.

1. At confidence level of 95% cutting depth was found to most substantial factor contributing towards the cutting forces with contribution ration of 44.45% followed by type of tool being used (uncoated, AlTiN coated, multi coated)26.46%, cutting speed 14.33% and feed rate 10.81%.
2. Cutting Forces increased steadily with the rise in cutting depth. This is due to the statistic that chip load increment raised the cutting forces required for material removal.
3. Multi coated tool (AlTiN and SiN coating) was found to be best among other two cutting inserts while machining at low-speed bearing least cutting forces. This actually leads to lower friction, creating enough adhesion and increase resistance to wear and cracking.
4. AlTiN coated tool was considered to be better than uncoated tool but machining with multi coated tool showed far better performance considering cutting forces and tool wear or breakage as compare to both AlTiN coated and uncoated cutting inserts.
5. Cutting speed was found to be most substantial factor at 95% confidence level contributing towards tool wear with contribution ratio of 67.59% followed by type of tool being used 18.96%.
6. Feed rate and cutting depth had slight consequence upon wear of the tool with the contribution of 5.29% and 3.85% respectively.
7. Multi coated tool was considered to be superior among other two cutting inserts bearing least cutting forces and wear of the tool. While AlTiN was found to be

better than uncoated tool but it bears excess cutting forces and tool wear as compare to multi coated tool.

As far as tool wear is concern multi coated insert bears least wear at low machining speed as compare to other two cutting inserts followed by AlTiN coated tool and uncoated tool respectively.

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