TOOL WEAR ANALYSIS DURING HIGH SPEED MACHINING OF Ti-6Al-4V ALLOY

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Dedicated to my family whose tremendous support and cooperation led me to this wonderful accomplish

Abstract

This study examines tool wear during machining of titanium alloys. Suitable cutting tool material is selected on the basis of previous studies and tool wear during machining Ti-6Al-4V is measured and analyzed at different magnifications of microscope. This study also includes the analysis of tool wear using different coatings. Single and multi-layered coatings were deposited on cutting tool and their effect on tool wear is analyzed. Performance of multilayered coatings is observed to be much better and on this behalf recommendations are made regarding further study on multi-layered tool coatings.

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Chapter 1

1. INTRODUCTION TO MACHINING

1.1. MACHINING

Manufacturing things has always been a basic human need from the beginning and there are a lot of different methods that have been used for manufacturing things i.e. casting, bending and welding etc. Machining is also one of the processes that is used for manufacturing. Major advantage of machining over other manufacturing process is that a large variety of products can be formed with good accuracy and precision. That's why machining has wide application in manufacturing industry. In machining, material is removed from a workpiece using a sharp tool to get the desired shape. The sharp edge tool used in the process is called cutting tool and the material on which operation is performed is called workpiece. Machining is itself a very broad term and there are a lot of operations that can be performed through machining.

There is a wide range of shapes that can be obtained by machining using different machining setups and cutting tools. On this basis, machining can be classified into a number of types such as turning, drilling and milling etc. All these operations are used in current manufacturing industry depending on the required shape to be produced. While many other machining operations are used on large scale, turning is the most commonly used process[1].

1.2. TURNING

In this machining process, a single-point cutting tool is used to remove material from the surface of a rotating workpiece to reduce diameter of cylindrical workpiece. Turning is conventionally carried out on lathe that converts electrical energy into mechanical energy providing power to rotate the work-piece at a given rotational speed. However, CNCs are also widely used in industries and replacing lathe in past few decades. CNC is the abbreviation of computerized numerical controlled and as its name suggests it is controlled by computerized panel. Program or code is generated for required operation and fed in CNC so there are less chances of human error and it provides higher accuracy. Turning reduces the diameter of workpiece. Diameter before the operation is termed as original diameter while diameter after turning is called final diameter. A sharp cutting edge is used for material removal called cutting tool that is mounted on tool holder. Workpiece is clamped in machine jaws and machine rotates it at specified velocity called cutting velocity. Tool is positioned at a specific depth (that depends on the desired specimen diameter to be obtained in one cut) and the linear distance or depth that tool is moved perpendicular to the axis of rotation of work-piece from work-piece surface is termed as depth of cut. Cutting tool is then moved parallel to the axis of rotation of work-piece at a specific speed called feed or feed-rate generally expressed in mm/rev (in/rev). Rotation of workpiece, depth of cut and feed rate provide the relative motion among tool and workpiece. Due to this motion of tool on workpiece, excessive material is sheared off by from workpiece surface. As shown in fig. 1.1 cutting tool moved from right to left with feed rate ‘fr’ while workpiece is rotating with a rotational speed N. D1 and D2 are diameters of workpiece before and after machining respectively.

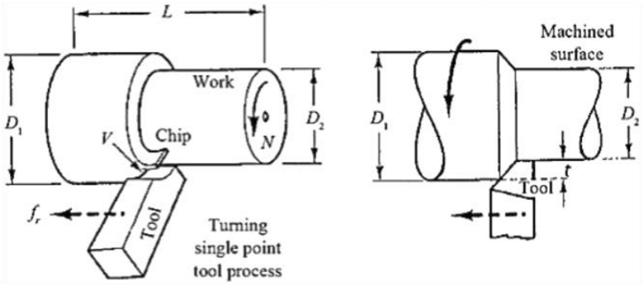


Figure 1.1 Turning Process [2]

1.3. CLASSIFICATION OF CUTTING TOOLS

There are different shapes of cutting tools depending on the type of operation, however each cutting tool has wedge shaped part with sharp edge for cutting material smoothly. Cutting tool may have different number of cutting edges. Generally, Cutting tools are classified on the base of number of its main cutting edges participating in cutting at a time. On this basis, these tools are classified as Single point cutting tools and Multi point cutting tools.

Single point tool has only one main cutting edge that performs material removal at one time in single pass. Insert based tools may have multiple cutting edges; however, only one edge participates in material removal action at one time. Turning tools are good example of single-point cutting tools as shown in fig. 1.1. Example of multi point cutting tool is shown in fig 1.2 below.

Figure 1.2 Multi Point Cutting Tool

1.4. GEOMETRY

Single point tools are used in almost all turning processes. Basic geometry of tools used for turning remains same in around 75 percent of operations. Turning inserts are used in modern CNCs in which inserts are mounted on tool holder. In that case geometry of inserts plays an important role in turning process. All basic terms are same for turning inserts and single point turning tools i.e. relied of clear angle, Flank side, rake side and nose radius etc.

Multiple angles of tool play a significant role in turning operation. These include angle of inclination, rake angle, side rake angle, back rake angle, side relief angle end relief and clearance angle etc. The tool's rake angle is “the angle between the cutting edge and the cut itself” that can also be positive or negative. The entry angle is “the angle between the direction of the cutting tool feed and the cutting edge”. The nose radius is also important as it may be large providing strength to the tool, or sharp for fine radius turning. In micro machining nose radius is few tens of microns while conventionally it can go from 0.2 to 2mm. Geometry of single point cutting tool is given in fig. 1.3 showing the shank that is base of the tool (tool is held in tool holder from shank), rake angle and relief angle etc.

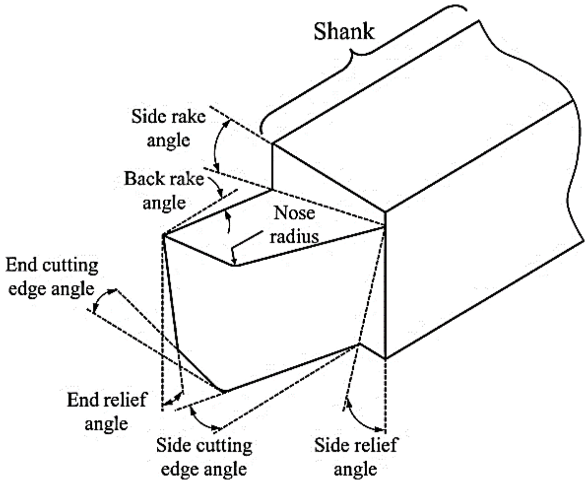


Figure 1.3 Geometry of Single Point Cutting Tool [3]

In turning, material is removed in the form of chips and those chips also interact with workpiece and tool and have considerable effect on quality of finish and efficiency of process. Chips can be discrete or continuous and chip breaking is done to limit the interaction of chips with workpiece and tool. Changing the depth of cut and geometry also effects the formation of chips so balancing these parameters can also provide the required output. Appropriate chip breaking can be achieved by using chip breakers usually molded in inserts.

1.5. TOOL WEAR

Cutting edges get damaged after usage due to friction between edge and workpiece that not only causes abrasion but also generates heat on the tool tip. This deterioration of tool is referred as tool wear. Wear of cutting tool is very important as it not only defines the machining cost but also affects surface finish of machined surface. Tool wear occurs at flank side of tool as well as on the crater size and is called flank wear and crater wear respectively. The deteriorated region on flank side is known as wear land and width of wear land is taken as a measure of wear that is measured through microscope. Notch wear is an excessive localized wear due to adhesion of chips on the tool surface. It is ignored in measurement of flank wear and second highest wear in the region is termed as maximum flank wear. Fig. 1.4 presents flank, notch and crater wear in single point cutting tool. Nose radius wear is also shown in figure, as material is removed from the nose as it wears out during machining.

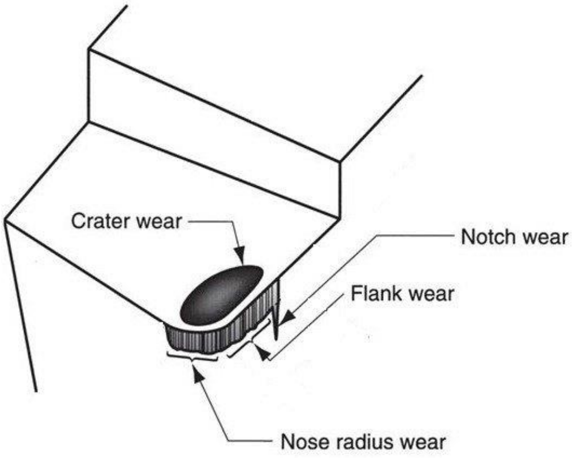


Figure 1.4 Wear Modes in Cutting Tools [4]

1.6. TOOL COATINGS

Many types of tool coatings can be found on inserts that include physical vapor deposition, chemical vapor deposition, electrodeposited coatings, Spray coatings and organic coatings. Among these coating, majority of them are either PVD or CVD that are being used for carbide tools having application in machining industry.

1.6.1. CHEMICAL VAPOR DEPOSITION

It is a chemical process that is used for producing high quality and high performance materials. CVD is mostly used in semiconductor industry for making thin films. In this process, substrate is exposed to one volatile precursors, that decompose or react (or both) on surface and produces desired deposit. As it is a chemical process so some by-products are also produced in this process. These by-products are then removed by flowing gases through reaction chamber.

1.6.2. PHYSICAL VAPOR DEPOSITION

In Physical vapor deposition, coating material is deposited on substrate through purely physical process and there is no chemical reaction involved in coating process. In this method, coating material is vaporized and then condensed on the workpiece surface or it can also be in the form of plasma sputtering. Vapors of target materials are produced through vacuum evaporation, electron beam heating or resistance heating. Process of physical vapor deposition is shown in block diagram below. Targets are made-up of different percentages of elements of coating material. And substrate material is material on which coating is to be performed. Reactive gas is introduced to start the reaction among elements to achieve the desired coating. Substrate in rotated at constant speed to produce uniform coating while condensation occurs on the surface.

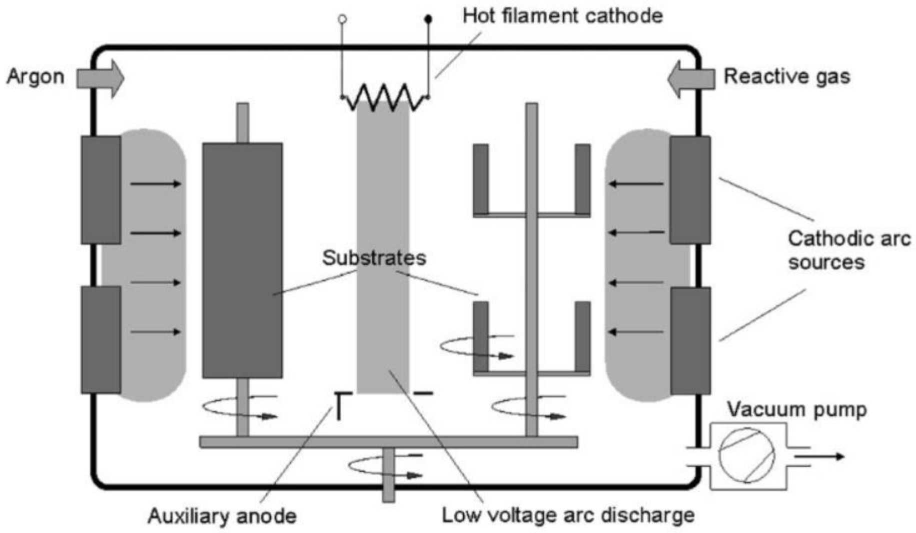


Figure 1.5 Block Diagram of PVD [5]

1.6.3. PVD vs CVD

PVD and CVD are different process that have their own specific areas of application. One of the reasons to choose PVD instead of CVD is that temperatures required for CVD processes are much higher than PVD, usually from 300°C to 900°C. This temperature is achieved through furnaces, RF coils or lasers etc. This high temperature also affects substrate which is heated up. So the substrates which cannot withstand these high temperatures should be coated by using PVD process.

Another advantage of PVD over CVD is safety issues and environmental issues as some by-products in CVD are toxic, hazardous or corrosive. That not only can damage health of operators but also affects the environment and makes handling of material and its storage difficult.

PVD coatings are also proven to be sometimes harder and have more resistance against corrosion than those produced by electroplating. Most of these coatings have higher temperature resistance and higher impact strength and extraordinary abrasion resistance.

As PVD coatings are used for improvement in hardness, resistance against wear and oxidation, such coatings are widely used in aerospace industry, automotive industry and surgical/biomedical industry.

Chapter 2

2. MACHINING OF TITANIUM ALLOYS

2.1. IMPORTANCE OF TITANIUM ALLOYS

Although composite materials are being used extensively and their usage is growing in different types of industries like aerospace and biomedical industry [6], in this era, however the demand of titanium alloys has not been reduced in these fields. Due to high thermal resistance, stress bearing capability and ability of corrosion resistance titanium alloys are termed as super alloy [7]. While having interest in multiple industries, these extra-ordinary properties also make titanium and its alloys very interesting for researchers. Commercially, pure titanium has alpha structure and exhibits superior corrosion resistance but titanium alloys have better mechanical properties than titanium itself [8]. In comparison to beta alloys of titanium, alpha alloys have higher heat resistance and easy to weld but lower strength and workability [9]. With a dispersion of the beta form in the alpha phase, two phase α–β alloys have properties of both. While a variety of titanium alloys is available, α−β Ti-6Al-4V alloy is most popular. Use of Ti-6Al4V alloy is estimated to be 60% of all titanium-based alloys being used [10, 11]. The composition of Ti-6Al-4V is shown in table 2.1 below, having maximum contents of titanium, followed by aluminium and vanadium.

Table 2-1 Composition of Ti-6Al-4V

Component	Wt. %
Ti	90
Al	6
V	4
Fe	Max 0.25
O	Max 0.2

Comparison of yield strength of different materials with titanium and Ti-6Al-4V is given below in a graph that shows higher yield strength of grade 5 titanium alloy comparative to other material at all temperatures. Pure titanium shows higher strength at all temperatures but at the same time pure titanium is quite expensive too.

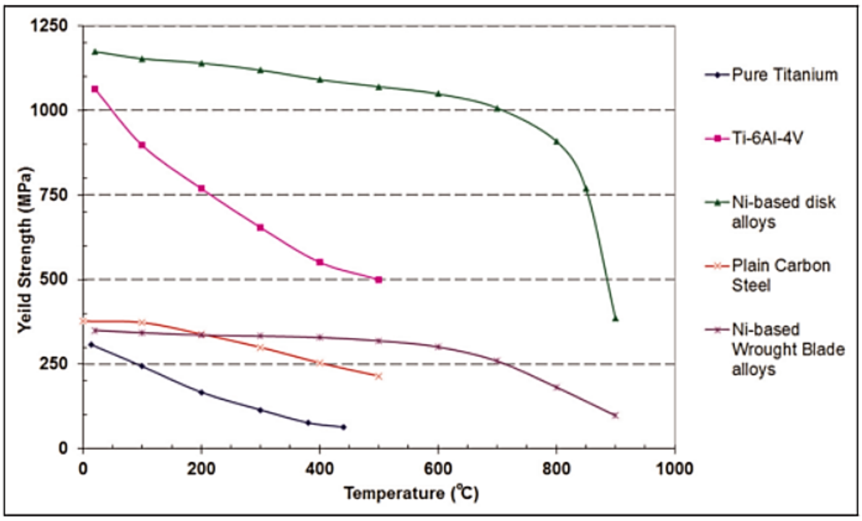
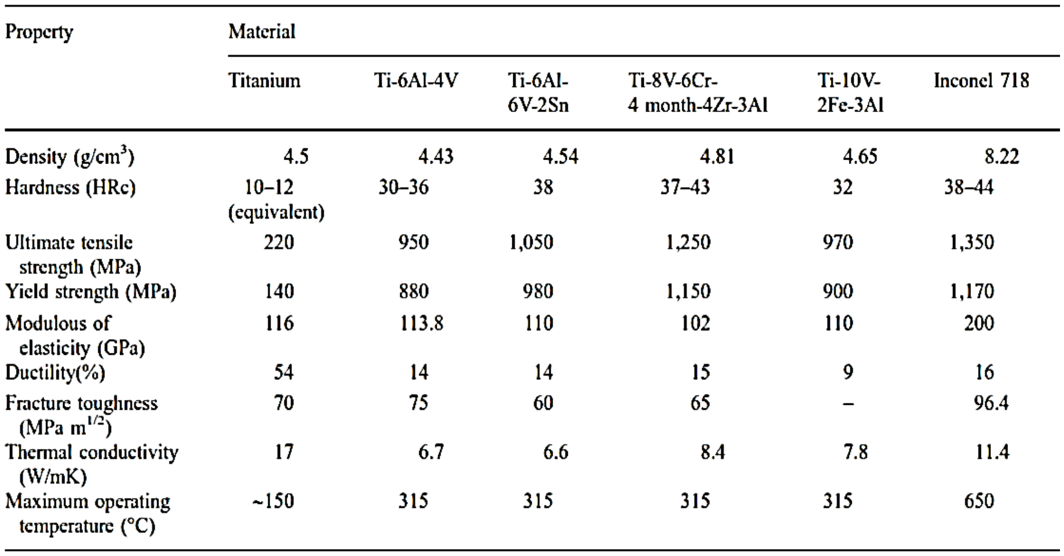


Figure 2.1 Yield Strength of Different Materials [12]

Table 2.1 presents the comparison of properties of different alloys. From the table, it is clear that Ti-6Al-4v has less density and higher relative strength and toughness while more workability at higher temperatures which highlights the importance of Ti-6Al-4V compared to other alloys of this category.

Table 2-2 Comparison of Properties of Different Alloys [8]



Property	Material					
	Titanium	Ti-6Al-4V	Ti-6Al-6V-2Sn	Ti-8V-6Cr-4 month-4Zr-3Al	Ti-10V-2Fe-3Al	Inconel 718
Density (g/cm^3)	4.5	4.43	4.54	4.81	4.65	8.22
Hardness (HRc)	10–12 (equivalent)	30–36	38	37–43	32	38–44
Ultimate tensile strength (MPa)	220	950	1,050	1,250	970	1,350
Yield strength (MPa)	140	880	980	1,150	900	1,170
Modulous of elasticity (GPa)	116	113.8	110	102	110	200
Ductility(%)	54	14	14	15	9	16
Fracture toughness (MPa m$^{1/2}$)	70	75	60	65	–	96.4
Thermal conductivity (W/mK)	17	6.7	6.6	8.4	7.8	11.4
Maximum operating temperature (°C)	~150	315	315	315	315	650

2.2. Machinability of titanium alloys

Titanium alloys are categorized as very difficult to machine materials [13]. The reason of poor machinability of titanium alloys is its several inherent properties. Titanium and its alloys have low thermal conductivity and high chemical reactivity with many materials used in cutting tools [14]. Due to low thermal conductivity, temperature at the edge of the tool increases during machining so cutting tools wear off very quickly because of high temperature and also strong adhesion among the materials of cutting tool and workpiece. Moreover, low elasticity modulus and high strength at high temperatures also reduces machinability of these alloys. A lot of work has been done by the researchers to understand causes of poor machinability of this alloy and effect of different cutting parameters was also studied. A wear map has been developed to represent tool wear in machining to Ti-6Al-4V [15]. This wear map represents tool wear at different cutting parameters i.e. feed rate and cutting speed. It points several high wear regions that have been interesting topic for research. The Wear rate map of turning titanium alloy grade 5 is shown in fig. below that is drawn among cutting speed on x-axis and feed rate on y-axis. Points where feed rate is below -6.0 are designated as low wear regions. Similarly, moderate and high wear regions are also highlighted in wear map.

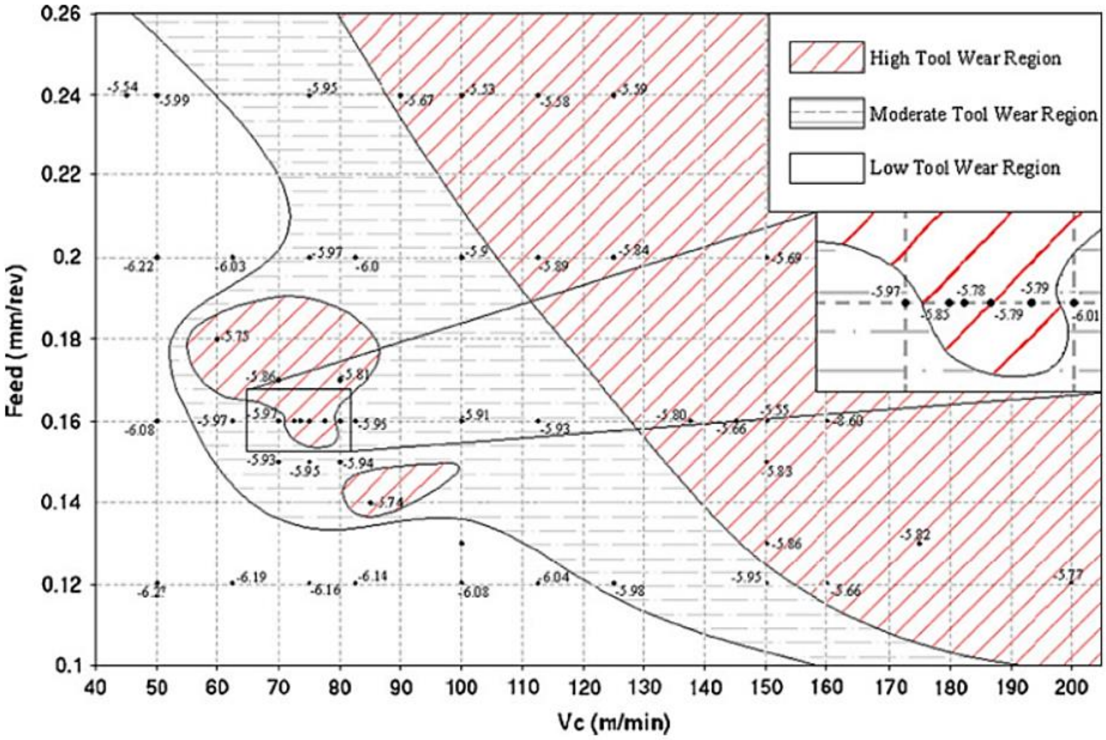


Figure 2.2 Wear map of Ti-6Al-4V [15]

Researchers showed their inserts in selection of most appropriate tool material for machining these alloys to improve machinability and a number of tool coatings have also be found to be effective while machining these alloys that are discussed in next chapter. Despite a few of those coating worked well but still there is room to study the behavior of tool with new coatings and multi coating while machining this alloy.

2.3. PROBLEMS STATEMENT

As reported by previous researchers, the major problems that occur during machining of Ti-6Al-4V and that reduce the machinability are high temperatures at the tool tip and adhesion of materials. These reasons lead to high tool wear and so higher machining cost while reducing finishing quality at the same time. For this purpose, it is important to study the effect of different tool coatings in machining Ti-6Al-4V to reduce machining cost and surface finish. Tool wear analysis during machining of titanium alloys and a study of effect of multi-coatings on tool wear will not only help improving quality of the products but also reduce machining cost.

2.4. OBJECTIVES

Major objectives of this research are

1. Selection of suitable tool material for turning Ti-6Al-4V.
2. Selection of appropriate tool coatings for turning of this alloy.
3. To analyze the effect of single layer tool coating on tool wear
4. To analyze the effect of multi-layered tool coatings on tool wear
5. Comparison of effect of single and multi-layered tool coatings

2.5. ADVANTAGES:

As the project deals with the tool wear during machining of Ti-6Al-4V so its major advantages are:

1. Less tool wear
2. Reduced tooling cost
3. Improved tool life
4. Cheaper machining of the alloy.

And all these advantages lead to overall reduced cost of products.

2.6. AREAS OF APPLICATION:

Application areas of this alloy include aerospace industry, biomedical and food processing industry. So tool wear during machining of this alloy is directly related to the cost of products in all these industries.

Chapter 3

3. Materials and methods

There are many important considerations to achieve the objectives mentioned in previous chapter. These considerations include selection of materials and other parameters. A detailed literature review is required for the selection for these parameters and materials. This chapter includes detailed literature review regarding selection of these parameters. It also includes the methodology used to achieve the objectives i.e. analysis of average and maximum flank wear.

3.1. SELECTION OF PARAMETERS

Selection of parameters include selection of insert material, tool coatings, feed rate, cutting speeds, depth of cut, length of cut and other machining parameters.

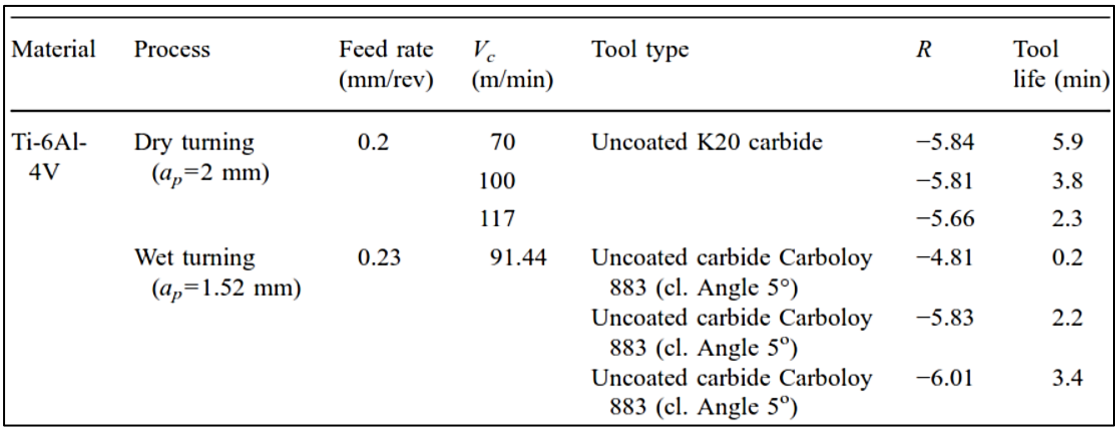
3.2. SELECTION INSERT MATERIAL

Regarding the selection of tool material, tools having lower grade of cobalt and finer carbide grain size were found to have longer tool life [16], however, sharp cutting edges were reported to be more fragile in comparison to honed cutting edges. While, finer grain carbide inserts showed more resistance to wear [17]. But use of finer grain carbide tools was discouraged [18], as they were reported to cause more solubility of insert particles due to more surface area. Ceramic inserts have also been reported to be not suitable for machining titanium alloys [16]. Choudhary & Paul [19] used tungsten carbide inserts while turning Ti-6Al-4V as they were reported to have better performance and also reported that PVD coated tungsten carbide inserts perform better than uncoated ones. Ren, Qu, Zhang, Li, & Yang [20]recommended the investigation of PVD coatings performance on carbide inserts for turning grade 5 titanium alloys. Kumar, Prabu, & Kumar [21]preferred carbide inserts for machining Ti-6Al-4V. Aihua, Jianxin, Haibing, Yangyang, [22] and Narasimha & Ramesh, [23] also mentioned in their study that carbide inserts perform better than other commercially available inserts while machining titanium alloys.

As reported by Ezugwu et al. [24], super hard tool materials i.e. cubic boron nitride, CBN and polycrystalline diamond etc, perform better in machining titanium. Later, Ezugwu et al. [25] reported CBN and PCBN tools to be better than other tool materials for machining of titanium alloys at higher speeds. Contrary to that, Lopaz et al. [10] claimed CBN to be highly reactive with these alloys. Ezugwu et al. [26] observed that carbide inserts show higher performance than CBN. Reasons reported for low performance of CBN ware quick notching and chipping of cutting edge. So the use of CBN and PCD was recommended for dry machining at lower speed and feed rates only. Zareena et al. [27] reported BCBN tools to be better than CBN and PCD for machining of these alloys, as they provide better surface finish at lower cost. Surface quality was found to be improved by using high pressure coolant as they provide lubrication [27].

Due to conflicted reports on the feasibility of cutting tools of diamond derivative for machining these alloys, selection of cutting parameters and conditions is very sensitive while machining such alloys. Therefore, for machining of these alloys PCD, BCBN and CBN are not suitable as for these insert materials machining conditions are highly sensitive making their selection and fine tuning critical and as a result process control also becomes difficult. Thus the use of carbide inserts is recommended as they are less sensitive towards these conditions and perform better than other insert materials. Tungsten carbide H13 grade inserts were reported to perform better than other but still their performance is limited. Carbide inserts provide better performance with coatings [23], thus authors recommended a combination of insert material and coating to improve high speed machining to Ti-6Al-4V. Carbide inserts were used by many researchers for the trial of different tool coatings during machining of titanium alloys [8]. Table 3.1 shows performance of carbide inserts at different feed rates and cutting speeds in dry machining of Ti-6Al-4V. Wear rate and estimated tool life is also stated for these inserts.

Table 3-1 Performance Of Carbide Inserts [8]



Material	Process	Feed rate (mm/rev)	V_c (m/min)	Tool type	R	Tool life (min)
Ti-6Al-4V	Dry turning (a_p=2 mm)	0.2	70	Uncoated K20 carbide	−5.84	5.9
			100		−5.81	3.8
			117		−5.66	2.3
	Wet turning (a_p=1.52 mm)	0.23	91.44	Uncoated carbide Carboloy 883 (cl. Angle 5°)	−4.81	0.2
				Uncoated carbide Carboloy 883 (cl. Angle 5°)	−5.83	2.2
				Uncoated carbide Carboloy 883 (cl. Angle 5°)	−6.01	3.4

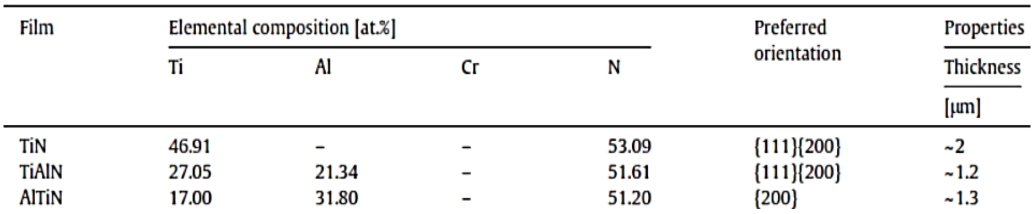
3.2.1. Selection of Coating

In terms of the use of tool coatings, it was reported that boride coated tools are superior to not only TiN, TiC and Al2O3 coated tools but also uncoated PCD and CBN tools while machining Ti-6Al-4V [28]. The reason behind is that boride coated tools are attributed to suppress dissolution–diffusion wear by thermal dissipation and formation of a protective layer. Dearnley et al. [29] reported better performance of crystalline WB-coated carbide inserts for crater wear. Cherukuri and Molian [28] also reported TiAlN-PVD carbide inserts performed better than uncoated in terms of tool life at Vc =61 m/min, f=0.15 mm/rev and ap=0.76 mm. Fitzsimmons and Sarin [30] tested different WC/Co coatings and found them to behave similar to uncoated C2 tools chemically, which were reported as most chemically wear resistant in terms of machining titanium.

Ezugwu et al. [31] reported TiN/TiCN/TiN multi-coated inserts to have shown increased tool life in comparison to TiN-coated, at feed rate 0.25 mm/rev compared to 0.13 mm/rev. Amin [13] showed improved performance of PCD tools than uncoated inserts for better tool life and better surface roughness. According to Lopez [10], TiCN- and CrN coatings produced high flank and notch wear at Vc =51 m/min.

AlTiN and TiAlN coatings provided better tool life than uncoated H10 cutting tools [32]. Sharif and Rahim also reported better performance of PVD coating of TiAlN on carbide drilling inserts [33] both in terms of surface finish and tool life. Comparison of composition of these coatings is given in table below. Table also presents the preferred according to the author. Ramanujam [34] compared tool wear of different tool coating on while machining Inconel and reported good performance of TiAlN and AlCrN, while AlCrN provided poor surface finish. Further, on the basis of generation of cutting forces multi-coating of TiAlN and AlCrN was also recommended.

Table 3-2 Properties of AlTiN, TiAlN and TiN Coatings [22]



Film	Elemental composition [at.%]				Preferred orientation	Properties
	Ti	Al	Cr	N		Thickness [µm]
TiN	46.91	–	–	53.09	{111}{200}	~2
TiAlN	27.05	21.34	–	51.61	{111}{200}	~1.2
AlTiN	17.00	31.80	–	51.20	{200}	~1.3

Wear rate of AlTiN was also shown to be higher than TiAlN as shown in fig 3.1. While TiAlN showed least wear rate according to the author. That makes TiAlN a desirable coating for titanium alloys machining.

Moreover, TiAlN also has more abrasive wear resistance than AlTiN as presented in fig 3.2. That also shoes the preference of TiAlN over AlTiN. That provided sufficient reasons to try this coating on turning Ti-6Al-4V.

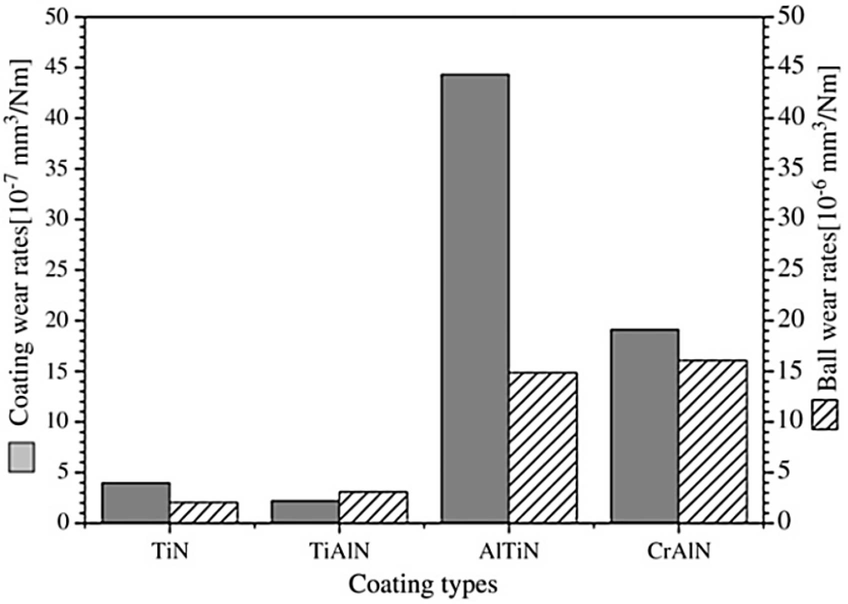


Figure 3.1 Wear Rates of Different Coatings[22]

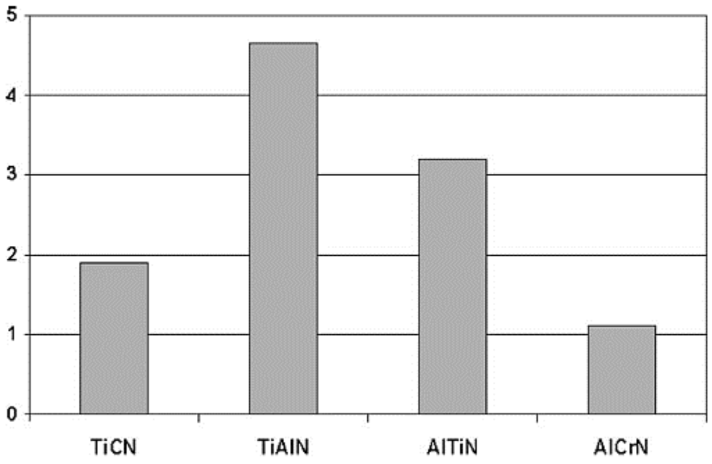


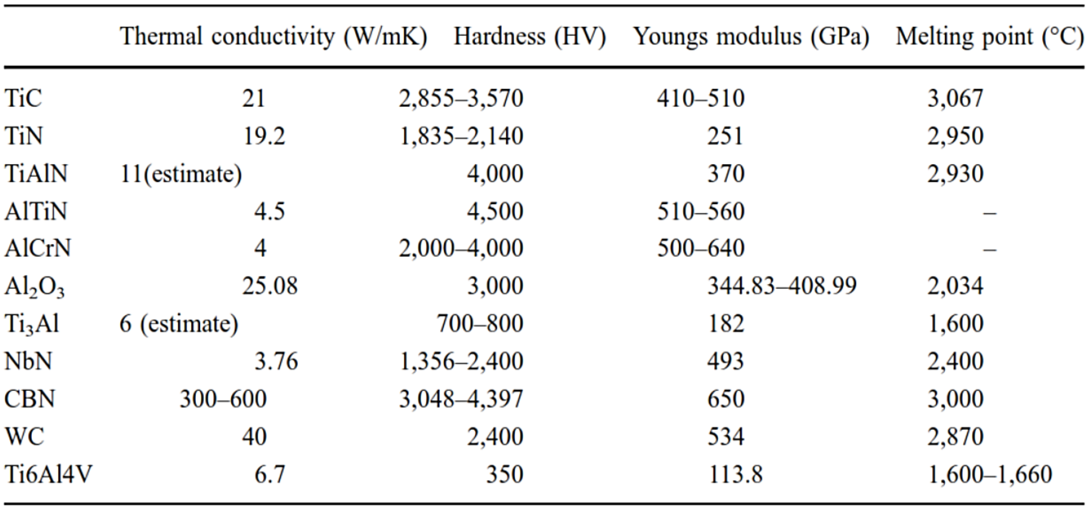
Figure 3.2 Comparison of Abrasive Wear Resistance Measured by Calo Wear Test [35]

It was also reported in previous work that multi-coatings on tools perform better at larger depth of cut, feed rate as well as cutting velocity [36] . In this regard, selection of another suitable tool coating is required in addition to TiAlN to study the effect of multi-coatings on turning to titanium alloys..

Table 3-3 Comparison of Thermal Conductivity of Different Materials At Different Temperatures [8]

	100°C	300°C	500°C	700°C	900°C
TiC	33	35	37	41	42
TiN	21	22	23	26	27
TiAlN	7.5–13	10.5–14	12(estimate)–15	17	18
AlTiN	5	7	12(estimate)	–	–
AlCrN	5.5	5.5	4.5(estimate)	–	–
Al_2O_3	28	18	13	6	5.5
Ti_3Al	11	13	15	16	17
WC	40	49	57	65	74
Ti6Al4V	7	11	12	16	19

Table 3-4 Comparison of Properties of Coating Materials with Ti-6Al-4V at Room Temperature [8]



	Thermal conductivity (W/mK)	Hardness (HV)	Youngs modulus (GPa)	Melting point (°C)
TiC	21	2,855–3,570	410–510	3,067
TiN	19.2	1,835–2,140	251	2,950
TiAlN	11(estimate)	4,000	370	2,930
AlTiN	4.5	4,500	510–560	–
AlCrN	4	2,000–4,000	500–640	–
Al_2O_3	25.08	3,000	344.83–408.99	2,034
Ti_3Al	6 (estimate)	700–800	182	1,600
NbN	3.76	1,356–2,400	493	2,400
CBN	300–600	3,048–4,397	650	3,000
WC	40	2,400	534	2,870
Ti6Al4V	6.7	350	113.8	1,600–1,660

As shown in Tables 3.3 and 3.4, AlCrN exhibits lower value of thermal conductivity with high hardness value. Moreover, thermal conductivity decreases at higher temperatures over 200 C in comparison to that of AlTiN and TiAlN categories [35]. Oxidation resistance of Ti1-xAlxN and Cr1-xAlxN categories improves with the increasing aluminum content, Cr1-xAlxN category was reported to have better resistance against oxidation [37]. Moreover, Kalss [35] also reported higher oxidation resistance of AlCrN

On behalf of above literature review regarding tool coatings, TiAlN and multi-coating of TiAlN and CrAlN was selected for the experiments. And for comparison, experiments were also performed with uncoated inserts to analyze the effect of these coatings. Coating thickness was taken to be 1.5 microns each as suggested by the manufactures and literature review. It provided three different levels regarding coatings that are uncoated, single coated (TiAlN) and multi-coated (TiAlN + CrAlN).

3.2.2. Selection of Feed, Speed and Depth of Cut

Following the previous work [8, 15], machining was done in dry conditions for sake of cleaner machining. Cutting speeds were varied from 50m/min to 150m/min. For the sake of simplicity, feed rate and depth were tested at single level. Feed rate was kept at 0.16mm/rev as many authors showed interest in this region of wear map because at this feed rate a variety of wear regions are observed. While depth of cut at 1mm following the previous work.

3.3. DESIGN OF EXPERIMENTS

The design of experiment was based on full factorial, in which all possible combinations of selected data points of these parameters were made. These were total 27 combinations as there were three levels of coating and nine different levels of speed while all remaining parameters were constant. So the design of experiment is as given in table on the next page. Speed is taken in m/min while federate in mm/rev. The detailed design of experiment is given in table on next page. Remaining factors are constant for all experiments.

Table 3-5 Design of Experiments

Exp. No.	**Feed (mm/rev)**	**Depth of cut (mm)**	**Speed (V) m/min**	**Coating**
1	0.16	1	50	Uncoated
2	0.16	1	55	Uncoated
3	0.16	1	60	Uncoated
4	0.16	1	62.5	Uncoated
5	0.16	1	65	Uncoated
6	0.16	1	70	Uncoated
7	0.16	1	100	Uncoated
8	0.16	1	130	Uncoated
9	0.16	1	150	Uncoated
10	0.16	1	50	TiAlN
11	0.16	1	55	TiAlN
12	0.16	1	60	TiAlN
13	0.16	1	62.5	TiAlN
14	0.16	1	65	TiAlN
15	0.16	1	70	TiAlN
16	0.16	1	100	TiAlN
17	0.16	1	130	TiAlN
18	0.16	1	150	TiAlN
19	0.16	1	50	TiAlN+CrAlN
20	0.16	1	55	TiAlN+ CrAlN
21	0.16	1	60	TiAlN+ CrAlN
22	0.16	1	62.5	TiAlN+ CrAlN
23	0.16	1	65	TiAlN+ CrAlN
24	0.16	1	70	TiAlN+ CrAlN
25	0.16	1	100	TiAlN+ CrAlN
26	0.16	1	130	TiAlN+ CrAlN
27	0.16	1	150	TiAlN+ CrAlN

3.4. EXPERIMENTAL PROCEDURE

3.4.1. Machining Setup

Experiments were performed on CNC Turning center as shown in fig. Specifications of CNC are also given. Machining setup included marking of both sides of inserts with respect to their specified experiment number. Similarly different portions of insert boxes were also marked to put the used inserts at their specified place to avoid the mixing up of inserts. Workpiece of total length more than 300mm was used such that after clamping in turning center jaws workable length will remain slightly greater than 300mm. This 300mm length was marked at 100mm distances specifying length of cut for three experiments to be performed on same diameter. This was done so that different levels of tool coating could be compared at same diameter. Workpiece was then clamped in center of jaws and zero point was defined.

Figure 3.3Turning Centre

SPECIFICATIONS OF
CNC LATHE MODEL ML-300
Diameter x Length: Ø300 x 600mm
Max travel range of Z/X axis: 600/240mm
Standard Accessories:
FANUC 0i-TC Controller
A2-8 Spindle, FANUC aP30 15/18.5KW
Spindle Motor Spindle Speed: 3500rpm
5 Sets of Clamps for O.D. Turning Tools
5 Sets of 40mm Boring Bar Holders
Boring Bar Brushings (7 Pcs) (~~Ø8~~, Ø10, Ø12, Ø16, Ø20, Ø25, Ø32) x O.D.40
Taper Sleeves (MT. No. 2, MT No. 3, MT No. 4) x O.D. 40
10-Tool Hydraulic Turret
Manual Body hydraulic Tailstocks
MT no.4 tailstock Quill, Coolant system
Chip Conveyor + Chip Bucket
Automatic Lubrication System, work Lamp

Figure 3.4CNC Turning Centre Specifications

After setting up machine zero and other machining setup, experiments were carried out. In first series, experiments were performed with uncoated inserts such that only first 100mm of workpiece was used in all nine experiments of uncoated inserts and diameter of workpiece decreased by 2mm at the end of each experiment. Similarly, for next 100mm single coated inserts were used and multi-coated were used on last 100mm. After performing all experiments, inserts were placed in their respective portion to avoid any physical damage as mentioned in machining setup.

3.5. OPTICAL MICROSCOPY

There are a number of methods used by the researchers to measure flank wear. Most commonly used and accurate method among them is by using microscope. For this, images are taken with microscope and after calibration and processing distance of wear is measured. In this study, both maximum and average values of flank wear were measured.

Optical microscope OPTIKA 600 was used to take the pictures of the flank side of inserts. This microscope has one lens on eye-piece that has 10x magnification while on objective side it has multiple options ranging from 5x to 50x. Microscope was calibrated before taking any images. Calibration was done using the calibration slides provided by the manufacturer for each combination of lenses. Images were taken with different objective lenses to observe the details of flank wear so that the final image contains maximum details covering the complete wear region. After taking images scaling was done using the manufacturer software OPTIKA view that adds a reference scale on image. Some sample images of 5x and 20x objective lens coupled with 10x eyepiece lens are shown in fig. 3.5 and fig. 3.6 on next pages.

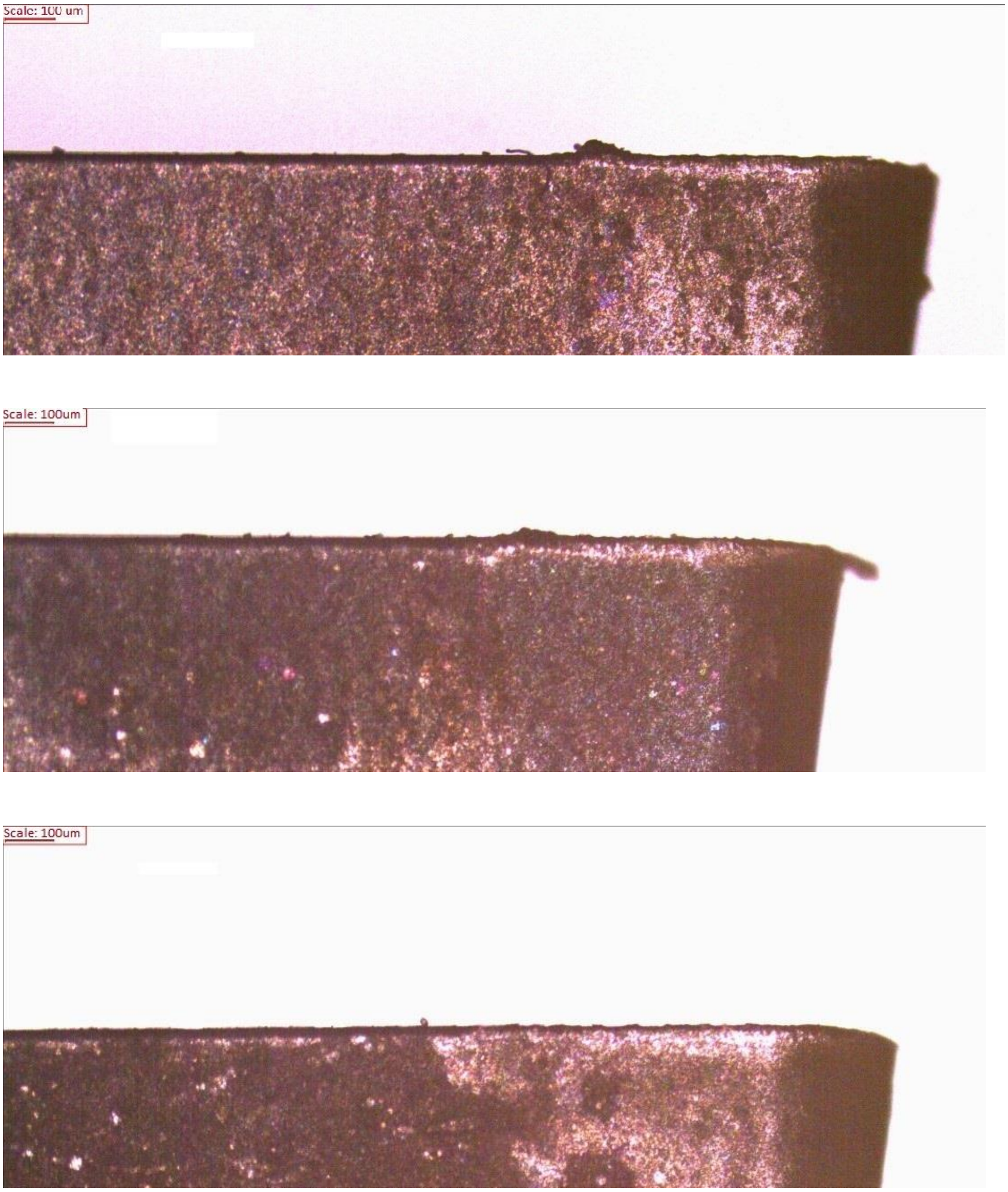


Figure 3.5 microscopic images with 5x objective lens and 10x eyepiece lens

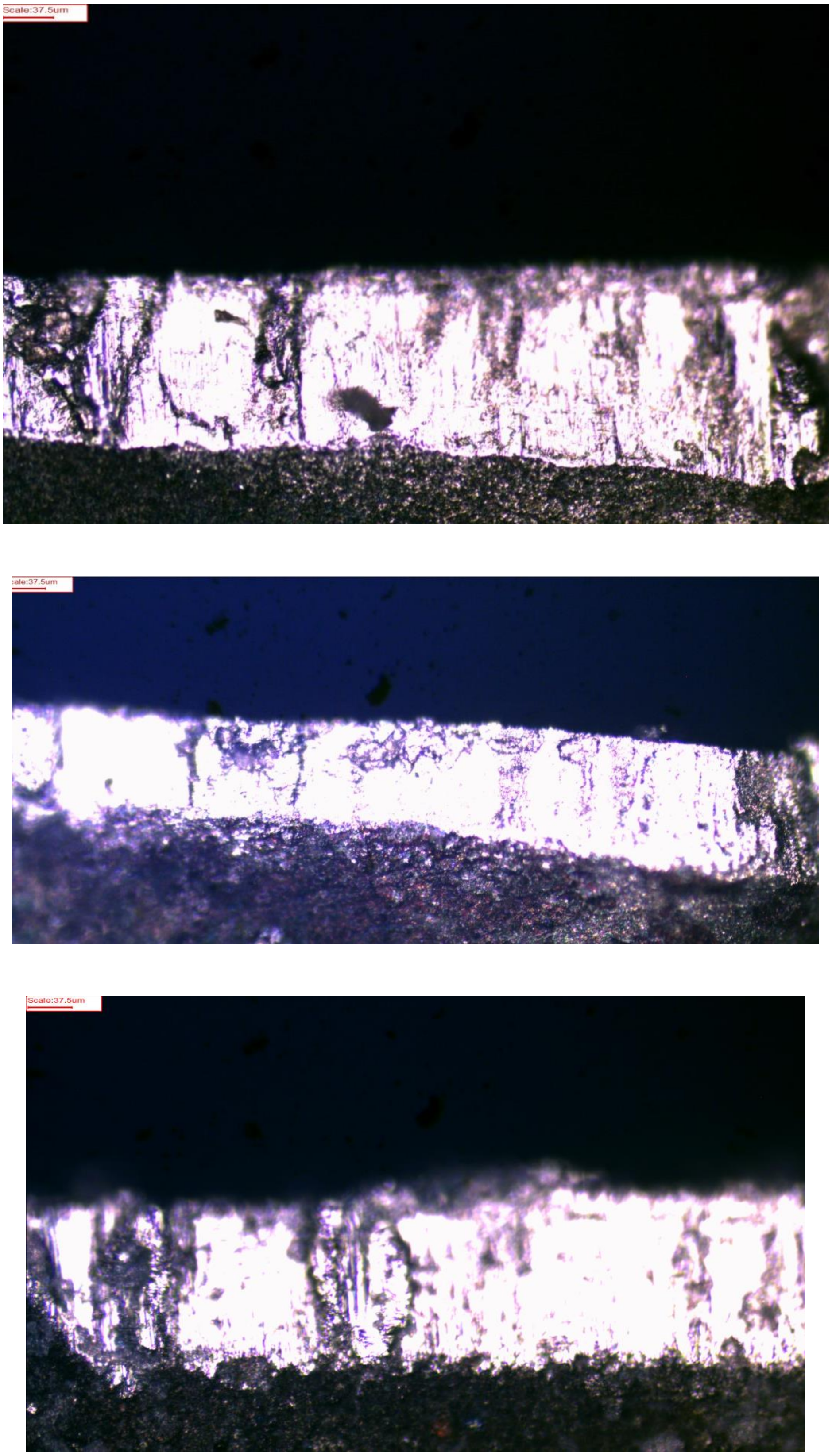


Figure 3.6 Microscopic images with 20x objective lens and 10x eyepiece lens

3.6. IMAGE PROCESSING AND MEASUREMENTS

The images captured with microscope need to be processed to make them convenient for measuring flank wear. This image processing can be done on multiple software. ImageJ is widely used software in engineering applications. This software has multiple tools for processing and measurements. Using this software, contrast and brightness was adjusted for highlighting the details in picture, reference line was drawn on the edge of the insert from the region of no wear up to the nose of inserts. During image processing, scaling of images was taken care so that processing could not affect the result. Average and maximum wear was measured from the reference line.

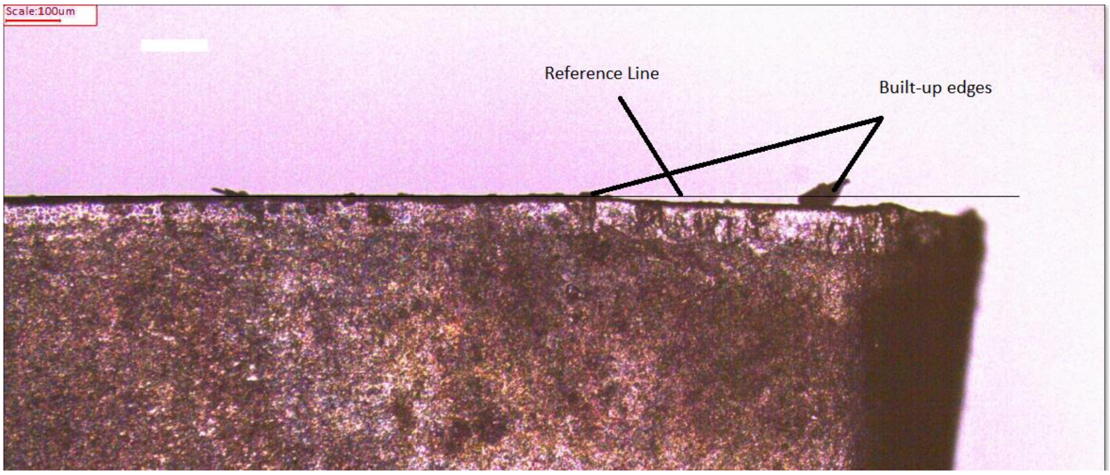


Figure 3.7 Processed Image

3.6.1. Maximum Flank Wear Measurement

Maximum wear on flank was measured from reference line to the deepest point of the crack produced on flank side. Notch wear was ignored for this measurement according to ISO 3685 standard. Scale was adjusted on ImageJ software according to the scale on microscopic image.

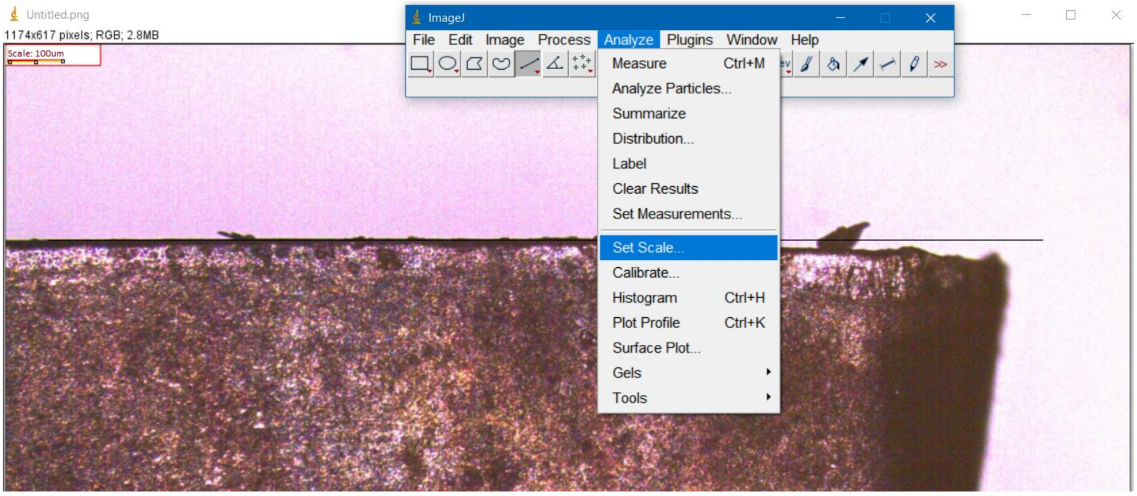
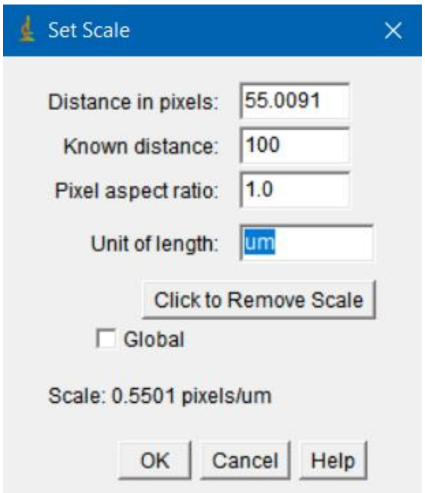


Figure 3.8 Scaling on ImageJ



Distance in pixels: 55.0091
Known distance: 100
Pixel aspect ratio: 1.0
Unit of length: um

Scale: 0.5501 pixels/um

Figure 3.9 Scaling values and units

A perpendicular line was drawn from point of maximum wear to reference line and its length was measured using built-in length measurement tool. Measurements were taken at three different points to get the actual maximum value.

3.6.2. Average Flank Wear Measurement

For measurement of average wear total area of the wear region was measuring using area measurement tool and length of wear was measured using length measuring tool. From these values, average width of the wear region was calculated by simply dividing area by length of wear.

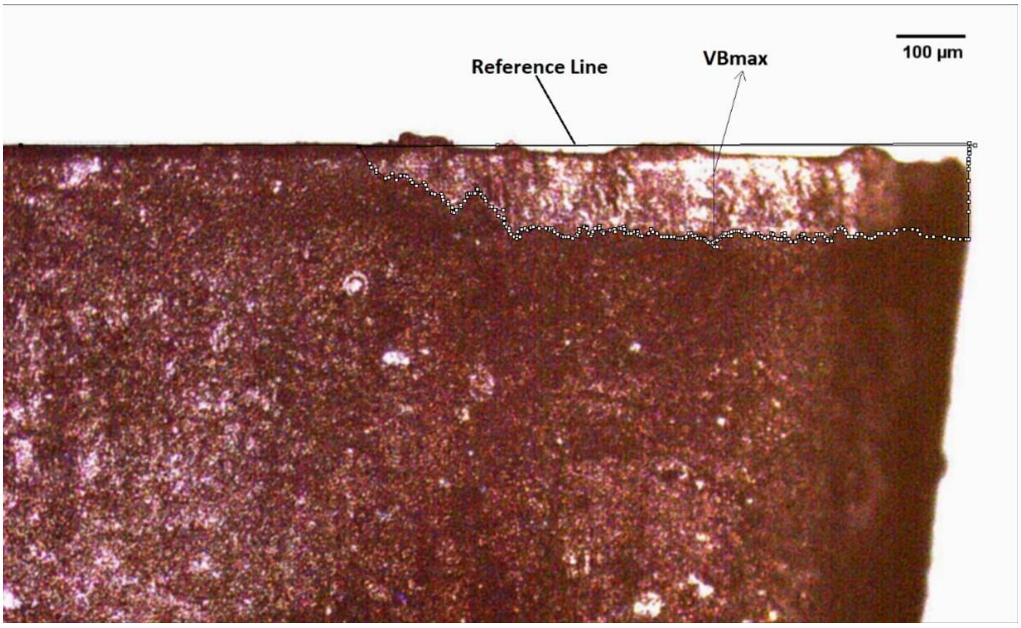


Figure 3.10 Area Measurement on ImageJ

3.7. CALCULATION OF WEAR RATE ‘R’

As the diameter of workpiece decreases with each experiment and could not be kept constant on each speed levels so this should be normalized to make a fair comparison. For this purpose, actual cutting time was calculated for each experiment using the following formula.

$$t = \frac{\pi D l}{1000 f V_c}$$

Where

t = actual cutting time in minutes

D = Workpiece diameter in mm

L = length of cut in mm

F = Feed in mm/rev

And

Vc = cutting speed in m/min

Wear rate was calculated by taking logarithm of ratio of flank wear to the spiral length of cut using the equation

$$R = log\left[\frac{VB}{l_s}\right] = log\left[\frac{VB}{1000tV_c}\right]$$

Where VB is flank wear and R is wear rate parameter.

It is the same normalizing approach that was used by H.I Jaffery [15].

4. Results and Discussions

4.1. RESULTS

Tables below present the values of maximum flank wear, average flank wear and wear rate parameter ‘R’ occurred in uncoated, single coated and multicoated inserts at all different levels of speed. Table 4.1 contains results of experiments performed with uncoated inserts. Table 4.2 and table 4.3 present results for single coated and multicoated inserts respectively. VB_{max} is maximum flank wear and VB_{avg} represents average flank wear. Wear rate parameter is denoted by R. As mentioned above, feed rate and depth of cut were kept constant in all experiments. Average flank wear and maximum flank wear is in microns while the wear rate parameter ‘R’ has no dimension.

Table 4-1 Maximum Wear, Average Wear and Wear Rate Values of Uncoated Inserts

Exp. No.	**Speed(V) m/min**	**Coating**	**VB_{max} (um)**	**R**	**VB_{avg} (um)**
1	50	Uncoated	76.623	-6.0618	48.502
2	55	Uncoated	81.598	-6.0148	51.651
3	60	Uncoated	83.588	-5.9836	52.911
4	62.5	Uncoated	87.568	-5.9417	55.430
5	65	Uncoated	97.512	-5.8721	61.725
6	70	Uncoated	107.499	-5.8056	68.046
7	100	Uncoated	137.358	-5.6736	86.947
8	130	Uncoated	160.474	-5.5789	101.580
9	150	Uncoated	176.049	-5.5097	111.439

Table 4-2Maximum Wear, Average Wear and Wear Rate Values of Single Coated Inserts

Exp. No.	Speed(V) m/min	Coating	VBmax (um)	R	VBavg (um)
10	50	TiAlN	73.639	-6.07913	46.613487
11	55	TiAlN	76.627	-6.04211	48.504891
12	60	TiAlN	77.618	-6.01585	49.132194
13	62.5	TiAlN	85.613	-5.95155	54.193029
14	65	TiAlN	92.533	-5.89493	58.573389
15	70	TiAlN	100.517	-5.83485	63.627261
16	100	TiAlN	131.35	-5.69311	83.14455
17	130	TiAlN	148.262	-5.61336	93.849846
18	150	TiAlN	169.046	-5.52742	107.006118

Table 4-3Maximum Wear, Average Wear and Wear Rate Values of Multi-Coated Inserts

Exp. No.	Speed(V) m/min	Coating	VBmax (um)	R	VBavg (um)
19	50	TiAlN + AlCrN	66.529	-6.12323	42.112857
20	55	TiAlN + AlCrN	69.659	-6.08352	44.094147
21	60	TiAlN + AlCrN	70.38	-6.05836	44.55054
22	62.5	TiAlN + AlCrN	73.639	-6.01698	46.613487
23	65	TiAlN + AlCrN	81.598	-5.94955	51.651534
24	70	TiAlN + AlCrN	84.583	-5.90981	53.541039
25	100	TiAlN + AlCrN	106.472	-5.78430	67.396776
26	130	TiAlN + AlCrN	128.374	-5.67591	81.260742
27	150	TiAlN + AlCrN	151.257	-5.57571	95.745681

4.2. DISCUSSIONS

According to ISO 3685 tool life criteria [38], a cutting tool is useable until its maximum flank wear in under 0.6mm or 600 microns. This standard also defines the workability of cutting tool on the basis on average tool wear that average tool wear must not increase 0.3mm or 300 microns. As shown in results, average and maximum tool wear remain under their standard limit for all experiments, which shows the validity of this analysis.

Cutting speed as has strong impact on tool wear as higher cutting speeds tend to produce more tool wear. At higher cutting speeds higher temperature is produced and due this higher temperature hardness of tool material decreases that causes abrasion and diffusion [39]. This phenomenon increase both maximum and average tool wear. Effect of speed is similar for all coating levels.

The fig. 4.1 shows the performance of coatings in terms of maximum flank wears with respect to speed. Maximum tool wear has higher values for uncoated inserts at all cutting speeds. At lower speeds, from 50 to 65 m/min, single coated performs slightly better than uncoated inserts, while performance of multi-coating is significantly higher than both uncoated and single coated inserts. At lower speeds, temperature generated is relatively lower than temperature at higher cutting speeds. According to [8], at lower cutting speeds uncoated inserts already have a stable external layer and hence they perform nearly equal to coated inserts at low speeds. At higher cutting speeds, 70 and 100m/min, multi-coated inserts perform much better than uncoated inserts. At higher speeds, coating layers also start to chemically react. Built-up edges are also observed on inserts at higher speeds. At speed 130 m/min single layer performed nearly equal to uncoated inserts while in case of multi-coating maximum wear was around 20 microns less than both uncoated and single-coated inserts.

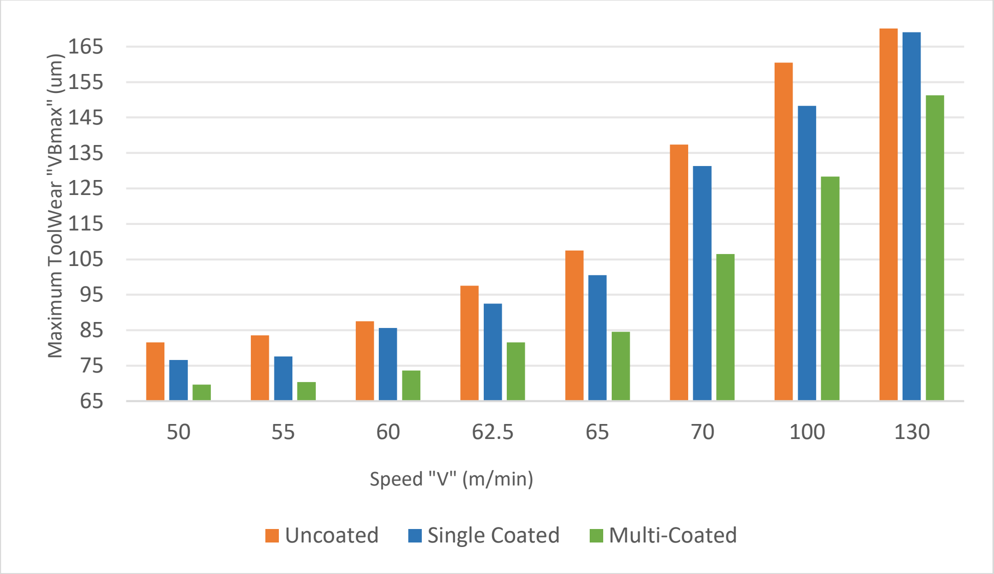


Figure 4.1 Comparison of Maximum Flank Wear of Coated and Uncoated Inserts

Effect of coatings on average flank wear was also found to be identical to maximum wear. The graph of average tool wear and speed for all three coating levels is given below. As shown in graph, maximum performance of multi-coating is observed at higher speeds in terms of average tool wear too.

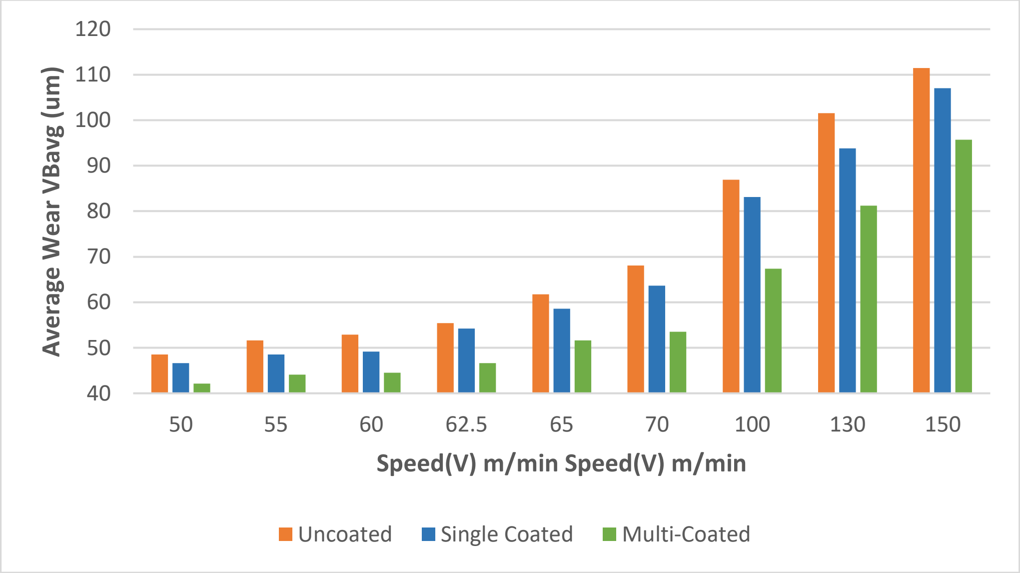


Figure 4.2 Comparison of Average Flank Wear of Coated and Uncoated Inserts

As starting diameter at each experiment was different, comparison of wear rate is also necessary for normalizing the tool wear. Values of wear rates are negative therefore higher wear rates represents more tool wear i.e. tool wear is higher for R=-5.5 than for R=-6.0.

From comparison of wear rates graph in fig. 4.3, it is obvious that wear rates of uncoated inserts have higher values than both other coatings. At lower speeds wear rates are mostly below zero that represent these points belong to low wear regions in wear map. At higher speeds, effect of coatings increases as at higher temperature aluminum oxide is produced that prevents excessive heat from penetrating further into the inserts. Further, less tool wear at higher temperatures can be attributed to oxidation resistance of AlCrN coating. At maximum speed 130 m/min wear rates are much higher, so this speed is not recommended for machining Ti-6Al-4V at these conditions.

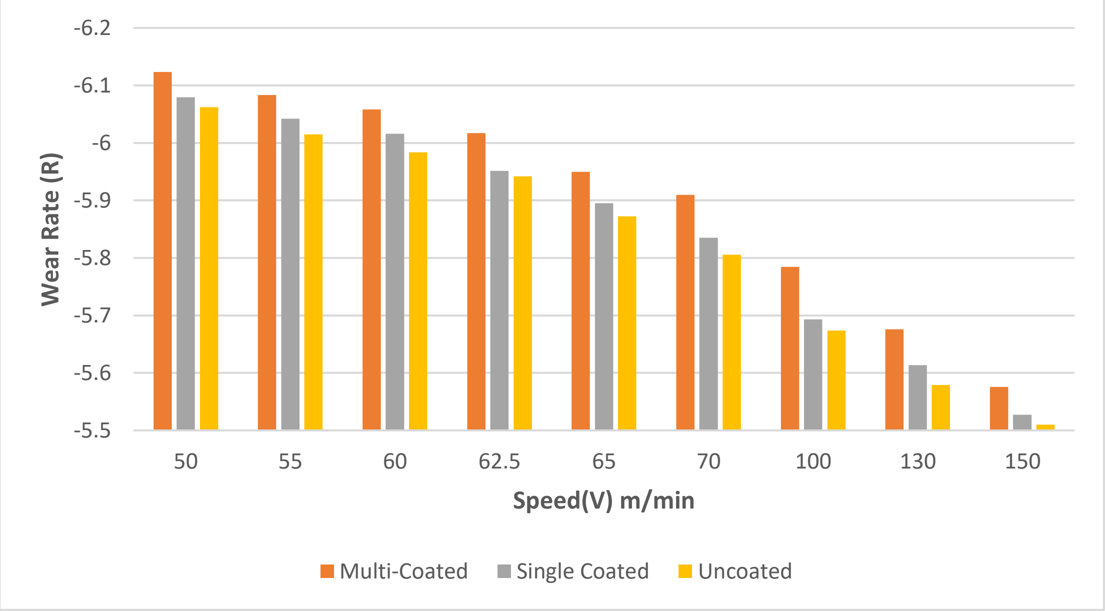


Figure 4.3 Comparison of Wear Rates

5. CONCLUSION AND FUTURE PROSPECTS

5.1. CONCLUSION

Titanium alloys have vast applications in aerospace, biomedical and other industries due to their extra-ordinary properties. They are super hard alloys with very low machinability as high speed machining of these alloys causes cutting tools to wear out quickly. This study is carried out to analyze tool wear in machining of Ti-6Al-4V and examine the effect of tool coatings on tool wear. Suitable tool material and coatings were selected on the basis of literature review. TiAlN and multi-coating of TiAlN and AlCrN was selected as a suitable coating for turning Ti-6Al-4V. Effect of TiAlN and multi-coating of TiAlN and AlCrN was studied and compared with uncoated inserts at a variety of speed levels in terms of maximum and average tool wear. Both coatings contributed considerably in reducing tool wear. Performance of multi-layered coating was considerably higher at higher speeds. Multi-coating performs better than uncoated and TiAlN at all cutting speeds. Effect of TiAlN coating was better at higher cutting speeds as compare to lower speeds.

5.2. LIMITATIONS AND FUTURE PROSPECTS

In this study, the effect of cutting speed on tool wear is compared with coatings while keeping others parameters i.e. feed rate and depth of cut etc constant. Exploring the effect of coatings on furthers points of wear map and chemical analysis of chips and inserts can also help to better understand the process. Effect of different cutting conditions i.e. wet machining etc. can also be studied using these coatings. Cryogenic machining for these coatings is also an interesting area to work on. All these studies can help to optimize turning of titanium alloys for less tool wear. Ideally a single coating should be developed having all the specifications of multi-layered coating.

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