Influence of CVD Multilayer Coating on Machinability Characteristics of Aerospace Grade Stainless Steel

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CERTIFICATE

This is to certify that the thesis entitled, **"Influence of CVD Multilayer Coating on Machinability Characteristics of Aerospace Grade Stainless Steel"** submitted by **Mr Aveek Mohanty** in partial fulfilment of requirements for the award of Degree of Master of Technology in **Mechanical Engineering** with specialization in **"Production Engineering"** at National Institute of Technology, Rourkela is an authentic work carried out by him under my guidance and supervision. To the best of my knowledge the matter embodied in the thesis has not been submitted to any other University or Institute for the award of any Degree or Diploma.

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True guidance is like a small torch in a dark forest. It does not show everything at once, but gives enough light for the next step to be safe.

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ABSTRACT

In the recent years, aeroengine superalloys have gained high amount of research interest owing to their wide engineering application particularly in strategic environment.17-4PH (precipitation hardened) stainless steel (SS) is one such grade of aerospace alloys used to manufacture mostly small parts and mainly stator of aircraft engine in place of Titanium alloy for material cost saving.17-4PH SS falls under the category of difficult-to-cut material because of its low thermal conductivity and high ductility. Although most of the research work was concentrated on machinability of Nickel-based and Titanium based superalloy, no such work on the 17-4PH has been reported so far. Today different coated tools are widely used in machining industries. Therefore it is also essential to select suitable coating material for machining such aeroengine alloys. In order to achieve some of the objectives, the research work has been under taken aiming at investigating the influence of cutting speed (100, 140 & 190 m/min) and feed rate (0.16, 0.20 & 0.24) on various machining characteristics like chip morphology, chip reduction coefficient, tool wear, cutting force, cutting temperature and machined surface roughness. The machining operation was carried under constant depth of cut 0.5 mm and at dry environment.CVD multilayer coated (TiN/TiCN/Al_2O_3/ZrCN) cemented carbide (ISO P30 grade) insert has been chosen for the current study. The performance of the coated tool has also been compared with that of uncoated carbide insert of similar grade and geometry in order to understand the effectiveness of CVD multilayer coated tool during dry machining of 17-4 PH stainless steel.

Keywords— Machinability, 17-4 PH stainless steel, CVD multilayer coated, tool wear, chip morphology

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CHAPTER 1: INTRODUCTION

Machining is a primarily finishing process by which workpiece of desired shape, size and surface finish are generated by gradual removal of extra material from the blank in form of chips by movement of cutting tool across the surface of workpiece. Despite that the major development has been taken place in near-net shape forming techniques, the machining still exists as primary activity in the industries. The problem associated during machining operations are use of high cost tooling material, improper selection of cutting parameters leading to high ideal time along with wastage of material as scrap, dimensional inaccuracy etc.The machining system comprises of cutting tool , workpiece and machine tool.. The cutting tool has greater role to play as the cutting parameters set largely depend upon the material of cutting tool. Hence the main motive of the machining is to explore the workpiece-tool interaction in order to get optimized set of cutting parameter to improve overall productivity of the industries along with improvement of quality of products produced.

The term machinability is described as the easiness with which a material can be cut to the desired size, shape (tolerance and surface finish) with reference to the machining operations involved. During machining process the machinability can be assessed through rate of metal removal, life of cutting tool, power utilization and component forces, surface roughness obtained and surfaceintegrity of the machined surfacealong with chip morphology. The machinability index is significantly influenced by the properties and geometry of the cutting tool, material properties being machined, cutting parameters used along with factors such as cutting environment, machine tool rigidity etc. The proper combination of machining parameters, cutting tools and machine tool can lead to improvement in the productivity of any machining operations.

This will result in high speed machining of difficult-to-cut aero-engine alloys without undermining the dimensional accuracy and as well as other aspects of machinability.

1.1. Aeroengine Alloys

An aeroengine compromise of three major subassemblies which are compressor, turbine and combustor housed in a casing. All these components are made of aeroengine materials which in general are metal alloys which are mostly developed for use of aerospace applications. The main use of aeroengine alloys comes in the aircraft engine components. The main requirement of any aeroengine for its high efficiency performance is that it should able to sustain high temperature and harsh environment, able to bear high thrust , should have high strength to specific weight ratio so as to be fuel efficient along with to keep noise to a optimal level [1]. The overall requirement of such material properties lead researchers to development of aeroenginesuperalloy such as aluminium based, nickel-basedsuperalloy, titanium based alloy, magnesium based alloy and stainless steel.Owing to its unique aggregation of properties such as high mechanical strength at higher temperature, resistance to wear resistance and chemical degradation, the aerospace alloys are mostly used in the field of nuclear, marine, chemical, aeronautics and power plant sectors. The properties which make them to be used in above mentioned application sometime impairs its machinability hence they are referred as difficult-to-cut material [2].

Aeroengine superalloys are mainly found in cast, forged, powder metallurgy (sintered) and wrought forms. Components manufactured by casting process show excellent toughness along with creep strength. These characteristics makes its machinability difficult due to unsuitable segmentation of chip. Forged and wrought components mostly exhibit high strength, fracture resistance and improvement in fatigue. However, they have higher affinity to wear the tool during machining because of abrasion. Powder metallurgy method can used to produce components with high dimensional accuracy, but these components are difficult to machine and are abrasive in nature.

1.2. Classification of aeroengine alloys

1.2.1. Nickel-based superalloy

Nickel-based superalloy nearly accounts for 40-50 % of total mass being used in the aeroengine with most widely used in the turbine parts and combustion chamber where high temperature sustainability is of prime importance. Its properties such as ability to maintain high mechanical strength at elevated temperature, capacity to sustain high thermal and mechanical fatigue as well shock along with resistance to corrosion and oxidation makes it to be useful in other fields such as marine, petrochemical, defense, food processing and nuclear [3].

The major constituent of the superalloy being nickel whose composition range varies in between 38 to 76 % along with other next major constituent being chromium (upto 27 %) and cobalt (upto 20 %). It may also consist of other alloying elements in small quantity such as aluminium, tungsten, titanium, molybdenum, tantalum and other elements.

The commercially available grades of Ni-based superalloys are listed below:

a) Inconel (901,718, 706, 625, 617, 601, 600, 597, 587)
b) Nimonic (C-263, 942, 115, 105, 90, 80A, 75)
c) Rene (95, 41)
d) Udimet (720, 710, 700, 630, 520, 400)
e) M-252
f) Astroloy
g) Waspalloy
h) Haynes 230

1.2.2. Titanium- based alloy

Titanium alloys got exceptionally high strength to weight ratio at elevated temperature makes them highly suitable for manufacturing airframe along with strong and lightweight components foraircraft engine. Titanium alloys are also highly resistant to corrosive environment

In aircraft engine, they are highly used in both high and low pressure compressors. Also they are used to manufacture partswhich are critically exposed to centrifugal loads such as blades and disks.Due to its good range of physical and mechanical properties along with its high corrosive resistant properties makes titanium alloys to be used in other industrial applications, such as surgical implantation, petroleum refining, pollution control, chemical processing, pulp and paper, nuclear waste storage, marine, food processing and electrochemical applications. Despite its high number of applications in various fields the titanium alloys are quite expensive in comparison to other alloys due to its difficulty in process of extraction and also melting with other difficulty in fabrication and machining.

Titanium alloys can be classified into four categories depending on its basic metallographic characteristics [3]:

a) α alloys

   Basically a pure grade of titanium alloy with iron and oxygen as its other basic constituents and are generally an allotrope of titanium alloy existing at lower temperature with hexagonal cubic phase (HCP). These alloys comprise of α- stabilizers (Sn, Al, O, C, N) which tends to upgrade the transformation temperature of titanium. These alloys are applicable in harsh corrosive environment and low temperature generation region of upto 300° C. One such example of such alloy is Ti $5 - 2\frac{1}{2}$ (Ti-5Al $- 2\frac{1}{2}$Sn) besides pure titanium.

b) Near- α alloys

These types of alloys are mostly α- stabilizers with some minor contents of β- stabilizers in them. β- Stabilizers (V, Mo) are that alloy which tends to retard the transformation temperatures which are of body centric cubic form (BCC). They can be operated in the high temperature range of 400 – 520̊ C. Ti-8-1-1 (Ti-8Al-1Mo-1V) and Ti-6-2-4-2S (Ti-6Al-2Sn-4Zr-2Mo) are some kinds of these alloys.

c) α- β alloys

These groups of alloys are mainly characterized by mixture of microstructures of both α phase which is HCP structure and β phase which is of BCC structure. Mainly useful where high strength at elevated temperature in the range of 300-400̊ C is of prime concern. Ti-6-4 (Ti- 6Al- 4V) and Ti-6-6-2 (Ti-6Al-2Sn) are some of these kinds of alloys.

d) β-alloys

These kinds of alloy are identified by high hardenability and mostly consist of significant amount of β- stabilizers (V, Mo) in it. They are highly stress corrosion resistant and can be imparted to high strength with heat treatment and are also easily fabricated to required shape by cold rolling.

1.2.3. Aluminum based alloy

From many decades the unique combination of high strength, light weight, ductility, corrosion resistant, ease in assembling and low cost makes them one of highly dominating aerospace materials. The conventional grades of aluminum alloy which are being highly utilized in aerospace applications are:

- 2000 series (Al-Cu-Mg)

- 6000 series (Al-Si-Mg)
- 7000 series (AL-Zn-Mg-Cu)

Apart from conventional grades of aluminum alloy new engineered materials and alloys of aluminum such as powder metallurgy based 7000 series alloy, aluminum based metal matrix composites (MMCs), metallic-polymer hybrid composites and aluminum-lithium alloys of lower density have great prospective of replacing above mentioned conventional grades of aluminum alloys [5].

1.2.4. *Cobalt-based alloy*

Cobalt-based alloy posses excellent combination or wear resistant, heat resistant and corrosion resistant at elevated temperature which makes them to be useful in generation of several parts of gas turbines used in aeroengine such as vanes and combustion chamber. Some of major cobalt based alloys used are [6]:

- L-605
- Rene 41
- HA-188
- HA-25
- X-40
- X-45
- FSX-414
- FSX-418
- MAR-M 302
- MAR-M 509

1.2.5. *Stainless Steel*

Stainless steel (SS) is popularly known to be highly corrosion resistant due to high amount of chromium (minimum of 11.5 %) content in it which provides SS both oxidation and corrosion resistance. These steels also comprises of other essential elements in it such as manganese, nickel and molybdenum in order to improve its corrosion resistance property. Stainless steel can be mainly divided into five categories [7]:

a) Ferritic Stainless Steel

   These groups of SS have chromium contents in the range of 11.5 – 27 % mostly between 17-26 % and are nickel free. They are ferritic in structure till its melting point. They may contain small amount of carbon (0.08-2 %) in it with addition to silicon, manganese, aluminium and titanium.Compared to austenitic stainless steel this kind of SS possesses lower thermal conductivity, better machinability and stress-corrosion free. They are particularly ferromagnetic in nature. Type 430 SS is typical example of ferritic SS.

b) Martensitic Stainless Steel

   These types of stainless steel contain chromium in the range of 12-17 % and carbon in 0.1-0.2 %, and are normally heat treatable type. The corrosion resistant nature is of moderate type with poor formability. They are also ferromagnetic in nature. Type 410 and 440 C are few types martensitic grade stainless steel.

c) Austenitic Stainless Steel

   Stainless steel consisting of high chromium amount (16-25 %) with adequate amount of austenite stabilizing elements such as nitrogen, nickel or manganese, so as these are in austenitic form at room temperature and hence are known as austenitic stainless steel. Due to high chromium contents it posses' excellent corrosion resistance property and are non-magnetic in nature. The AISI 200 series has manganese as its austenite stabilizing elements whereas in case of AISI 300 series its nickel. AISI 300 series are most widely used in various application and few of them are listed below:

- Type 301
- Type 302
- Type 316L/316
- Type 304L/304
- Type 321
- Type 347

d) Duplex Stainless Steel

This stainless steel compromise of two-phase structure i.e. both austenitic and ferritic in its microstructure. Thus possess high corrosion resistant property along with highstrength. The proportions of different phases are controlled during the heat treatment process.

e) Precipitation-Hardenable(PH) Stainless Steel

The precipitation hardened stainless steel makes use of chromium and nickel as their major constituent alloying elements.The matrix of these types of alloy could be either austenitic or martensitic depending upon the temperature and other working conditions. Hence, offering a perfect amalgamation of high strength property of the martensitic structure and corrosion resistant property of austenitic phase. The hardness and strength of these precipitation hardened alloys are enhanced by the generation of nano-scale precipitates of another phase mainly at the grain boundaries of the original metal matrix. The hardening of these alloys are achieved by addition one of alloying elements such as aluminium, niobium, molybdenum and copper. This whole process is accomplished after necessary heat treatment process and thus these alloys are known as precipitation hardened alloy. These are expensive and hence are restricted to high-strength to weight ratio applications.

On the basis of its final morphology of the microstructure after appropriate heat treatment it can be classified basically into three categories:

- Austenitic alloys (E.g. A286)
- Semi-austenitic alloys (E.g. 17-7 PH SS)
- Martensitic alloys (E.g. 17-4 PH SS)

1.3. 17-4 PH stainless steel

17-4 PH stainless steel is basically a martensitic precipitation hardenable stainless steel whose microstructure is dominantly a austenitic at high annealing temperature but when brought down to room temperature at high cooling rate the austenitic phase changes to lath martensitic structure. These types of PH stainless steel have around 17 % of chromium and 4% of nickel as its major constituent elements with slight % of copper and molybdenum as its precipitates in its structure [8].

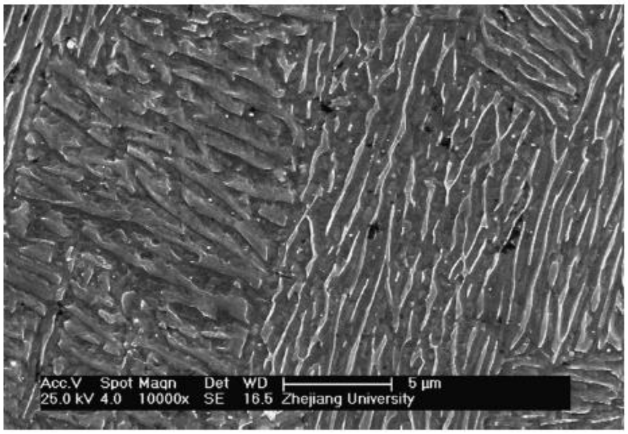


Fig.1 SEM image for 17-4 PH stainless steel[9]

The Fig. 1 shows the SEM microstructure image of the 17-4 PH type stainless steel depicting presence of lath martensitic structure in microstructure.

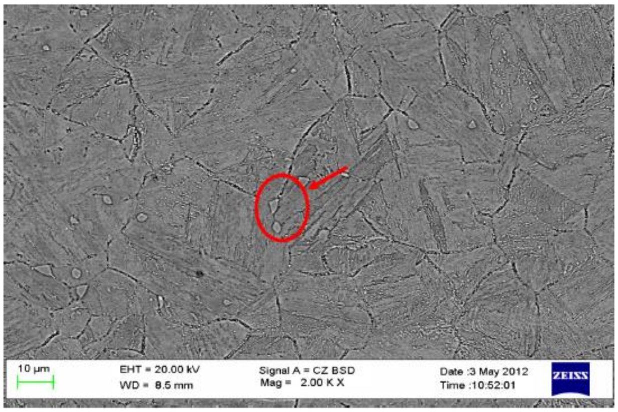


Fig. 2 SEM image for 17-4 PH stainless steel[10]

Presence of the copper precipitants at the grain boundaries of the microstructure of the 17-4 PH stainless steel have been shown in Fig. 2.

1.3.1. Designation of alloys

These types of precipitation hardened stainless steel are designated by following names:

- AMS 5643
- UNS S17400
- AISI 630

1.3.2. Properties of 17-4 PH stainless steel

The property of the 17-4 PH stainless steel which makes them to be used in various sectors are [8]:

- High tensile strength
- High hardness
- Good toughness
- Highly resistance to corrosive environment
- Good weldability and formability

1.3.3. Application of 17-4 PH stainless steel

The above combination of the high mechanical and chemical properties upto a temperature of 316̊ C makes them highly suitable aerospace applications used to manufacture mostly small parts and mainly stator of aircraft engine in place of Titanium alloy for material cost saving . It is mostly used to manufacture the heavy load components, such as, fasteners, valves, gears, aircraft fittings, coupling, chemical processing components, hydraulic actuators, rocket & missile components, jet engines, parts of nuclear reactor, pump shafts,wear rings, valve stems and braces,the shafts and blades of steam turbine[11]. Hence they are mainly used in the strategic field of:

- Aeronautic
- Petroleum
- Nuclear industry
- Astronautic
- Oil and Gas
- Petrochemical Industries
- Paper Industry

1.3.4. Machinability of 17-4 PH stainless steel

The machining of 17-4 PH martensitic type stainless steel at its annealed state is quite easy. However there may be some issue pertaining to the built-up edge formation and control of long gummy chips at this state[11, 12]. But when cooled to room temperature it attains its hard martensitic phase and the machinability of 17-4 PH stainless steel at this stage becomes difficult. The main problem related to machinability at this stage is due to [12]:

- Work hardening
- Built-up edge formation
- Control of chip
- Chip breakage

1.4. Other applications of aerospace alloys

Apart from their high applications in the aerospace industries these types of alloys find tremendous use in other sectors too. Some of sectors which found to be use these alloys are:

- Nuclear
- Defense sector (tanks, submarines etc.)
- Power Plant Industries
- Pollution control equipments
- Paper and Pulp Industries
- Medical applications
- Food Processing
- Oil and Petroleum
- Chemical Industry

1.5. Properties impeding the machining of aeroengine alloys

Despite being having many advantageous properties which makes aeroengine alloys to be applicable in harsh environment such as high temperature, high corrosive and oxidizing environment, high fatigue load, high shock load etc. also impairs its machining. Hence it cannot be machined into intricate or complex shapes with easiness, termed to be difficult-to-cut materials. The properties which hinder the machinability aspects of these aeroengine alloys are [3]:

- High mechanical strength and hot hardness resulting in low tool life due to high deformation taking place during machining.
- Expeditious work hardening of material during machining may also affect surface integrity and tool life.
- Hard abrasive particles present in the microstructure of the machined material may hamper the tool life.
- Low thermal conductivity of the work material leading to generation of high temperature at tool-workpiece contact region may also lessen the tool life.
- High chemical affinity of workpiece material towards majority of the tool material causing diffusion type of wear mechanism in the tool.
- Formation of built up edge may also hamper the surface integrity and tool life.

1.6. Machinability

The prime objective of machining is that its each operation should be carried out in efficient, effective and economic manner by removing workpiece material at high rate along with lower consumption of power, tool wear, surface roughness and lower generation of temperature. But under a given circumstances or conditions such as workpiece property variation, change in cutting parameters etc. it is very difficult to get the entire desired objective as specified above. Hence the machining characteristics of the workpiece material may differ in accordance with different conditions, so term machinability was defined in order to grade workpiece material with respect to its machining characteristics.

Earlier the gradation of machining characteristics of any workpiece material was done by comparing it with a given standard material. Hence the machining rating can be evaluated by following given equation:

Machinability rating/ index

$$= \frac{Cutting\ speed\ of\ machining\ work\ material\ providing\ 60\ minutes\ of\ tool\ life}{Cutting\ speed\ of\ machining\ standard\ work\ material\ providing\ 60\ minutes\ of\ tool\ life}$$

The above method of defining the machinability faced lots of criticism as it has only considered tool life for rating the machinability index. But there are lots of other factors which have to be taken into consideration such as composition of the workpiece, its microstructure, treatment method, cutting parameters etc. The slight variation in above mentioned parameters may result in different machinability rating, so there have to be other factors taken into account for properly defining the machinability rating.

Hence the term machinability can be described as the ease with which a workpiece can be machined. But again the term ease is qualitative and relative. In machining this can be quantitatively assessed by following [13]:

- Cutting forces
- Cutting temperature
- Tool life or tool wear
- Surface integrity
- Chip morphology

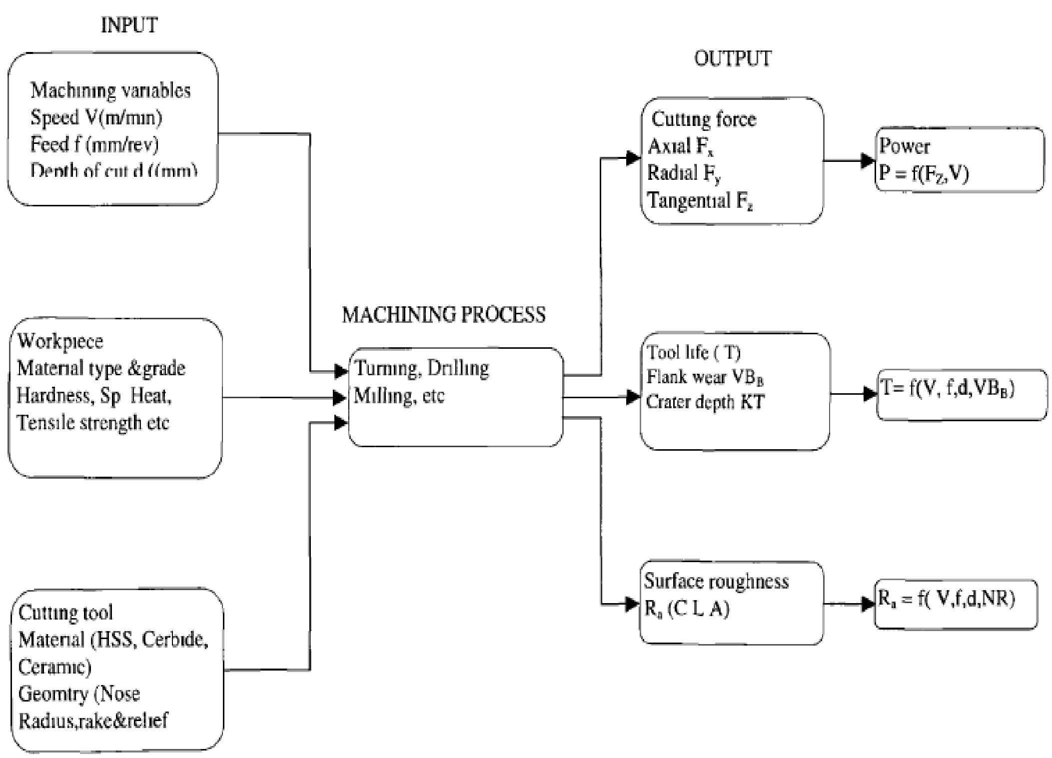


Fig. 3 Different machinability parameters [14]

1.7 Factors influencing the machinability

The machinability index or criteria of workpiece i.e. cutting temperature, surface finish, cutting force and tool life is influenced by number of factors such as:

a. Workpiece material Properties

The property of a material which play an important role in affecting the machinability criteria are:

- Nature of workpiece material (ductile or brittle)
- Microstructure
- Thermal conductivity
- Mechanical property (strength, hardness, work hardening)
- Chemical property

b. Cutting tool material and its geometry

Material of cutting and its geometry are another major factor influencing the machinability index. There are different cutting tool materials such as carbide tools, high speed steel, cubic boron nitride, ceramics tool etc. with different mechanical property and chemical stability which may result in different machinability index. Different coating of various layers and combination on the cutting tool also influences different machinability criteria. Tool geometry (Fig. 4) which governs the machinability index is:

- Rake angles
- Cutting angles
- Clearance angle
- Radius of tool nose
- Inclination angle

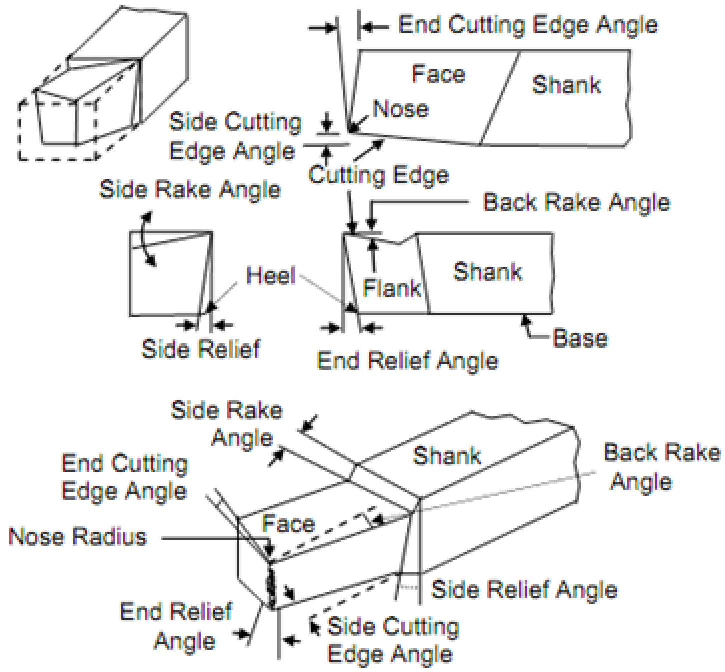


Fig. 4 Cutting tool geometry [15]

c. Cutting parameters

Selection of proper cutting parameters is necessary for efficient and effective machining to take place. The various cutting parameters that influence the machinability criteria are:

- Cutting velocity
- Depth of cut
- Feed rate

d. Machining environment

The machining operation may take place in absence of cutting fluids called dry machining or in the presence of the cutting fluids. There are several beneficial effects of using cutting fluids such as:

- Reduction in cutting forces and consumption of power
- Decrement in cutting temperature
- Improvement in tool life
- Improvement if surface integrity

1.8. Methods of improving machinability

The various methods that can be employed in order to improve the machinability criteria are:

- By applying a suitable variation in the composition of workpiece and its microstructure along with mechanical property by suitable addition of various elements.
- By appropriate choice of cutting tool material and the tool geometry in accordance with workpiece and other criteria.
- Optimal selection of cutting parameters
- By appropriate selection of cutting fluids and cooling technique.
- By applying special techniques such as hot machining, cryogenic machining etc.

1.9. Chip mechanism

Machining is practically a material removal process from a given workpiece material to get desired shape with high dimensional accuracy and surface integrity. Machining generally involves gradual removal of material in form of chip. Machining at variable condition and different workpiece may yield different pattern and types of chips. Even tool geometry and machining environment do play an influential role on formation of different types of chips. The mechanism of chip formation and its characteristics such as chip shapes, pattern, color and size may give indirect or direct knowledge of machinability of workpiece under consideration. Hence it becomes necessary to have a proper understanding of chip formation mechanism along with its characteristics.

1.9.1 Need for studying chip formation mechanism

The attribute chip developed during machining may indirectly or directly indicate:

- Workpiece material nature
- Cutting temperature level
- Degree and nature of tool-chip interaction
- Conditions of the cutting edge of tool
- Influence of various machining parameters
- Application of cutting fluid

1.9.2 Chip formation mechanism in machining

The mechanism of the chip formation is mainly of two types depending upon the nature of the work material used for machining:

- Yielding or Shearing : For the ductile materials
- Brittle Fracture : For the brittle materials

1.9.3 Chip classification

The types of chip formed during machining of workpiece material whether of ductile or brittle nature can be classified (Fig. 5) into following forms:

a. Discontinuous chips

These types of chips are basically formed during machining of brittle material such as cast iron or when machining ductile material at very low cutting velocity in dry environment. The discontinuous chips formed maybe of:

- Irregular shape and size
- Regular shape and size

b. Continuous chips

The continuous types of chips are mostly produced during machining of ductile material. They may form during machining with:

- With built-up edge (BUE)
- Without BUE

c. Segmented or jointed chips

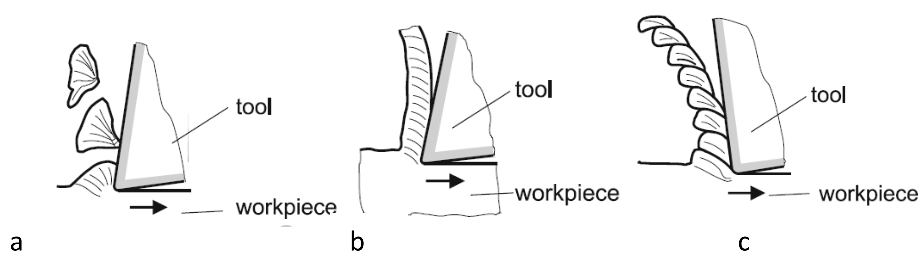


Fig. 5 Types of chip a) discontinuous type b) continuous type and c) segmented type [16]

The types of chip formed play a significant role during productivity of machining especially when it comes to automation of machine. According to ISO 3685-1977 (E) the chips type and form can be classified under five different sets as given: 1. ribbon, tubular, spiral, washer-type, conical helical, arc; 2. long, short, snarled; 3. ribbon long, ribbon snarled, tubular long, tubular short, tubular snarled, spiral flat, spiral conical, washer-type long, washer type short, washer type snarled, conical long, conical short, arc connected, arc loose; 4. flat, short, snarled, long, conical, connected, loose; 5. good, acceptable, dangerous. The formation of long continuous curl chip may have a negative impact for the workpiece, tool and machine. They may cause some safety issue to operator with regards to its transportation and disposability. The small segmented chips formed are easy to handle, transport, store and disposable, hence possess no threat to machine as well as operator. The following table gives some of classification made by "Fundamentals of Machining and Machine Tools," 2d Edition, by Boothroyd and Knight, p. 227.

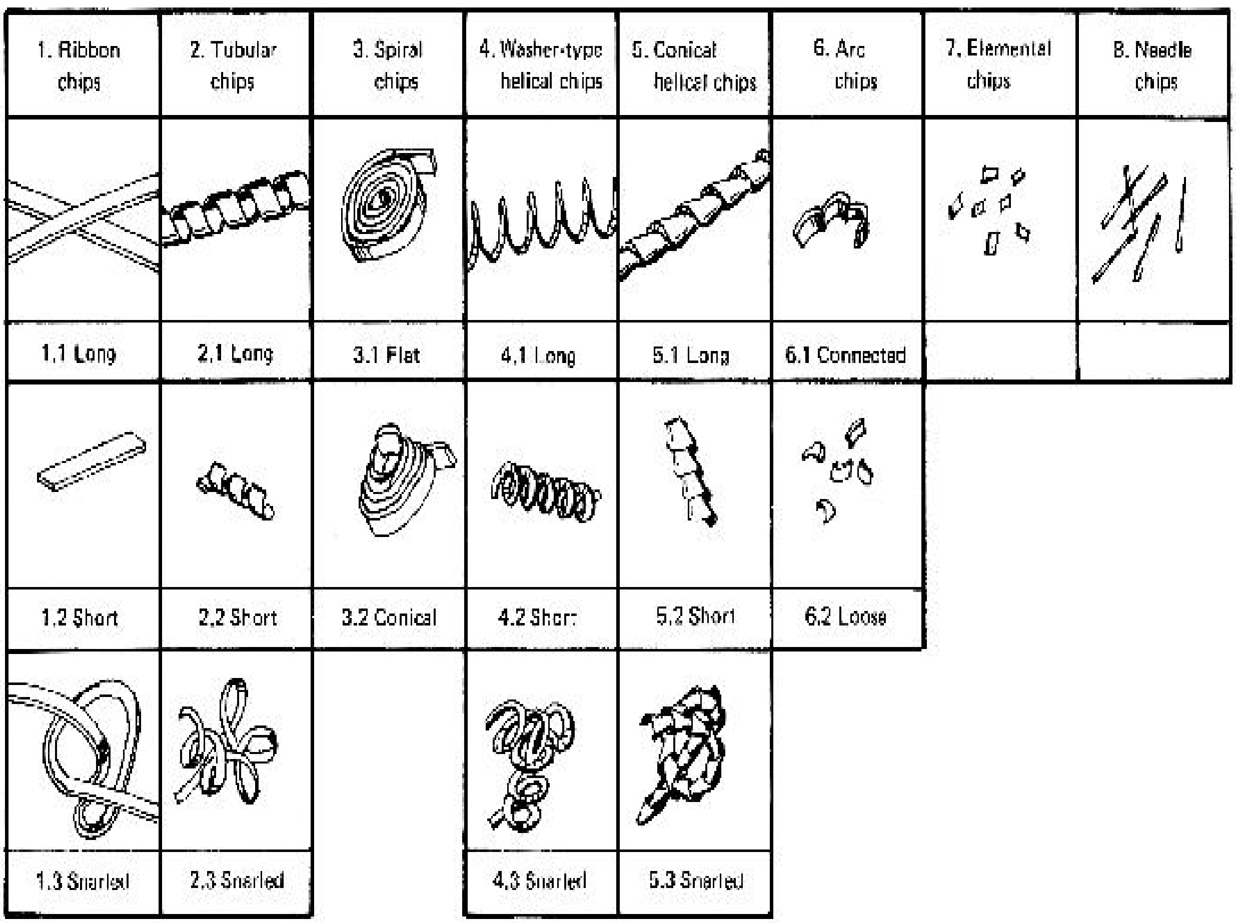


Table 1 Classification of different type of chips [17]

1.10 Surface integrity

Surface integrity is a term which broadly covers all the aspects of machined surface present at various machining conditions. The aspects or characteristics which it covers may exist at or on the machined surface and also beneath the machined surface. The surface integrity basically covers two aspects:

a. Surface Topography

Surface topography mainly covers the top layer characteristics of the machined surface which mainly is in direct contact with the environment. Mainly it describes surface texture, lay, waviness and surface roughness.

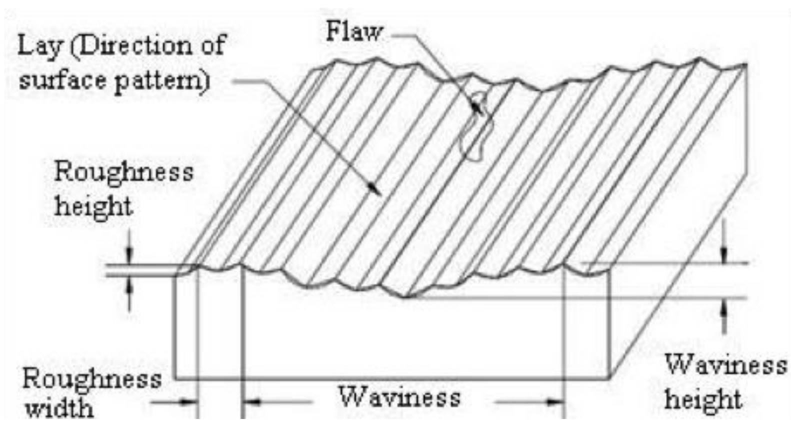


Fig. 6 Surface topography of machined surface

Surface Roughness during machining

Surface roughness basically gives an indicative of micro and macro irregularities present produced at machined surface.

Factors influencing surface roughness

The surface quality generated at the machined surface during machining process mainly depends upon following factors:

- Machining parameters
- Geometry of tool
- Condition and type of cutting tool
- Use of cutting fluids
- Chip removal method
- Rigidity of machine tools

Estimation of surface roughness

Based on the ISO recommendation the surface roughness can be evaluated by following three methods:

- Centre line average (Ra) method

  It is the mean of the vertical deviations from the nominal surface over a given specified sampling length. This can be estimated by:

$$Ra=\frac{1}{L}\int_0^L |Yi|\ dx$$

- Route mean square (R_{rms}) method

  It is the square root of addition of all the squares of the peaks and valleys from the nominal surface and is given by:

$$R_{rms}=\sqrt{(\frac{1}{L}\int_0^L |Yi|^2\ dx)}$$

- 10-point average (R_z) method

  It is the difference between the average height of five highest peaks and five lowest peaks within the specified sampling length. It is calculated by:

$$R_z=\frac{(R1+R3+R5+R7+R9)-(R2+R4+R6+R8+R10)}{5}$$

Where R1, R3, R5, R7 and R9 are the height of five consecutive peaks from datum line and R2, R4, R6, R8 and R10 are height of five consecutive valleys from the datum line.

Methods of surface roughness measurement

There are basically two methods by which we can know the quality of the machined surface:

- Qualitative Method

  This method does not make use of any kind of instruments for the measurement of the surface quality but by rather visual inspection or by touching the quality is known.

- Quantitative Method

  This method makes use of instruments to get a quantitative value of the surface quality to be measured. The instruments used for measurement are:

  - Tamlison surface meter
  - Surface profilograph
  - Talysurf
  - Abbots profilometer
  - Piezoelectric crystal

b. Surface Metallurgy

Surface metallurgical aspects of surface integrity deals with the effect of the machining on the sub-surface layers i.e. surface below the topmost machined surface. These sub-surfaces characteristics are usually referred to as altered material zones (AMZ's) which are as a result of mechanical, thermal and chemical alteration of the sub-surface layers during the machining. These AMZ's can be classified into four modes:

- Mechanical modes

  This type of changes on the sub-surface layer is mainly because of mechanical or plastic deformation taking place at machining hour. This may include microscopic and macroscopic cracks, change in hardness, residual stress, laps, tears etc.

- Thermal modes

  During machining high heat generation may also result in sub-surface alteration which includes mainly formation of white layer or heat affected zone (HAZ) and secondary deformation zone below HAZ.

- Chemical modes

  These changes take place due to interaction with the environment or some other reactive agents such as coolant, electrolyte etc. this may include intergranular attack, oxidation, corrosion, pits, embrittlement etc.

- Metallurgical modes

  Due to both mechanical and thermal deformation there may occur some metallurgical changes in the sub-surface layer such as phase changes, changes in shape and size of grains, recrystallization, redistribution etc.

1.11. Cutting temperature

The machining operation is congenitally correlated to generation of high temperature and heat at the zone of machining. The heat generated in the machining zone or cutting zone is primarily due to plastic deformation of chip or friction generated at work-tool and chip-tool interface. The cutting zone can be divided basically into three regions:

a. Primary shear zone

This is the zone where maximum generation of heat takes place nearly 60-80 % because of the plastic or mechanical deformation of the shear zone during the machining operation. The major portion of the heat generated at this region is taken up by the chip and little by workpiece material.

b. Secondary deformation zone

It is the zone at the chip-tool interface where the heat generation is in the range of 10-15 %. Here the heat produced is as a result of both mechanical deformation and friction generated due to rubbing action between the tool and chip. The maximum amount of the heat being carried away by chip.

c. Tertiary heat zone

In this zone the friction between the workpiece and tool interface results in generation of heat which nominal around 5-10 %.

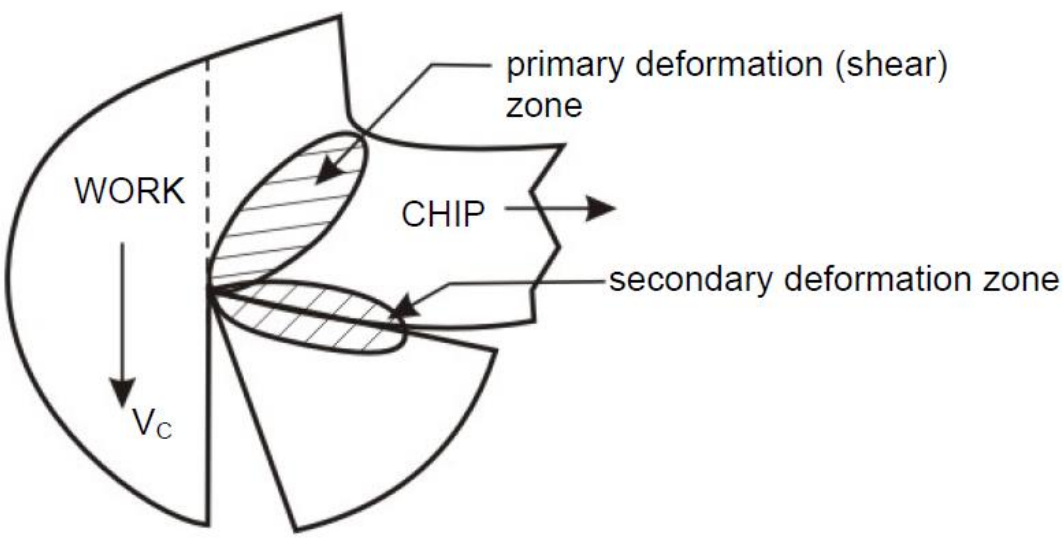


Fig. 7 Cutting zones in the chip [13]

1.11.1 Effect of cutting temperature

a. On cutting tool

Excessive generation of the heat at the chip-tool interface is not favorable and may result in:

- High tool wear rate
- Built-up edge formation
- Fracturing and thermal flaking of the cutting tool edge due to thermal flaking

b. On surface integrity of workpiece

The high generation of heat may also affect the machined surface integrity in following manner:

- Generation of white layer due to excessive temperature
- Formation of micro-cracks
- Residual stress (tensile) generation
- Dimensional inaccuracy of the machined material due to thermal distortion

1.11.2 Cutting temperature measurement

The generation of high temperature and heat at cutting zone do reduces the cutting force due to softening of the material but it also shortens tool life by promoting the tool wear, may cause dimensional inaccuracy and also may degrade the surface integrity of the machined surface. So it is necessary for estimating the cutting temperature produced during machining operation. The cutting temperature can be determined by following two methods:

a. Experimental method

The cutting temperature determined by this method is although difficult but highly accurate and reliable, often expensive method. The experimental method includes following techniques:

- Use of calorimetric set-up
- Optical pyrometer
- Thermocouple principle
- Infrared technique

b. Analytical Method

Analytical method of determining the cutting temperature includes use of mathematical equations or models which are although much simpler and inexpensive than previous method but with less accuracy.

1.12. Cutting force

Cutting force is also one of the major criteria for determining the machinability index of any workpiece during the machining. The measurement of the cutting forces will help in:

- Determining the power consumption during machining.
- Design (structural) of the machine, fixture and tool system.
- Evaluating the effect of various machining parameters on the cutting forces.
- Online monitoring condition of cutting tool along with the machine tool.

1.12.1 Cutting forces in the turning operation

Turning which is a single point cutting operation is generally characterized by only one cutting force called resultant force (R) which is resolved in the x, y and z direction for further analysis. The three components of the resultant force (Fig. 8) are:

a. Main cutting force (P_z)

   It is major component of the resultant force present in the direction of cutting speed and hence called as main cutting force. This force accounts for large proportion of the resultant force and is used for determination of cutting power consumption.

b. Thrust force (P_y)

   The thrust force acts in the direction perpendicular to the machined surface. This force is of lower magnitude but it actuates vibration during machining and dimensional accuracy of machined surface produced.

c. Feed force (P_x)

   Feed force which acts in the direction of the tool travel. The effect of feed force during machining is of least significant and is generally harmless.

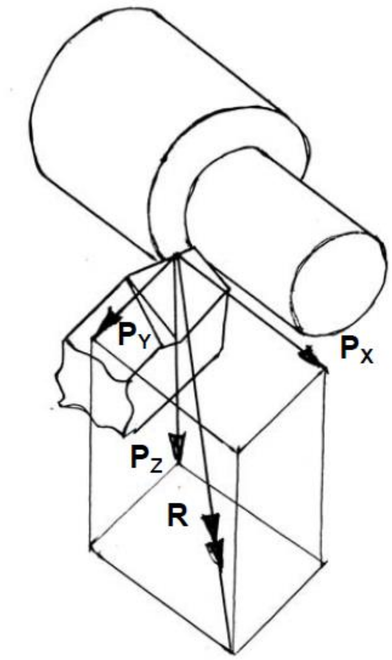


Fig. 8 Cutting force in turning [13]

1.13. Tool wear

Tool life one of most important and most widely used criteria used to determine machinability criteria of any material. Hence much research has been carried out in machining field to improve the tool life by selection of proper machining condition, tool material, use of coolant, use of coated tools etc. Tool wear mechanism is to be understood in proper way to make proper improvement in the tool life.

1.13.1 Tool wear mechanism

The different tool wear mechanism is as follows:

a) Diffusion

This type of wear mechanism generally takes place at high temperature where the atoms of the generally hard material diffuse into the softer material.

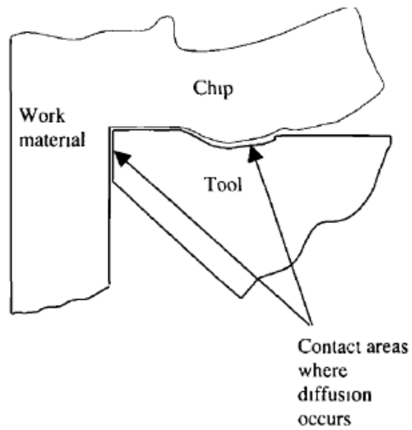


Fig. 9 Diffusion wear at chip tool-interface [14]

b) Adhesion

Due to high friction, pressure and temperature generated at the cutting zone the softer workpiece particle may stick to the hard tool material. During subsequent machining these large chunks of material may remove out along with some material from the tool.

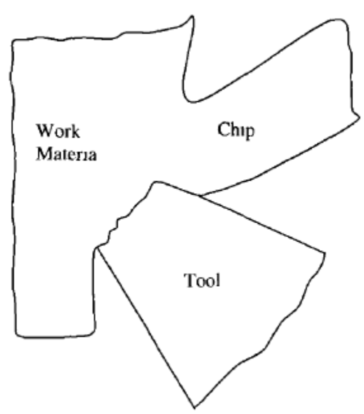


Fig. 10 Adhesion wear [14]

c) Abrasion

These type of wear occurs when the abrasive or hard particles of one of the material rubs over the surface of other constituent material.

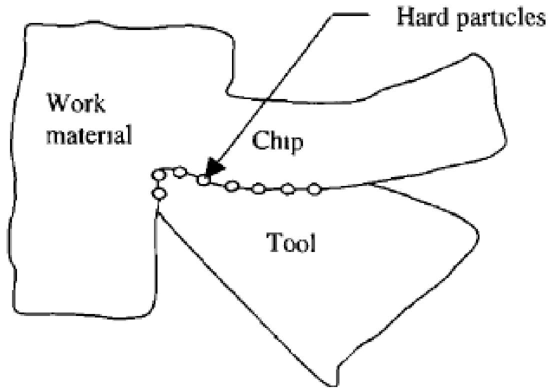


Fig. 11 Abrasive wear [14]

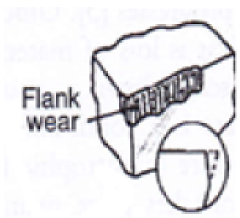
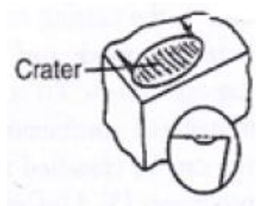
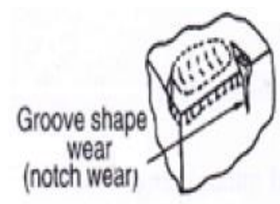
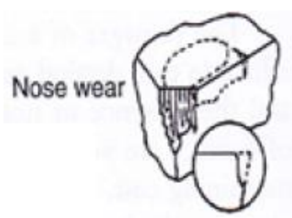
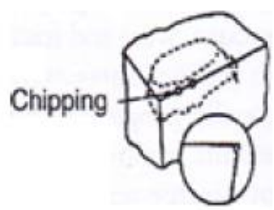
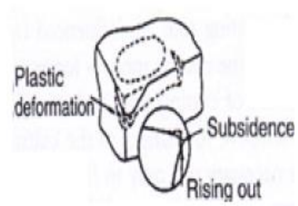
d) Chemical wear

Chemical wear occurs due to the presence of the active environment at the tool-workpiece interface. E.g. oxidation

1.13.2 Modes of tool wear

The various modes by which tool wear takes place during the machining has been shown in given below in Table 2:

Table 2 Modes of tool failure [18]

 Flank wear	 Crater wear	 Notch wear
 Nose wear	 Chipping	 Plastic Deformation

CHAPTER 2: LITERATURE REVIEW

2.1. Influence of machining parameters on tool wear

The low resistances to tool wear when machining SS with ceramic tools can be attributed to high temperature generation at rake surface with adhesion-spallation being dominant tool wear mechanism [19]. Machining of powder metallurgical made duplex stainless steel 2205 and austenitic stainless steel 316L was carried out with the TiN-coated high speed steel insert and TiN-coated cemented carbide tools. The TiN-coated cemented carbide inserts were used to machine SS in higher cutting range of 100- 250 m/min while HSS insert was used for machining at the lower ranges. The abrasion, adhesion, diffusion and fatigue induced wear mechanisms were responsible for the tool wear when machining both types of stainless steels [20]. Different wear modes of Ti[C, N] mixed alumina inserts and SiC whisker reinforced alumina inserts were investigated while machining martensitic SS of grade AISI 410. The flank wear, crater wear and notch wear for both the types of alumina-based inserts increased with both increase in cutting speed and as well as with progress in the machining duration. Ti[C, N] mixed alumina inserts showed better resistance to both flank wear and crater wear than that of SiC whisker reinforced alumina inserts. The low resistance of SiC whisker reinforced alumina inserts can be attributed to higher solubility of silicon towards Fe at high temperature. Higher hardness and better toughness of SiC whisker reinforced alumina inserts helped it to resist abrasive action of the workpiece and chip thereby reducing the notch wear [21]. Dry turning of precipitation hardening semi-austenitic stainless steels (Cr12Mn5Ni4Mo3Al) was carried out with two different types of carbide tools (WC/Co and WC/TiC/Co). The dry turning was carried out within cutting speed range of 100-160 m/min, at constant feed of 0.1 mm/rev and DOC of 0.2 mm. Under same machining condition the WC/TiC/Co tool performed well in terms of tool life than that when machined with

WC/Co tool. The high resistance of WC/TiC/Co tool can be attributed to its higher hardness of than WC/Co tool. Flank wear and rake wear were most prominent wear observed in all tools. The adhesion wear mechanism was more responsible for the crater wear at the rake surface of the tool while it was abrasion and adhesion for the flank wear. Hard martensite structure of the workpiece which acted as small indenters were responsible for the abrasion at the flank face of the tool [22]. Performance of two grades of coated carbide insert one CVD-Ti(C,N)/TiC/Al_2O_3 (T1) and other PVD-TiN (T2) were investigated in terms of tool life and surface integrity during dry and wet machining of martensitic stainless steel (JETHETE) under varying cutting speed (100, 150, 200 & 250), two different feed rates (0.2 & 0.4 mm/rev) and at constant DOC of 2 mm. Chipping/fracture of principal cutting edge of insert and nose wear were prominent modes of tool failure. Presence of cubic carbides (TiC &Ta(Nb)C) in the substrates of T1 grade insert provides higher strength and diffusion resistance at elevated cutting temperature produced at higher cutting speeds. Also the Al_2O_3 upper layer offers adequate oxidation and diffusion wear resistance to T1 insert during machining. T2 grade insert was found to be more susceptible to diffusion wear which weakened the substrate and resulting in chipping of the cutting edge of the insert [23]. Ultra-precision machining of LH-S (STAVAX with a hardness of 40 HRC) and HH-S (STAVAX with a hardness of 55 HRC) workpiece were carried out under both dry and wet condition with uncoated and PVD-coated carbide inserts (2000 alternate layers of AlN and TiN with thickness of layer being 1.5 nm) and carbide insert coated with 0.5 μm TiN layer, 5.5 μm TiCN layer and 0.5 μm TiN layer). Machining HH-S workpiece of higher hardness generated in more stress at the cutting edge of tool making it more susceptible to fracture. Uncoated tool showed low tool wear resistance. The multilayered coated carbide insert provided greater resistance to tool wear than the three layered PVD coated carbide inserts. Chipping/fracture of cutting edge was found to be major tool wear failure modes. At lower cutting speeds the tool was more susceptible to fracture [24]. Milling operation of austenitic stainless steel was carried out at different cutting speeds (30, 60 and 90 m/min) at constant feed rate of 0.3 mm/rev and DOC of 1.6 mm. Formation of stable adhering layer on the rake face at medium cutting speed due diffusion mechanism between the work-tool interface tends to increase the tool life. At low cutting speed due to low temperature and at high cutting speed because of less contact time the diffusion does not take place hence the formation of adhering layer is prevented [25]. The effect of grain size and its distribution on the tool life and chip deformation during dry turning of AISI 304L austenitic stainless steel with Sandvitcoormant make Al_2O_3- Ti(C, N) coated cutting insert GC 4025 of geometry CNMG 120412-QM. The turning operation was carried out at cutting speed of 200 m/min, feed rate of 0.3 mm/rev and DOC of 2 mm. Comparison of different machining performance of hot forged bar was made with that of bars water quenched at different holding temperatures 1050℃, 1100℃, 1150℃ and 1200℃ for duration of 1hr.Tool life of hot-forged bar was found to be less than that of all quenched bars. The main tool failure mode for hot-forged rod was tool edge breakage. This was due to crack initiation taking place either due to mechanical and thermal fatigue of plastic deformation of tool at workpiece-tool interface. Normal flank wear was tool failure criterion for the quenched bars [26]. The pin-on-disc wear resistance of the 17-4 precipitation hardened stainless steel at a specified condition was carried out at three different level of hardness (33, 37 and 43 HRC) by altering the precipitation heat treatment procedure. The mechanism of wear for the worn out surfaces of the pin were also analysed with the help of scanning electron microscopy. The 17-4 PH stainless steel pins with hardness value of 43 HRC showed highest wear resistance while the lowest was shown by pins having least hardness of 33 HRC in the range considered [27].

Dry turning of two grades of austenitic steel AISI 304 and AISI 316 was carried out with two different types of coated cemented carbide tool i.e. TiC/TiCN/TiN and TiCN/TiC/Al2O3 coated cemented carbides at four different cutting speeds (120, 150, 180, 210 m/min) with constant feed rate of 0.16 mm/rev and DOC of 1 mm. Chipping of tool was found to be main failure mode. The SEM analysis of worn surfaces of the TiCN/TiC/Al2O3 cemented carbide coated tools when machining AISI 304 SS showed that the highest tool wear occurred for the low cutting speed of 120 m/min decreased till the cutting speed of 180 m/min. This can be attributed to the decrease in the tendency of the BUE formation with increase in speed. But further increase in the cutting speed resulted in increase in the tool wear as with increase in the cutting speed the temperature at the cutting zone increases which leads to softening and decrease in the strength of the BUE. Hence less chipping of tool is observed at higher cutting speed due to the less adhesion strength between the BUE and tool [28]. Machining of martensitic stainless steel (SS 410) was carried out at dry environment to measure tool wear characteristics with four different types of alumina-based ceramic cutting tools such as zirconia toughened alumina (tool A), Ti[C, N] mixed alumina with zirconia addition (tool B), Ti[C, N] mixed alumina (tool C) and SiC whisker reinforced alumina (tool D). The cutting operation was carried out at four different cutting speeds (120, 170, 220 and 270 m/min) at a constant feed of 0.12 mm/rev and DOC of 0.5 mm. At low cutting speed the flank wear of all alumina-based ceramic tools takes place but at high cutting speed either it is crater wear or notch wear. Because of strong affinity of silicon carbide towards the iron crater wear mainly takes place at the high cutting speed when machined with SiC whisker reinforced alumina (tool D) and for the rest of the tool its notch wear. In terms of tool life the tool B cutting insert performed best followed by tool C and tool A respectively while tool D showed lowest tool life [29]. Turning of AISI 304 SS was carried out with ISO P10 cemented carbide tool under dry cutting environment. The lower thermal conductivity of the material results in poor dissipation of heat at the low cutting speed making the tool performance poor. At lower cutting speed due to large contact period between the chip-tool interface the chips movement is slower which may hamper the tool face. In the cutting range with increasing cutting speed the tool wear decreases [30]. Experimental investigation on some of machinability aspects during hard machining of AISI 420 martensitic SS was carried out in dry condition with PVD TiAlN coated cemented carbide wiper tool. This kind of wiper geometry tool consists of wiper radii near to the tool nose radius and has very little or negligible clearance angle in order to get better surface finish by burnishing action of the flank face of the tool. A total of ten experimental runs were designed considering 3 level of cutting speeds (1100, 130 & 170 m/min), 3 level of feed rates (0.125, 0.16 & 0.20 mm/rev) and at a constant DOC of 0.4 mm. A minimum of above two minutes of tool life and maximum of 17.6 minutes tool life were observed. With increase in both cutting speed and feed rates the tool life shortened. Cracks at the coating layer of flank face of worn out tool was observed but at the rake face the crack was observed at the substrate of the tool suggesting that the severe thermal and mechanical loading occurred at the rake face than at the flank face of the tool. Crater wear can be ascertained as dominant tool failure mode occurring due to diffusion or abrasion wear mechanism [31]. Dry turning of 8/8 AISI 304 austenitic stainless steel with multi-coated (TiC, TiCN, Al_2O_3, TiN) carbide inserts were carried out at varying cutting speeds of 120, 150, 180 m/min at constant feed rate of 0.24 mm/rev and DOC of 2.5 mm. the tool wear decreased with increase in the cutting velocity upto 180 m/min but further when cutting velocity was increased beyond 210 m/min the tool wear increased. The high tool wear at the lower cutting speeds can be attributed to thermal softening of the tool material due to high generation of the heat due to more contact period between the chip-tool interfaces increasing the friction [32]. In the present investigation the SUS304 SS was machined by P15 coated carbide inserts under both dry and wet conditions. The cutting speed was varied in the range of 250 – 360 m/min with constant feed rate and DOC of 1 mm/rev & 1 mm respectively. Initially with increase in the cutting speed the tool wear decreased upto a maxima and then started to increase with increase in the tool wear. This can be attributed to the reason that at lower cutting speed the workpiece retains its hardness due less generation of heat which causes tool to wear more but with increase in the cutting speed the softening of work material takes place which lessens the tool wear. But further increase in the cutting speeds results in temperature generation more than the hot hardness temperature of the tool which deteriorates the tool life [33]. In the present investigation the machining of AISI 304 SS was carried out with P10 cemented carbide insert. The dry turning operation was performed under cutting speeds of 120,135,150,165, 180 m/min and with varying feed rates of 0.2, 0.25, 0.3 mm/rev. DOC was kept constant at 2.5 mm and the workpiece was machined for length of 150 mm for each cutting condition. It was observed that with increase in the cutting speed the tool wear decreased. But when feed rate was increased from 0.2 to 0.25 mm/rev the tool wear decreased which got further increased when at feed rate of 0.3 mm/rev. With increase in the cutting speed the BUE formation decreased but with increase of feed rate it was found to increase [34]. In the present investigation the dry turning of AISI 440 SS was carried out with cubic boron nitride (CBN) and polycrystalline cubic boron nitride (PCBN) inserts under cutting speed range of 100-200 m/min with varying feed rates of 0.1, 0.2, 0.3 mm/rev and for constant cutting length of 150 mm. Flank wear, crater wear and notch wear were major modes of wear during machining. Flank wear was mainly due to abrasion of hard martensitic particles in SS along the flank face of the tool. At low cutting speed the contact period between the tool-workpiece was more and the rubbing action continued for more time. But at higher cutting speed although the rubbing action became much faster but the heat generated was more which softens the tool edge hence lowering the tool wear resistance. Flank wear of CBN tool was found to be more than that PCBN tool. The tools wear increases with increase in the cutting speed. At higher cutting speed and low feed rates the BUE formation is prevented so it is the recommended range for difficult-to-cut material [35]. Turning operation of Stavax ESR SS was performed under dry environment to compare tool performance with CVD coated carbide tool (TiCN/Al_2O_3/ TiCN/ TiN) and TiN/TiCN/TiN PVD coated cermet tool. The varying cutting speeds considered were 100, 130 and 170 m/min along with three different feed rates of 0.09, 0.16 and 0.28 mm/rev,except at low feed rates and lower cutting speeds the CVD coated carbide tool outperformed PVD coated cermet tool at every other cutting condition. It was observed that the tool life decreases with increase in the cutting speed, feed rate and also machining duration. The tool-chip contact increases with change in side cutting edge angle (SCEA) from 0° to -5° resulting in higher chip equivalent which lowers the temperature generated in cutting zone, improving the tool life. In comparison to cemented carbide tool which have lower thermal conductivity, higher coefficient of thermal expansion and tensile strength the cermet tools have very low resistance to thermal as well mechanical loads. Flank wear and catastrophic modes of failure were found to be most dominating for PVD coated cermet tool whereas it was flank wear and end clearance wear for CVD coated carbide tool [36]. When drilling SS in the cutting range 18-28 m/min under different cutting fluids except for cutting speed of 20 m/min where tool life for semi-synthetic emulsion was better otherwise for rest conditions the machining with vegetable oil provided better tool life. The most influencing failure mechanism for drill was edge wear. Because of chip breaking problems at lower feed rate of 0.15 mm/rev the bright uncoated drills cannot be used but at feed rate of 0.2 mm/rev it outperformed the TiN coated drill. With increase in the feed rate thereafter, the difference in the tool life between the uncoated and coated drills when machining SS reduced. Machining with more expensive bright drill tools both uncoated and coated resulted in lower productivity than the less cost black drills [37]. The influence of the variable feed on the tool life was studied in a quantitative manner with the help of a reliability model. Both the flank and crater wear were taken into account to develop the model. The outcome of the reliability model showed an increase in the mean tool life of about 20-43 % for the tool subjected to the varying feed condition than that of the constant feed [38]. The higher hardness and better ductility of TiN/(Ti, Al) N multilayer coated tool resulted in higher tool performance than that when machining SS with monolayer (Ti, Al) N coated insert under cutting speed of 220 m/min at feed rate of 0.2 mm/rev and DOC of 0.2 mm. The flank wear increased with progress of machining duration [39]. Machining of 1Cr18Ni9Ti austenitic stainless steel with ceramic cutting tool was carried. It was observed the tool wear decreased upto the cutting speed of 210 m/min [40]. The recommended cutting conditions for the machining of AISI 440C SS was suggested to be at cutting speed of 175 m/min, feed rate of 0.125 mm/rev and DOC of 0.5 mm with regard to tool wear [41].

Superior toughness and lower chip-tool interaction provided resistance to comb crack density resulting in better tool performance of multilayered TiN/TaN coating than that of single layered TiN and TaN. Chipping of the cutting edge was found to be tool failure mode while milling of austenitic stainless steel [42].Machining with coolant gave better tool life for most of cutting conditions as the coolant was able to suppress the high temperature generated at cutting zone with on other hand also flushing out entrapped chips at chip-tool and work-tool interfaces [23]. The performances of three different cutting fluids (coconut oil, soluble oil and straight cutting oil) are compared w.r.t tool wear and surface roughness when machining AISI 304 SS with Sandvik's carbide CNMG 12 04 08 insert at different cutting conditions. Machining with coconut oil resulted in better tool performance than other two cutting fluids because of its higher viscosity which results in decrease in the friction between chip-tool interfaces and hence tool wear. The cutting speed was found to be most dominating factor affecting the tool wear [43]. An experimental analysis of the influence of high-pressure coolant on tool wear, temperature and surface roughness during machining of 17CrNiMo6 and 42CrMo4 steels using Sandvik make SNMG and SNMM uncoated carbide inserts was carried out and compared to that under dry cut condition. The use of high pressure coolant reduces friction at chip-tool interface as well work-tool interface thereby reducing the temperature at cutting zone reducing the BUE formation and hence improving the tool life as compared to dry machining. Flank wear under the dry condition was found to be more than when machining with high pressure coolant [44]. But uses of lubricant in case of coated tool prevented tool wear but not when machined with uncoated tool [24]. The effectiveness of the coolant can be analyzed at lower cutting speeds only [33]. The effect of different lubrication and cooling conditions on wear mechanism of the tool were studied during end milling of the 15-5 PH stainless steel. Better tool life performance was observed when machining in presence of neat oil followed by dry and emulsion cutting respectively. The main tool wear mechanism was found to be the combination of attrition and adhesion [45].

In order to determine the influence of free-cutting additives on the machinability of austenitic stainless steels dry and wet machining was carried out using K10 carbide tools. Cutting speed considered was in the range of 12.5-100 m/min along with feed rates of 0.05 and 0.1 mm/rev and at constant DOC of 0.1 mm. At higher cutting speeds the tool wear when machining resulphurized SS was less than that of 304 and 304Bi SS. Addition of Cu to resulphurized SS lead to improvement in the tool life also the addition of Bi did not cause any improvement in the tool life [46]. Tool failure mechanisms of TiN-coated cemented carbide insert during dry turning of X5 CrMnN 18 18 austenitic SS have been carried out. Solid carbide inserts were of type SNMG 120408-PM P15/K15 were used during machining which was CVD coated with TiN and Al_2O_3 layers. The cutting speeds taken were 60, 65, 70 and 100 m/min with constant feed rate of 0.24 mm/rev and DOC of 1.6 mm. The effect of nitrogen percentage on the machinability was also investigated. The tool performance degrades when machining lower nitrogen content SS. The tool wear increases with increase in the cutting speed for the tools when machining both lower and higher content nitrogen SS. Chipping of the tool cutting edge and nose breaking were found to be dominant tool failure modes [47]. Presence of free-cutting additives in the austenitic SS improves the machinability although it lowered some of mechanical properties as compared to 1Cr18Ni9Ti austenitic stainless steel. Machinability of free-cutting additives and 1Cr18Ni9Ti austenitic stainless steel was compared when machining with cemented carbide K30 insert under cutting speed of 20, 40 and 80 m/min at constant feed of 0.2 mm/rev and DOC of 0.5 mm. Under similar cutting condition the free-cutting additives SS showed less flank wear compared to 1Cr18Ni9Ti austenitic stainless steel. MnS inclusion present in free-cutting additive SS helps in formation of stable BUE layer on the cutting edge which helps in improving tool life. Cu helps to lower the strain hardening and also provides lubricant effect hence improves the machinability. Other inclusions such as $Ti_4C_2S_4$ and Bi also helps in improving the machinability of free-cutting additive SS [48]. The machinability characteristics such as tool wear, cutting force, surface roughness and chip breakability of Ca-S free stainless steel was compared with that of ordinary stainless steel when machined with P10 TiC carbide tool. The formation of protecting adhering layer on the rake surface of the cutting tool when machining Ca-S free SS leads to increase in tool life by three fold as compared to tool life when machined ordinary stainless steel. Due to formation of adhering layer the chip- tool interface contact lessened thus preventing abrasive wear. Also the good adhering and wettability character of some of inclusions of adhering layer with TiC coating prevented adhesive wear. Diffusion wear was restricted due to low thermal conductivity of adhering layer which helped to prevent any heat generation at chip-tool interface. The adhering layer increased with cutting speed but after cutting velocity of 300 m/min it decreased. Also with increase of the feed the adhering layer increased [49]. Turning of three different grades of cast austenitic steel was carried out with titanium-nitride coated carbide and uncoated carbide tools of same geometry & size. Steel 1 corresponds to CF8M grade while in other two grades of steel (steel 2 & steel 3) compositions were varied with nitrogen percentage and with some other alloying element. SEM observation of tool wear revealed high crater wear on the rake surface of coated tools. Chips were adhered to the rake surface when machined with coated tool but it was not same when machining with uncoated tool. The mechanism attributed to this type of wear is failure of coating to rapid diffusion of tool wear which was evident due to presence of high carbon content in under surface of the chip. Steel 3 grade of cast austenitic steel was less prone to the crater wear as compared to other two grades [50]. Taguchi methodology was used for design of experiment with cutting speed and depth of cut as controllable factors keeping feed constant during turning of 17-4 PH stainless steel. Back propagation neural (BPN) network has been used to predict average flank wear. Genetic algorithm (GA) was later used to determine optimal cutting parameters to achieve maximum material removal rate (MMRR) with predicted value of average flank wear as constraints [51].

2.2. Influence of machining parameters on chip characteristics

Machining at low cutting speed and at high feed rates the chip of low curl radii was obtained with high chip thickness [34]. Due to presence of BUE at the lower cutting speeds the friction between the chip –tool interface increased leading to more deformation of the chip. The chips obtained at this stage were of less curl radii and of yellow in color due to high heat generation. As the cutting speed increased the chip thickness decreased with increase in the chip curl radii. At high speed the chips obtained were of similar color to that of workpiece due to efficient dissipation of heat for bigger curl radii chip [32]. The chip curl radius and chip thickness increases with increase in the cutting speed. At lower cutting speed the chips obtained is of yellow color, brittle color chips are obtained at higher speed [30]. The chips obtained during machining of 0.57 % and 0.91 % SS with carbide tool resulted in similar type of chip morphology at same conditions. With increase in the cutting speed the chip shape changed from arc-type chip to spiral-type chip [47]. Machining with both PVD coated cermet insert and CVD coated cemented carbide insert produced segmented type chips at higher feed rates irrespective of any cutting speeds and SCEA. Long snarled type chips were generated at lower feed rates which changed to short snarled type at medium feed rates [36]. Short spiral or C-type chips were obtained during machining of Ca-S free SS while during machining of ordinary SS long chips with poor breakability were obtained [49]. With increase in both cutting speed and the feed rate there occurred a transition of chip to segmented type from continuous type [31]. Many researchers also reported the formation of saw-tooth type chip in machining of stainless steel. Saw-tooth type of chips was obtained while machining SS with alumina-based ceramic cutting tools [29, 21]. Machining of martensitic stainless steel with CBN and PCBN cutting inserts also resulted in saw-tooth chip formation [35]. Grain size does have a significant effect on the deformation of the chip. Homogeneous saw-tooth form of chip was noticed during machining of quenched bars while it was non-homogeneous in case of hot-forged steel. Segment height ratio known by ratio of peak height to valley height of a segment is higher for the hot-forged steel than compared to quenched bars. As the quenching temperature increases there is negligible difference in the segment ratio. However the thickness of secondary shear deformation increases with increase in the temperature. TEM study of chips shows presence of ε-martensite and strain induced twinning in high deformation zone of the chip [26]. The top as well as bottom surface of the chips as examined under SEM were compared for both the titanium-nitride coated and uncoated carbide tools. Presence of large number of voids and scratches were observed in chips obtained with coated type tool. This is due to greater amount of tool wear of coated type of tool than uncoated carbide tool. Chips produced by the coated tool suffered high amount of shear deformation which was evident due to greater degree of wrinkling observed on top surface chips obtained by coated tool [50].

2.3. Influence of machining parameters on surface roughness

The tendency of austenitic SS to form large and unstable BUE at lower cutting speed results in higher surface roughness. The surface roughness of both SS while machining with two different types of coated tool resulted in initial decrease in the surface roughness upto a cutting speed of 180 m/min. The decrease in surface roughness can be attributed to decrease in formation of BUE with increase in speed. Further increase in the cutting speed leads to increase in the tool wear, hence the surface roughness [28]. A separate investigation also reported that surface roughness decreased with increase in the cutting speed. At lower cutting speeds the formation of built-up edge (BUE) deteriorates the surface finish which improves gradually with increase in speed as at the high speeds the BUE formation is retarded due to less contact time between the chip-tool interfaces [32]. Reduction in surface roughness with rise in the cutting speed was noted when turning 1Cr18Ni9Ti austenitic steel with ceramic cutting tool [40]. With increase in both cutting speed and feed rate the surface roughness increases. At lower feed rates the tool vibration is lower hence producing better surface finish with decrease in the power consumption. Larger feed rates leads to higher elastic relaxation [30]. Fine surface finish were obtained at all experimental run. Machining under lower feed rate resulted in better surface finish which got coarser with increase in the feed rate. Although with increase in the cutting speed the surface quality improved but the effect is very slight [31]. Various grades of austenitic SS were turned with cermet tool. Lower feed rates generated much better surface quality than that at higher feed rates but lowering of feed rates below critical value may result into chatter which further deteriorates the surface finish. The critical feed value was found to be 0.02 for fine turning of austenitic SS [52]. The recommended cutting speed for getting better surface finish was 150 m/min and under feed rates of 0.25 mm/rev for machining of AISI 304 austenitic SS [34]. At high cutting speeds and low feed rates the machining with CBN tool produced better surface finish than PCBN tool [35]. Better surface finish was produced at cutting speed of 225 m/min with feed rate of 0.125 mm/rev and DOC of 0.50 mm during dry turning of AISI 440C martensitic SS with CBN tool [41]. Machining SS with multilayered PVD coated carbide tool produced better surface finish than that machined with three layered coated carbide inserts. The use of lubricant resulted in improvement in the surface finish of the machined surface [24]. Many other investigations also reported the improvement in surface roughness with the use of various kinds of coolants [43, 44, and 48]. Machining resulphurized SS under dry condition at lower cutting speeds produces poor surface quality. Calcium addition to austenitic stainless steels with inclusions of an anorthite composition showed a better surface finish on the other hand the addition of Bi did not cause any deterioration to surface of SS [48].The response surface methodology (RSM) was used to analyze and evaluate the surface quality of the materials used in the turbine blades made up of three different materials namely ST 174PH, ST T1/13W and ST 12TE. The CNC turning operation in presence of coolant was carried with cutting speed range of 75-200 m/min with variable depth of cut (0.25-0.8 mm) and as well feed (0.08-0.24 mm/rev). Machined surface roughness of 17-4 PH stainless steel was found to respond more quickly to changes in the parameters than other grades of steel. The cutting speed and the feed were found to be most significant parameters. The interaction effect such as speed vs. feed and feed vs. depth of cut also had significant effect. Best surface quality was achieved at high cutting speed of 200 m/min and for a medium feed rate of 145 mm/min for machining of 17-4 PHstainless steel. At lower cutting speed of 75 m/min, the surface roughness increased with increase in feed rate from 100-200 mm/min [10].

2.4. Influence of machining parameters on cutting temperature

The cutting temperature generated during machining of semi-austenitic SS with two types of carbide tools increases with increase in the cutting speed and was found to be above 500°C when cutting speed exceeded 140 m/min. The cutting temperature during machining with WC/TiC/Co tools is lower than that when machined with WC/Co tools [22]. In contradiction to above finding another researcher reported that due to increase in chip flow increases in cutting zone with increase in the cutting speed, there occurred high dissipation of heat resulting in decrease in the temperature at the cutting zone. But with increase in the feed rate the cutting temperature increases [30]. When machining with ceramic tools the cutting temperature measured over the rake surface was found to be higher for 18-8 SS than that of 1045 plain carbon steel due to its lower thermal conductivity as well as thermal diffusivity. Machining with Si_3N_4 ceramic tool produced low temperature at the rake surface than when machining with Ti(CN) type tool for 18-8 SS. With increase in the cutting speed the temperature distribution curves increased [19]. A reduction of 25 % in temperature was observed when machining under high pressure coolant as compared to dry machining. The effect of high pressure coolant was more significant at lower cutting ranges as the coolant got enough time for to function [44].

2.5. Influence of machining parameters on the cutting force

The machining with titanium-nitride coated carbide tool at 0.18 mm/rev and DOC of 1.5 mm resulted in greater amount of both tangential (Pz) and axial force (Px) than that uncoated carbide tools. There was not variation of forces for both types of tool at lower feed rate of 0.095 mm/rev. Machining of Steel 3 type required lesser force compared to other two grades of cast austenitic stainless steel [50]. For both grades of SS when machining with two types of coated tools the cutting force initially decrease upto cutting speed of 150 m/min which can be attributed to increase in the temperature with cutting speed. But with further increase in the cutting speed the tool wear increase leading to increase in the cutting force during machining. Presence of 2 % molybdenum in AISI 316 SS provides high temperature strength during machining which results in requirement of higher cutting force the AISI 304 SS during turning. Machining with TiC/TiCN/TiN coated inserts resulted in lower cutting forces than TiCN/TiC/Al2O3 coated ones. This is due to the lower coefficient of friction of TiN coating than that of Al2O3 which results in less chip-tool interface contact leading to low adhesion of workpiece material to the rake face of the cutting tool [28]. The different force components measured during machining with WC/TiC/Co tools were less than that when machined with WC/Co tools [22]. The cutting force during the machining of free-cutting SS was found to be lower than that of 1Cr18Ni9Ti austenitic SS due to presence of free-cutting additives [48]. A reduction of cutting force nearly of

25 % was observed during machining of Ca-S SS as compared to the ordinary SS [49]. Machining higher content nitrogen SS requires more cutting force during dry turning with carbide tools [47].

2.6. Motivation

From past study it was observed that significant amount of work on various machinability characteristics of austenitic grades of stainless steel has been reported. Systematicstudy on influence of various cutting parameters such as cutting velocity, feed rate and depth of cut on different aspects of machinability of especially austenitic steel such as tool wear, cutting force, surface roughness, chip morphology and cutting temperature has been carried out. The machining of austenitic stainless steel was carried mostly with cemented carbide tools. Various methods such as use of different coating techniques (PVD or CVD) with different coating layers (single or multi-layer) have also been used to improve tool life and also several other aspects of the machining.Several other methods such as use of different coolant techniques, addition of additives, heat treatment etc. has also been utilized for improving machining of austenitic stainless steel.

However similar study on machinability characteristics of martensitic grade of 17-4 PH stainless steel has hardlybeen reported so far. To the best of knowledge, very few research works has been reported with regard to various machining aspects of 17-4 PH stainless steel in turning. The researchers mainly concentrated there study to development of tool flank wear model and effect of cutting parameters on surface roughness under coolant with finding out of optimal cutting conditions with the help of some model.

Machinability is a broad term and also covers other aspects such as chip characteristics, cutting force and cutting temperature, which hardly has been reported for turning of 17-4 PH stainless steel.The effect of coatings with its uncoated counterpart on machining characteristics of 17-4 PH stainless steel under dry environment is yet to be reported. With 17-4 PH stainless steel being used in several strategic fields mentioned in previous chapter, there is every need to carry out a systematic study on various aspects of machinability with different tools.

2.7. Objective

The major objective of the current research is to study the influence of the cutting speed, feed rates and tool coating on different machinability characteristics of 17-4 PH stainless steel during dry machining. The detailed objectives include the following:

a. To carry out comparative evaluation of performance of a commercially available CVD coated tool having TiN, TiCN, Al_2O_3 and ZrCN in multilayer configuration with that of ISO P30 grade uncoated cemented carbide.

b. To investigate the influence of cutting speed, feed rate and tool coating on machinability aspects such as:

    - Tool wear with primary emphasis on mechanisms.
    - Chip characteristics with focus on macro morphology of chip and chip thickness.
    - Cutting force
    - Cutting temperature
    - Surface roughness

CHAPTER 4: EXPERIMENTAL METHODOLOGY

In this unit detail methodology of the experiment has been described. The detail aspect of machine tool used, equipment facilities, workpiece material, cutting tool, machining parameters and experimental set-up has been discussed.

3.1. Work material

17-4 Precipitation Hardening also known as Type 630 is a chromium-copper precipitation hardening stainless steel used for applications requiring high strength and a moderate level of corrosion resistance was used as workpiece material. 17-4 PH stainless steel of dimension 80 mm diameter and 600 mm length was used for the purpose of experimentation. Chemical composition of the 17-4 PH stainless steel has been given in Table 3.

Table 3 Chemical composition of 17-4 PH

Elements	C	Mn	Si	P	S	Cr	Ni	Cu	Nb+Ta
Wt %	0.07 Max	1.00 Max	1.00 Max	0.04 Max	0.03 Max	15.0-17.50	3.00-5.00	3.00-5.00	0.15-0.45

3.1.1 Properties of 17-4 PH stainless steel

Typical Mechanical Properties of Stainless Steel Sheets

- Ultimate Tensile Strength Ksi (MPa): 160 (1103)
- 0.2% Tensile Yield Strength Ksi (MPa): 145 (1000)
- Elongation % in 2" (50mm): 5.0
- Hardness Rockwell C: 35

17-4 Stainless Steel Physical Properties

- Melting Range: 2560-2625°F (1404-1440°C)
- Density: 0.2820 lb/in

3.2. Cutting tool material

In this experiment two types of cutting tools were used for machining the workpiece:

a. Uncoated cemented carbide inserts

   The commercially available (Make: Widia, India) ISO P30 grade of WC- 6% Co uncoated insert Consisting composition WC, Co, TiC, TaCandNbC was used as one of the cutting tool.

b. Coated cemented carbide inserts

   The commercially available (Make: Widia, India) multi-layer CVD (chemical vapor deposition) coated cemented carbide insert was used as another cutting tool. Themultilayer coated insert with CVD deposited multilayer coating consisted of $TiN/TiCN/Al_2O_3/ZrCN$arranged from the substrate to top layer. ZrCN is used as a top layer owing to its excellent toughness and anti-friction properties

The both types of cutting tool i.e. uncoated and coated cemented carbide inserts were of SCMT 12 04 08 designation which has been explained below:

S –Shape of insert square

C – Clearance Angle of insert = 7^0

M – Medium Tolerance = ±0.005 inch

T –Features of insert (Counter sinking hole with chip groove on top surface for easy flow of chip over rake surface)

12 – Cutting edge length of insert=12 mm

04 –Insert nominal thickness = 4 mm

08 – Nose radius = 0.8 mm

The tool geometry for both the cutting insert was [−6°, −6°, 6°, 6°, 15°, 75°, 0.8 (mm)]. A tool holder with ISO designation of SSBCR 2020K12 (Kennametal, India) was used for both uncoated and coated tools.

3.3. Cutting parameters

The machining operation was carried out under variable cutting speeds of 100, 140 and 190 m/min for the feed rates of 0.16, 0.20 and 0.24 mm/rev and at constant depth of cut 0.5 mm in dry environment i.e. without use of any coolant or cutting fluid.

Table 4 Cutting Parameters

Parameters	Range considered
Cutting Speeds (m/min)	100,140,190
Feed rates (mm/rev)	0.16,0.20,0.24
Depth of cut (mm)	0.5
Cutting environment	Dry

3.4. Machining operation

Heavy duty lathe (Make: Hindustan Machine Tools (HMT) Ltd., Bangalore, India; Model: NH26) was used for turning of 17-4 PHstainless steel with uncoated cemented carbide tools. Fig. 12 shows the photographs of machine tool used for turning of 17-4 PH stainless steel.

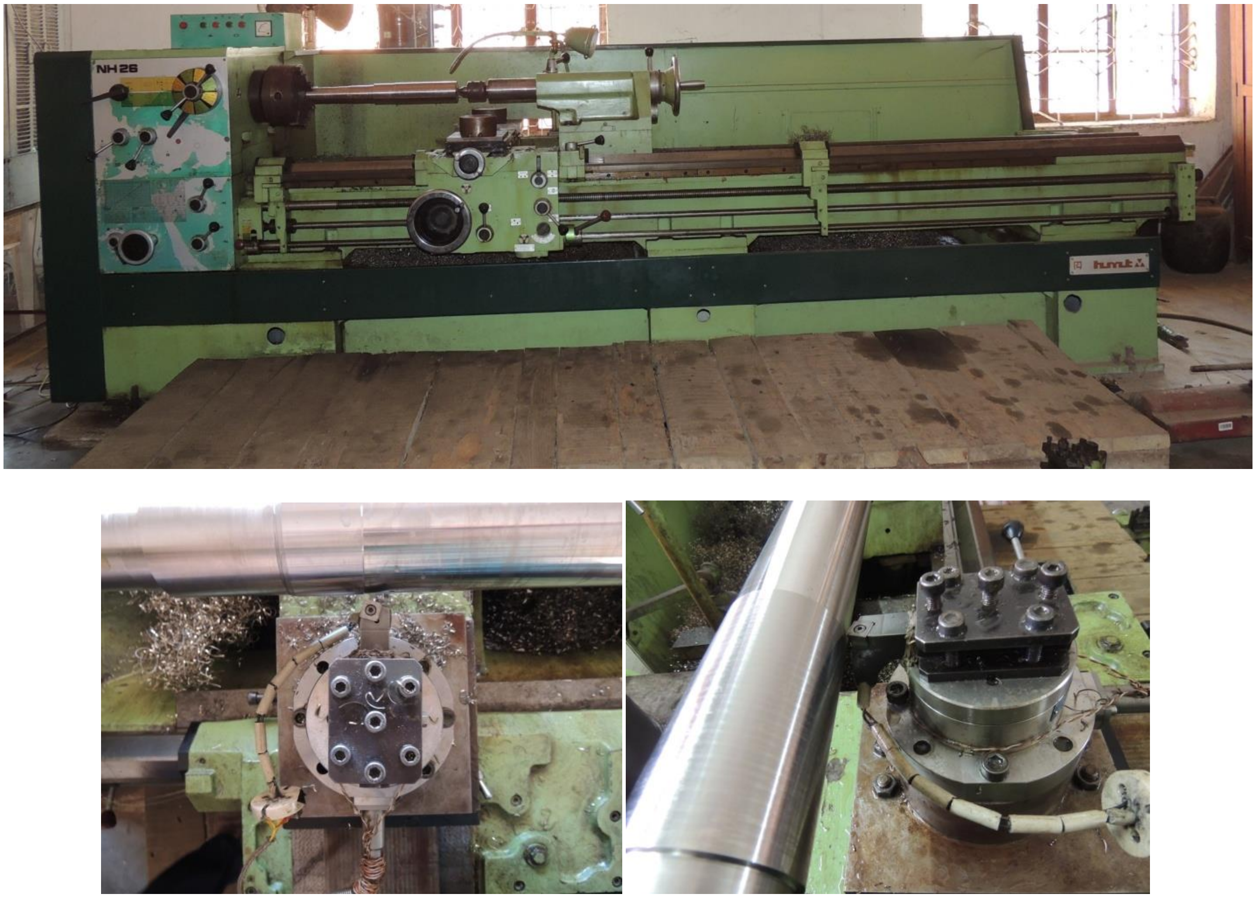


Fig. 12 Experimental Set-up

The dry turning of 17-4 PH SS was carried out with both uncoated and coated carbide insert at variable cutting speed and variable feed rates for different machining duration. Each of the experimental run was carried out for machining duration of 60 s. During the machining different forces and temperature were noted. The chips formed during the machining were collected for the further analysis. Tool wear of each insert for different condition was also measured. The estimation of various responses is given below:

3.4.1 Tool wear estimation

After each interval of machining duration the state of the cutting insert was monitored with the help of stereo zoom optical microscope (Make: Radical Instruments) to determine the tool wear mostly flank wear.

Fig. 13 Stereo zoom optical microscope

The common failure criteria that have been used to estimate failure of cutting tools are:

a) Catastrophic failure
b) Average flank wear of 0.3 mm.
c) Maximum flank wear of 0.6 mm.

3.4.2 Chip morphology study

During machining the chips were collected for the different machining duration for analysis purpose. The images of chip produced at each experimental run were captured to get the information regarding the shape, size and color of chip. Also the thickness of each chip collected was measured with the help of vernier caliper in order to determine the chip reduction coefficient.

3.4.3 Cutting force measurement

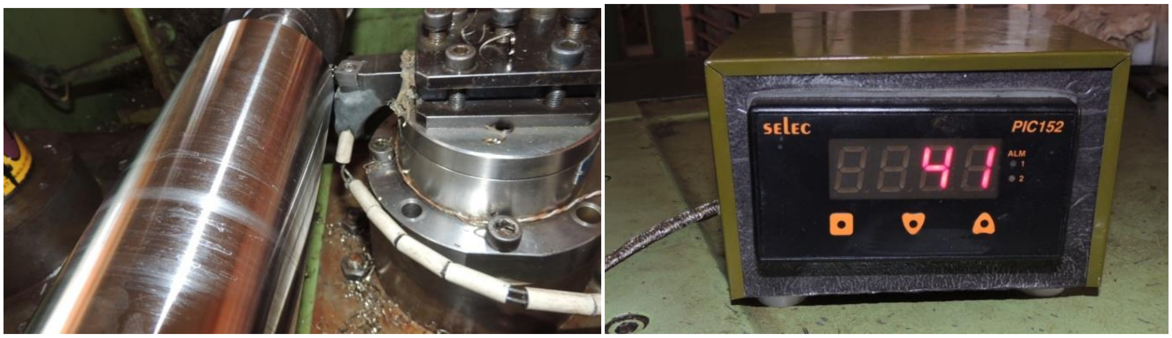
Three component piezoelectric dynamometer (Make: KistlerInstrumente AG, CH-8408 Winterthur, Switzerland; Model: 9257B) was used for the purpose of measuring various cutting forces during turning. A charge amplifier (Make: KistlerInstrumenteAG, CH-8408Winterthur, Switzerland; Model: Type 5814B1) connected to the dynamometer was used to give the required readings for the cutting forces.

a b

Fig. 14 Cutting force set-up a) dynamometer b) charge amplifier

3.4.4 Temperature measurement

A thermocouple attached at the bottom of the tool was used for the measurement of temperature attained at the cutting insert during the machining operation. For this purpose a 2 mm hole was drilled at the bottom of the tool holder approximately at distance of 9 mm from shim and onto that drilled hole the thermocouple was fixed (Fig 15 a). The thermocouple was attached to the recorder (Fig. 15 b) which gave the readings directly in terms of degree Celsius.



a b

Fig. 15 Temperature measurement set-up a) Thermocouple b) Temperature recorder

3.4.5 Surface roughness measurement

Surface roughness of each experimental run was measured with Talysurf (Model:Taylor Hobson, Surtronic 3+) with parameters sample length, Lc=0.8 mm, cut-off length, Ln= 4 mm and filter=2CR ISO. The set-up below shows (Fig. 16) the measurement of the surface roughness for each run.

Fig. 16 Surface measurement set-up

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Condition of the tool after machining

4.1.1 Effect of cutting speed and machining duration under low feed condition

The Fig. 17 depicts the condition of flank surface for both uncoated and CVD multi-layer coated carbide inserts showing the extent of flank wear at the flank surface when machining 17-4 PH stainless steel at a constant feed rate of 0.16 mm/rev and for varying cutting speeds. The machining was although carried out at an interval of 60 s for up to 300 s but only few representative images have been shown only.

Clearly from the figure, one can observe that with increase in cutting velocity the flank wear for both uncoated and coated tool increased which has been further discussed in upcoming section. It is also evident that the CVD multi-layer coating remarkably improved the resistance to flank wear of uncoated carbide insert particularly when the machining was carried out at medium and high cutting speed. The inability of the coated tool to exhibit similar performance during machining under lower cutting speed can be attributed to high frictional drag force. Slight chipping of nosefor uncoated tool was observed for machining duration of 240 s when machining at cutting speed of 140 m/min. However, due to lower wear resistance of the uncoated tool towards the hard particles (martensitic structure) present in the 17-4 PH stainless steel it could not perform well at the higher cutting speed of 190 m/min which eventually led to tool failure after 240 s of machining. High nose wear was also observed for the uncoated tool under the same machining condition.

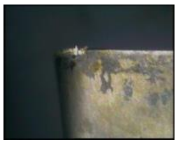
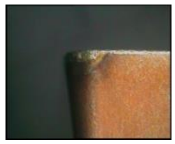
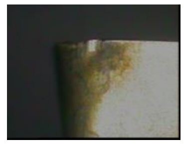
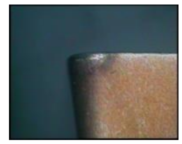
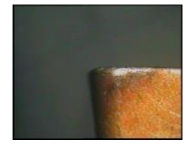
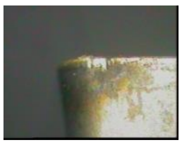
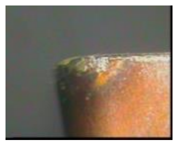
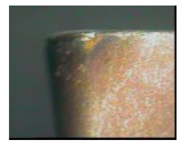
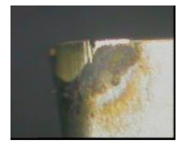
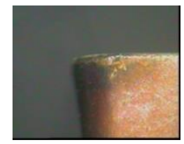
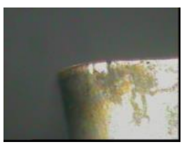
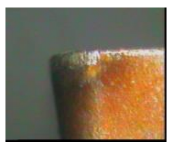
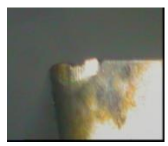
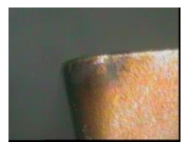
Machining duration (s)	Feed rate = 0.16 mm/rev and cutting speed = 100 m/min		Feed rate = 0.16 mm/rev and cutting speed = 140 m/min		Feed rate = 0.16 mm/rev and cutting speed = 190 m/min	
	Uncoated insert	Coated insert	Uncoated insert	Coated insert	Uncoated insert	Coated insert
60						
240					 Tool failed	
300						Machining not possible

Fig. 17 Flank wear of uncoated and coated tool at feed rate of 0.16 mm/rev

4.1.2 *Effect of cutting speed and machining duration under medium feed condition*

Similar kind of observations was found for medium feed rate of 0.20 mm/rev as can be observed from Fig. 18 i.e. the flank wear for both the types of tool increased with increase in cutting velocity, with CVD multi-layer coated tool outperforming its uncoated counterpart with respect to tool life till the machining duration of 300 s.

For uncoated carbide inserts, high nose damage was noted at cutting speeds of 140 and 190 m/min. Nose damage was more severe in case of the higher velocities with wear occurring immediately after machining duration of 60 s, while the tool failure occurred after 180 s of machining with a cutting speed of 140 m/min. The nose wear can be attributed to high heat generation at the cutting region leading to softening of uncoated tool resulting and consequently premature failure. The delamination of the rake surface near the nose region can be observed.

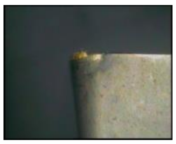
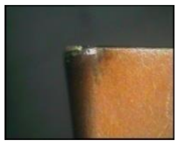
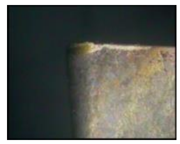
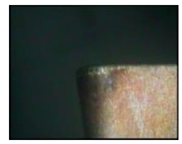
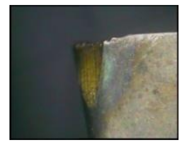
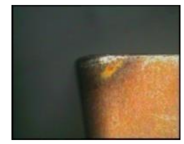
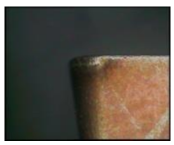
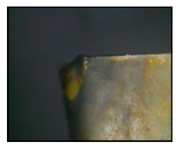
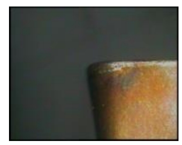
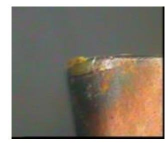
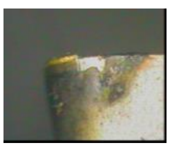
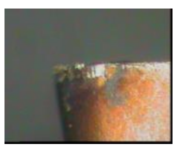
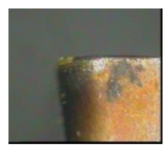
Machining duration (s)	Feed rate = 0.20 mm/rev and cutting speed = 100 m/min		Feed rate = 0.20 mm/rev and cutting speed = 140 m/min		Feed rate = 0.20 mm/rev and cutting speed = 190 m/min	
	Uncoated insert	Coated insert	Uncoated insert	Coated insert	Uncoated insert	Coated insert
60					 Tool failed imediately	
180			 Tool failed			
300						Machining not possible

Fig. 18 Flank wear of uncoated and coated tool at feed rate of 0.20 mm/rev

Fig. 19 below shows the condition of the rake surface and the nose region for the failure state of the uncoated carbide tool at cutting speeds of 140 and 190 m/min.

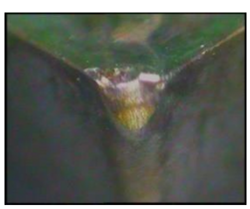
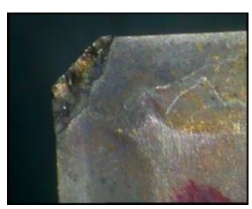
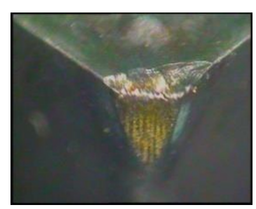
Uncoated tool at feed rate = 0.20 mm/rev			
Cutting speed = 140 m/min and machining duration of 180 s		Cutting speed = 190 m/min and machining duration of 60 s	
Rake surface	Nose region	Rake surface	Nose region
			

Fig. 19 Condition of rake surface and nose region after failure of uncoated tool at feed rate of 0.20 mm/rev

4.1.3 Effect of cutting speed and machining duration under high feed condition

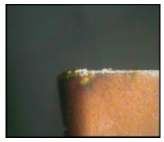
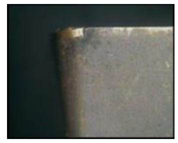
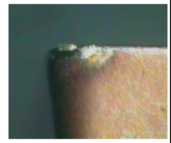
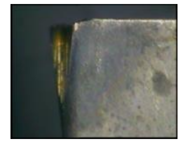
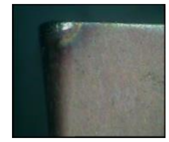
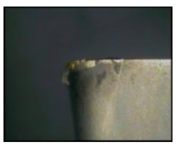
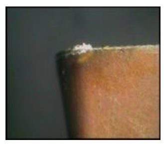
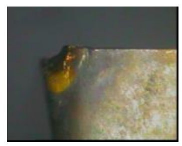
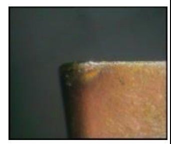
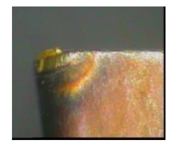
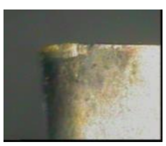
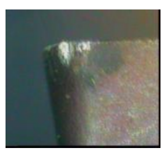
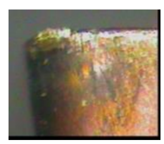
Machining duration (s)	Feed rate = 0.24 mm/rev and cutting speed = 100 m/min		Feed rate = 0.24 mm/rev and cutting speed = 140 m/min		Feed rate = 0.24 mm/rev and cutting speed = 190 m/min	
	Uncoated insert	Coated insert	Uncoated insert	Coated insert	Uncoated insert	Coated insert
60					 Tool failed immediately	
120			 Tool failed			
300						Machining not possible

Fig. 20 Flank wear of uncoated and coated tool at feed rate of 0.20 mm/rev

The tool wear at the high feed rate got intensified with increase in the feed rate to 0.24 mm/rev as can be observed from the Fig. 20 above. At higher feed rate also of the nose damage was main failure mode for the uncoated carbide inserts. The condition of the rake surface and nose region for uncoated failure condition has been given in Fig. 21.

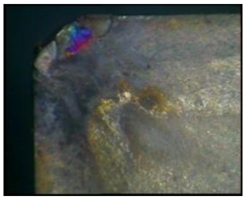
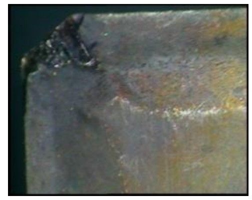
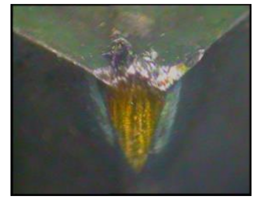
Uncoated tool at feed rate = 0.24 mm/rev			
Cutting speed = 140 m/min and machining duration of 120 s		Cutting speed = 190 m/min and machining duration of 60 s	
Rake surface	Nose region	Rake surface	Nose region
			

Fig. 21 Condition of rake surface and nose region after failure of uncoated tool at feed rate of 0.24 mm/rev

4.2 Effect of feed rate on machinability characteristics of 17-4 PH stainless steel

4.2.1 Flank wear

The Fig. 22, 23 and 24 depict the variation of flank wear with progression of machining duration with variable cutting speed at a particular feed rate when machining 17-4 PH stainless steel withuncoated carbide inserts and CVD multi-layer coated carbide inserts. It can be inferred from the graphs that with increase in the feed rate the tool wear increased for both uncoated and CVD multi-layer coated type carbide inserts. Machining with high feed rate results in more generation of temperature and as well vibration of the machine tool as compared to lower feed rate, hence resulting in high flank wear for high feed rate condition. The hard abrasive particles from martensitic structure of 17-4 PH stainless steel led to wear out the uncoated carbide tool at faster rate than the coated tool. But it was the anti-friction property and high resistance to abrasion of CVD multi-layer coating which provided higher wear resistance to the coated tool, hence outperforming its uncoated carbide insert.

It is interesting to note that initial running in wearfor CVD multi-layer tool under lower cutting condition is quite significant and more than that while machining with medium cutting speed for the same feed rate condition of 0.16 mm/rev. However, rate of flank wear stabilised subsequently with progression of machining duration. It is also of considerable interest thatimprovement of the coated tool during machining with lower cutting speed (Vc=100 m/min) gradually became more prominent when feed rate was increased from 0.16 to 0.24 mm/rev.

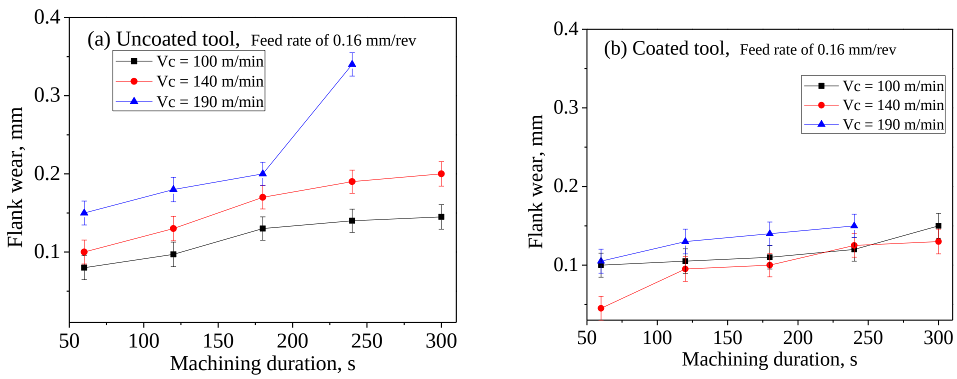


Fig. 22 Variation of flank wear with progression of machining duration with variable cutting speed at feed rate 0.16 mm/rev for (a) Uncoated and (b) Coated tool

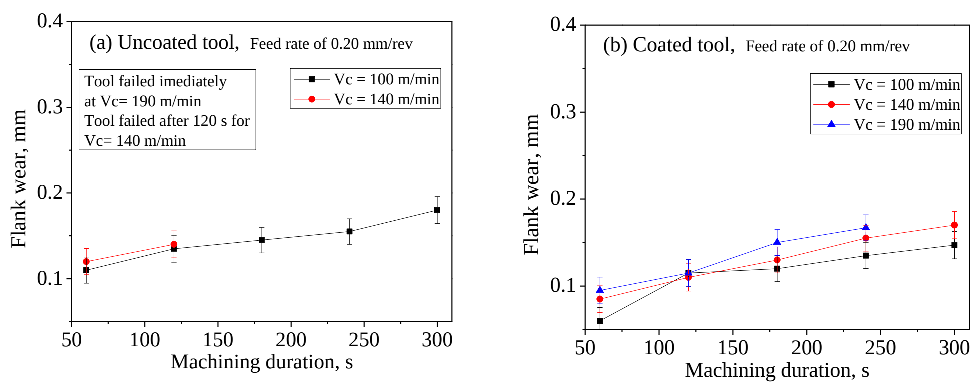


Fig. 23 Variation of flank wear with progression of machining duration with variable cutting speed at feed rate 0.20 mm/rev for (a) Uncoated and (b) Coated tool

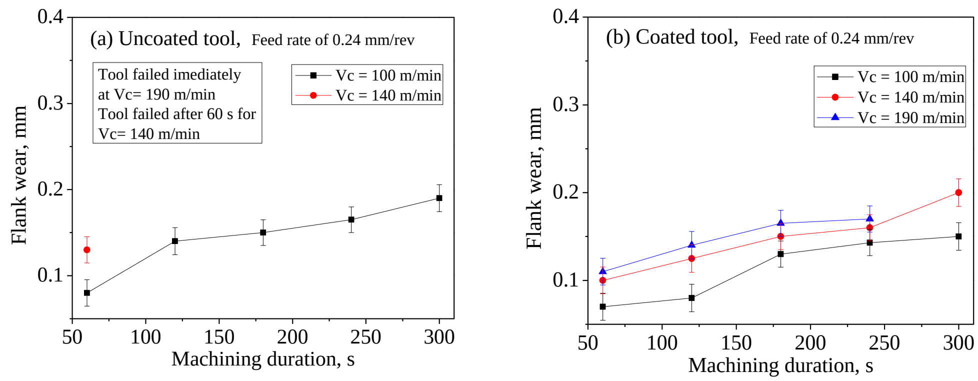


Fig. 24 Variation of flank wear with progression of machining duration with variable cutting speed at feed rate 0.24 mm/rev for (a) Uncoated and (b) Coated tool

Nearly 21 % improvement in average tool wear was obtained while machining with CVD coated tool for high feed rate 0.24 mm/rev at lower cutting speed (Vc=100 m/min) as compared to machining with uncoated tool during same cutting condition as can be noted from Fig. 24.

4.2.2 Nose wear

The progression of the nose wear with progression of machining duration with variable cutting speed at a certain feed rate for uncoated carbide inserts and CVD multi-layer coated carbide inserts has been shown in Figs. 25, 26 and 27. The pattern of nose wear with increase in the feed rate follows same as that of flank wear for both for uncoated carbide inserts and CVD multi-layer coated carbide inserts.

The nose wear for CVD multi-layer coated carbide inserts at low machining condition i.e. lower feed rate of 0.16 m/min and low cutting speed of 100 m/min was found to be higher than rest cutting speeds at same feed rate of 0.16 mm/rev due to higher friction generated. While the nose wear between the uncoated and coated tool for lower cutting speed of 100 m/min under feed rate of 0.20 mm/rev was comparable. While machining at higher cutting speed the coated tool showed a decrement of 14 % in terms of nose wear as contrast to its uncoated counterpart.

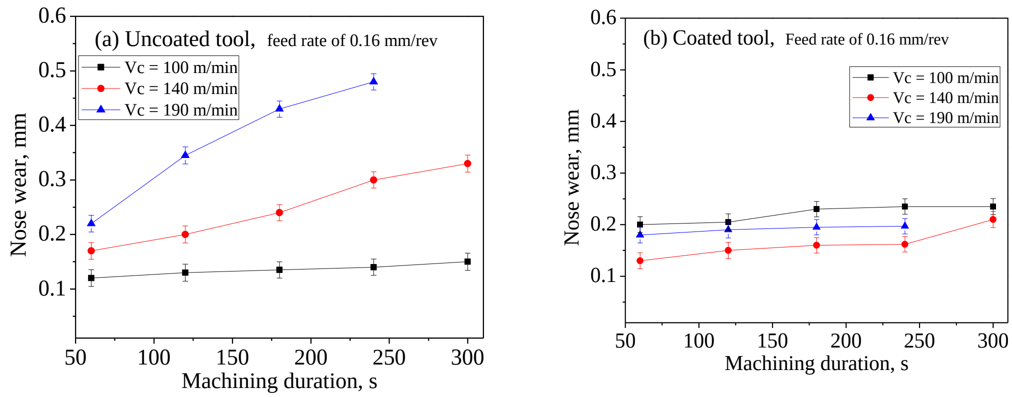


Fig. 25 Variation of nose wear with progression of machining duration with variable cutting speed at feed rate 0.16 mm/rev for (a) Uncoated and (b) Coated tool

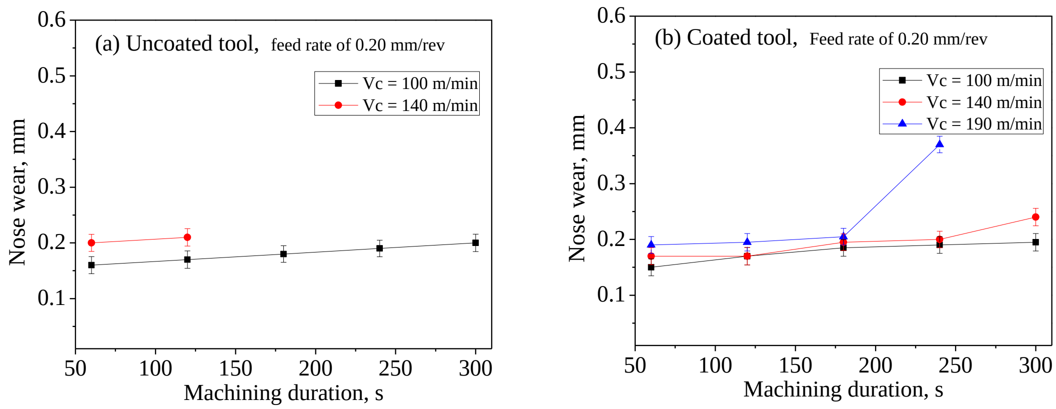


Fig. 26 Variation of nose wear with progression of machining duration with variable cutting speed at feed rate 0.20 mm/rev for (a) Uncoated and (b) Coated tool

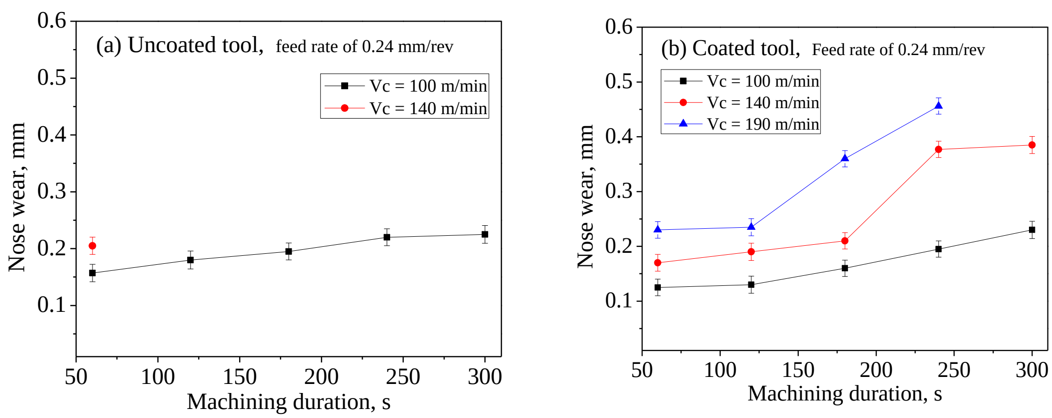


Fig. 27 Variation of nose wear with progression of machining duration with variable cutting speed at feed rate 0.20 mm/rev for (a) Uncoated tool and (b) Coated too

4.2.3 Chip morphology

The macro morphology of chip obtained using an optical microscope after machining 17-4 PH stainless steel with uncoated and CVD multi-layer coated cutting tool with progression of machining duration at feed of 0.16 mm/rev has been shown by Fig. 28.

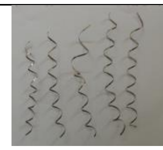
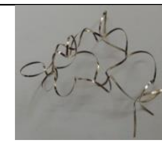
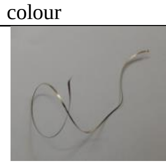
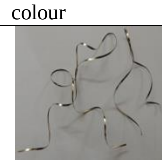
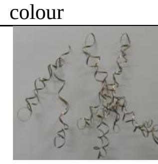
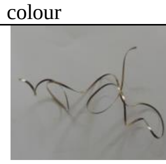
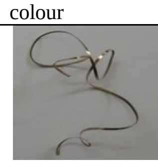
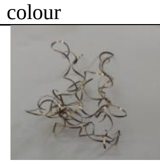
Machining duration (s)	Feed rate = 0.16 mm/rev and cutting speed = 100 m/min		Feed rate = 0.16 mm/rev and cutting speed = 140 m/min		Feed rate = 0.16 mm/rev and cutting speed = 190 m/min	
	Uncoated insert	Coated insert	Uncoated insert	Coated insert	Uncoated insert	Coated insert
60	 Continuous snarled type Light golden colour	 Continuous long spiral type Silver colour	 Continuous snarled type Light golden colour	 Continuous long spiral type Silver colour	 Continuous snarled type Light golden colour	 Continuous snarled type Light golden colour
120	 Continuous snarled type Light golden colour	 Continuous snarled type Silver colour	 Continuous snarled type Light golden colour	 Continuous long spiral type Silver colour	 Continuous snarled type Light golden colour	 Continuous snarled type Silver colour
180	 Continuous snarled type Silver colour	 Continuous snarled type Silver colour	 Continuous snarled type Light golden colour	 Continuous snarled type Silver colour	 Continuous snarled type Light golden colour	 Continuous snarled type Silver colour
240	 Continuous snarled type Silver colour	 Continuous snarled type Silver colour	 Continuous snarled type Light golden colour	 Continuous snarled type Silver colour	 Continuous snarled type Light golden colour	 Continuous snarled type Silver colour
300	 Continuous snarled type Light golden colour	 Continuous snarled type Silver colour	 Continuous snarled type Light golden colour	 Continuous snarled type Silver colour	failed	

Fig. 28 Chip morphology of uncoated and coated cutting tool with progression of machining duration at feed of 0.16 mm/rev

The chips obtained under this machining condition for both types of tool are continuous and mostly snarled type with few being spiral type. These types of chips are typically obtained due to lower depth of cut during machining of 17-4 PH stainless steel. These continuous and snarled types of chips are not suitable during machining operation as it may have disposable problem harming the operator. If the machining is done with inserts without provision of chip breaker then these continuous snarled type chip may cause chip clogging near the chip-tool interface, thus deteriorating the machined surface.

Light golden chips were obtained during machining with uncoated carbide inserts. This can be ascertained to the high frictional force at lower feed rate along with greater tool wear rate of uncoated carbide inserts which resulted in generation of high amount of heat at chip-tool interface and the heat mostly taken by the chip during machining. While the anti-fiction propertyof the CVD multi-layer prevented large heat generation at chip-tool interface, hence the chips obtained were of similar colour that of 17-4 PH stainless steel workpiece i.e. silver colour.

Similar type of continuous and snarled type of chips were obtained for the feed rate of 0.20 and 0.24 mm/rev when machining 17-4 PH stainless steel with uncoated and CVD multi-layer coated cutting tool.

4.2.4 Chip thickness

The variation of chip thickness with progression of machining duration for variable cutting speeds at constant feed rate when machining 17- 4 PH stainless steel with uncoated and CVD multi-layer coated carbide insert is illustrated Figs. 29, 30 and 31. It is evident from the graph that CVD multi-layer coated tool helped in significant reduction of chip deformation compared to uncoated tool.

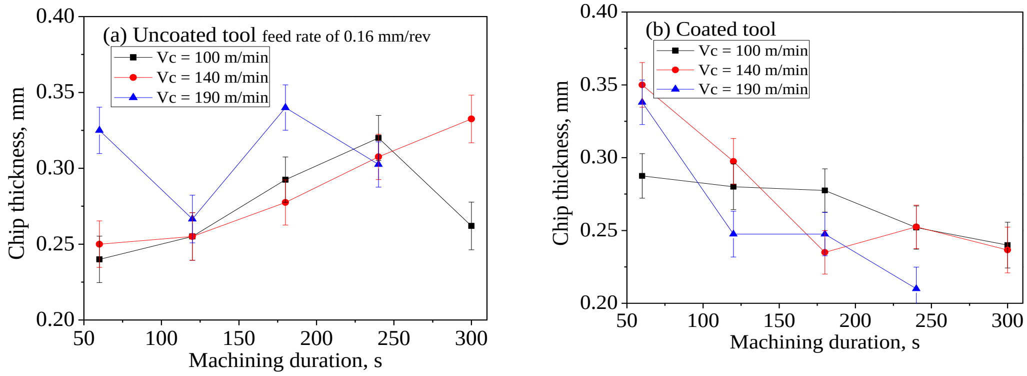


Fig. 29 Variation of chip thickness with progression of machining duration with variable cutting speed at feed rate 0.16 mm/rev for (a) Uncoated and (b) Coated tool

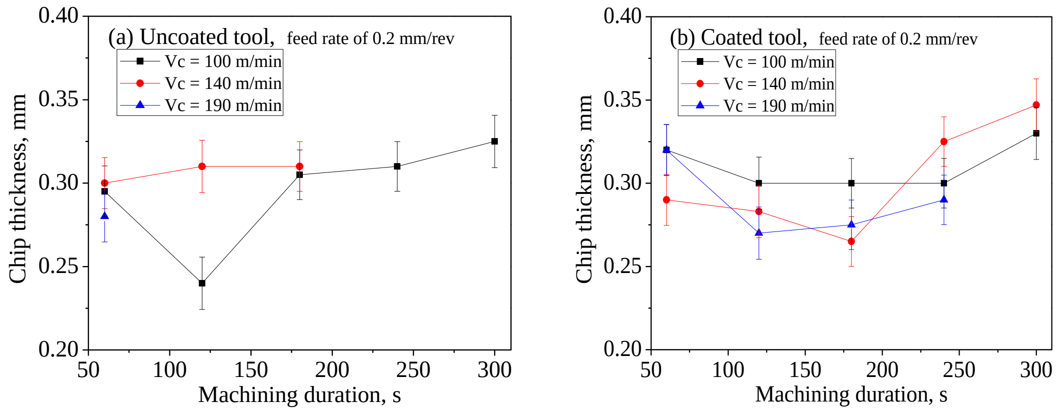


Fig. 30 Variation of chip thickness with progression of machining duration with variable cutting speed at feed rate 0.20 mm/rev for (a) Uncoated and (b) Coated tool

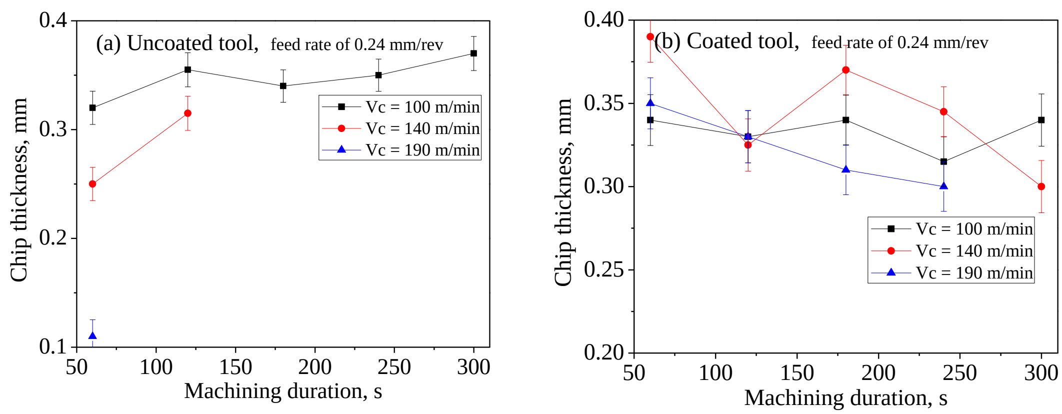


Fig. 31 Variation of chip thickness with progression of machining duration with variable cutting speed at feed rate 0.24 mm/rev for (a) Uncoated and (b) Coated tool

Comparing all the above figures, with increase in feed rate, the chip deformation was found to rise when machining 17- 4 PH stainless steel with uncoated and CVD multi-layer coated carbide inserts. The increasing tendency of chip thickness can be attributed to higher tool wear with increase in feed rate as discussed in preceding section.

For the uncoated carbide inserts, the predominant effect of tool wear led to higher chip deformation with progression of machining duration for any constant feed rate.

During initial machining duration of 60 s, the chip thickness was found to be higher at all machining conditions since due CVD multi-layer coated tool could sufficiently retain its edge strength. At later stage of 120 s, due to dulling of cutting edge the chip deformation was found to be lower. However, when machining was further continued with CVD multi-layer coated insert the chip thickness was found to mostly decrease with progression at a constant feed rate. This decrease in the chip thickness can be ascertained to removal of built-up edge (BUE) formed at early stage of machining and simultaneously gradual exposure of anti-friction layers i.e. TiN and TiCN. The Fig. 32 shows condition for the formation built-up edge (BUE) when machining with CVD multi-layer coated carbide inserts at constant feed rate of 0.16 mm/rev and for varying cutting speeds. It can be observed form the table that for machining duration of 120 s there is formation of BUE for the entire range of cutting speed. The BUE, however, got gradually removed with further continuation of machining.

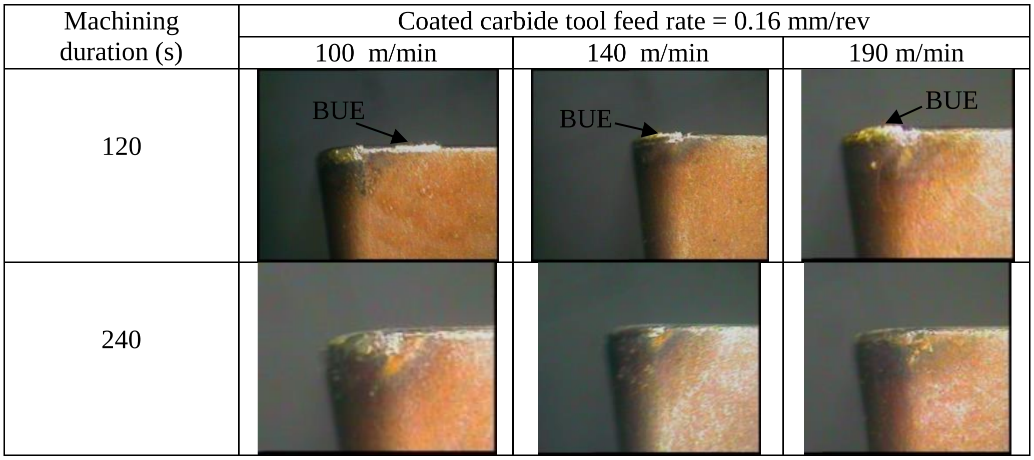


Fig. 32 Cutting tool condition for coated carbide tool at feed rate of 0.16 mm/rev

Similar kind of observations was noted for CVD multi-layer coated tools for feed rates of 0.2 and 0.24 mm/rev. Although at feed rate of 0.20 mm/rev there was some increase in the chip thickness after some interval of time which was due to the dominance of tool wear at later stage of machining leading to high chip deformation.

4.2.5 Surface roughness

The fluctuation of surface roughness obtained under specific feed rate at variable cutting speed with progression of machining duration when machining 17-4 PH stainless steel with uncoated and coated carbide inserts are demonstrated by Figs. 33, 34 and 35.Increase in the surface roughness with increase in the feed rate was observed for both types of tool. Machining under the higher feed rates leads to more heat generation, wearing the tool early leading to poor machined surface quality.

The very high tool wear rate for uncoated carbide inserts at low feed rate of 0.16 mm/rev and cutting speed of 190 m/min as can be seen by Fig. 33 resulted in higher surface roughness value than the CVD multi-layer coated tool at same machining condition. Also the surface roughness value prevailed under this particular low machining condition was highest among all other conditions. But at same condition the CVD multi-layer coated tool was able to arrest the deterioration of the machined surface because of low tool wear. The surface roughness was comparable between two types of tool for lower and medium cutting speed under low feed rate of 0.16 mm/rev.

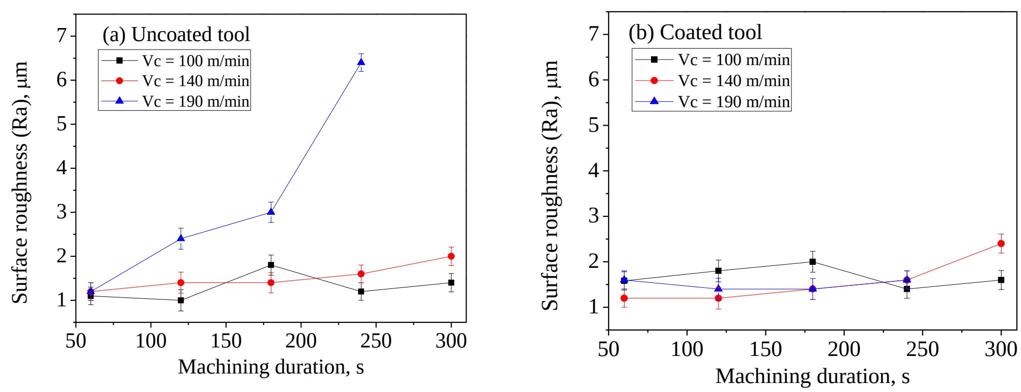


Fig. 33 Variation of surface roughness with progression of machining duration with variable cutting speed at feed rate 0.16 mm/rev for (a) Uncoated and (b) Coated tool

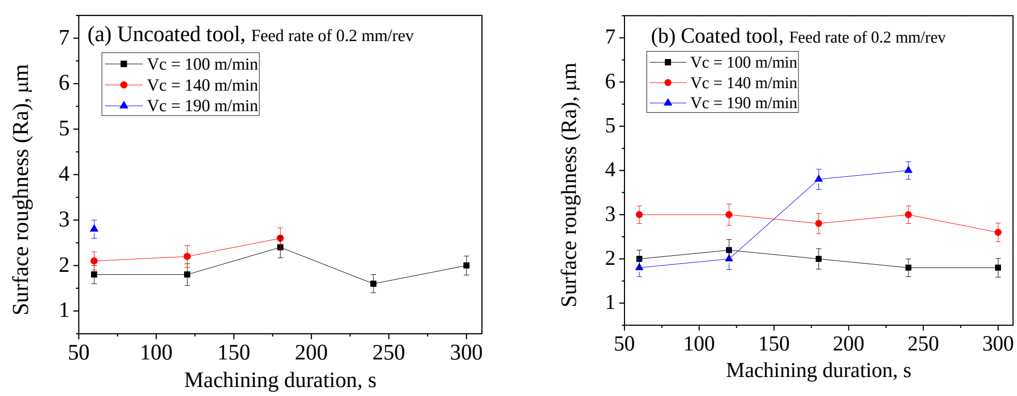


Fig. 34 Variation of surface roughness with progression of machining duration with variable cutting speed at feed rate 0.20 mm/rev for (a) Uncoated and (b) Coated tool

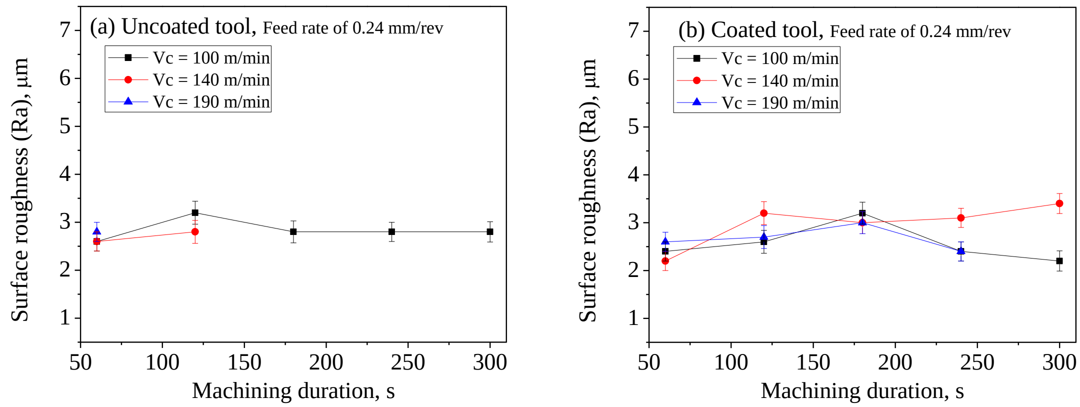


Fig. 35 Variation of surface roughness with progression of machining duration with variable cutting speed at feed rate 0.24 mm/rev for (a) Uncoated and (b) Coated tool

Overall it can be recommended to use CVD multi-layer coated tool can be used at lower feed rate for improvement of surface roughness.

4.2.6 Cutting temperature

The temperature of the CVD multi-layer coated tool obtained during the machining of 17-4 PH stainless steel was found to be higher than that of uncoated carbide inserts for machining condition as can be observed form Figs. 36, 37 and 38. The thermal conductivity of the uncoated carbide tool is higher than CVD multi-layer coated tool. Hence, the uncoated tool has greater ability to dissipate heat to the surrounding so the temperature of the uncoated cutting tool will be less. The lower thermal conductivity of the insulating coating layers of the coated tool prevented or restricted heat to dissipate into surrounding; hence the coated cutting tool temperature was high.

Rise in the temperature of the CVD multi-layer coated tool was observed with increase in the feed rate which can be attributed to the high tool wear rate at higher feed rate. This increase in the temperature was significant for the higher cutting velocity of 190 m/min. And there was increase in the cutting tool temperature of the CVD coated tool with progression of machining duration for high cutting velocity of 190 m/min at all feed rates.

With increase in the feed rate the cutting tool temperature for the uncoated and coated tools diminishes or rather say the difference lowers for machining done under low cutting speed of 100 m/min. This lowering of difference in cutting tool temperature can be attributed to higher tool wear rate of the uncoated tool compared to the coated counterpart.

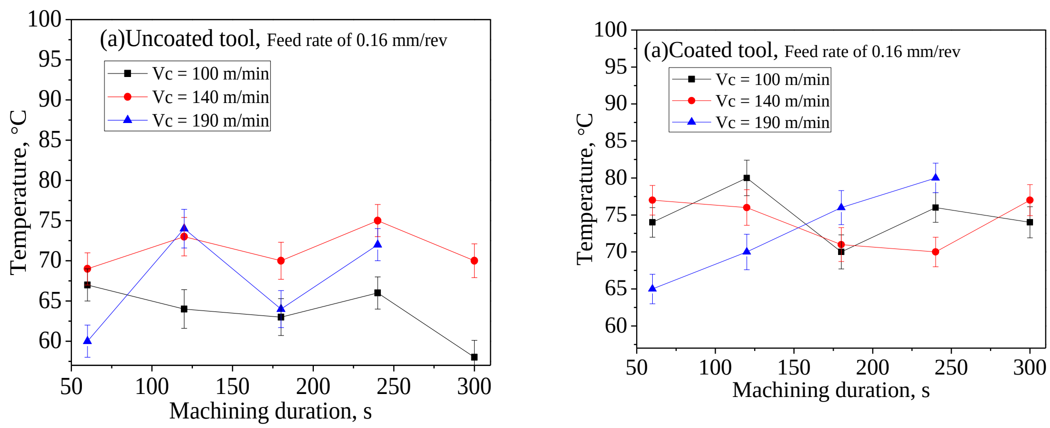


Fig. 36 Variation of cutting temperature with progression of machining duration with variable cutting speed at feed rate 0.16 mm/rev for (a) Uncoated and (b) Coated tool

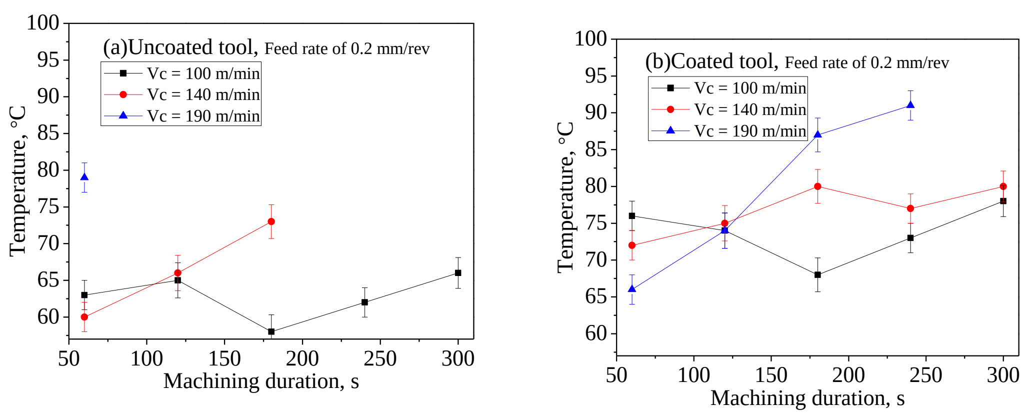


Fig. 37 Variation of cutting temperature with progression of machining duration with variable cutting speed at feed rate 0.20 mm/rev for (a) Uncoated and (b) Coated tool

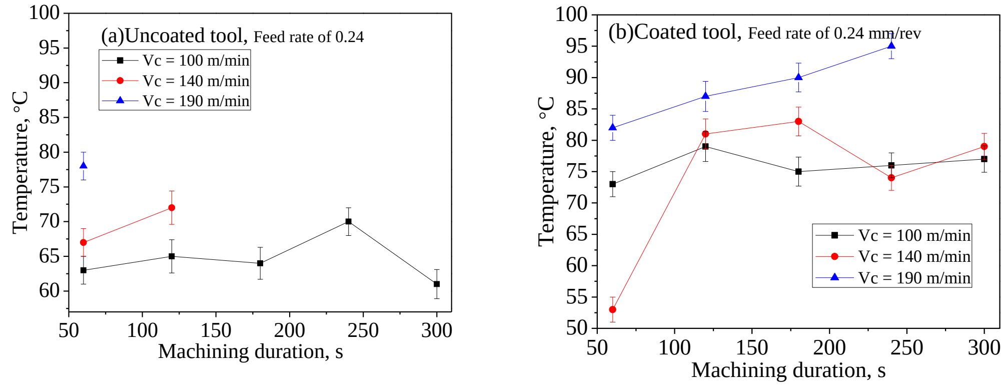


Fig. 38 Variation of cutting temperature with progression of machining duration with variable cutting speed at feed rate 0.24 mm/rev for (a) Uncoated and (b) Coated tool

4.2.7 *Cutting Force*

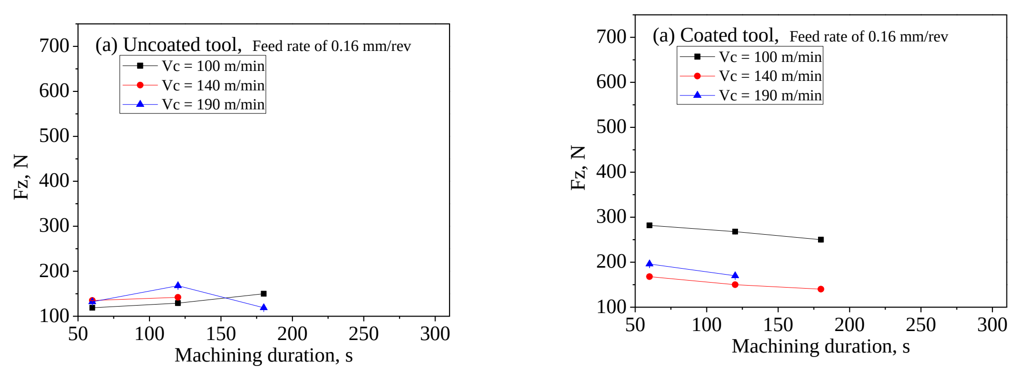


Fig. 39 Variation of tangential cutting force with progression of machining duration with variable cutting speed at feed rate 0.16 mm/rev for (a) Uncoated and (b) Coated tool

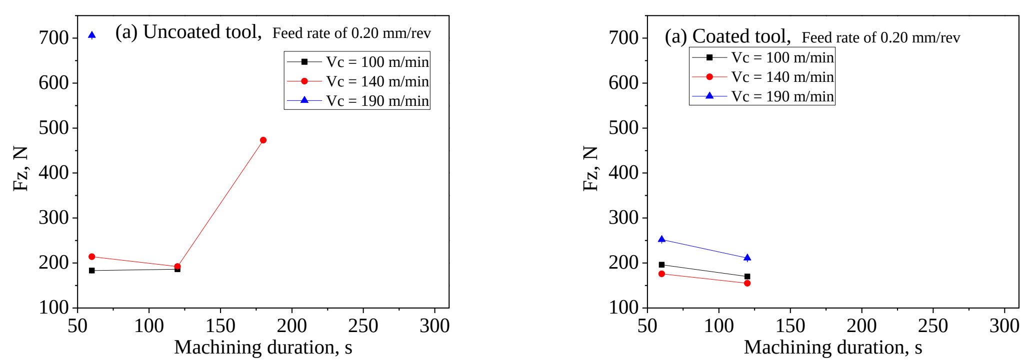


Fig. 40 Variation of tangential cutting force with progression of machining duration with variable cutting speed at feed rate 0.20 mm/rev for (a) Uncoated and (b) Coated tool

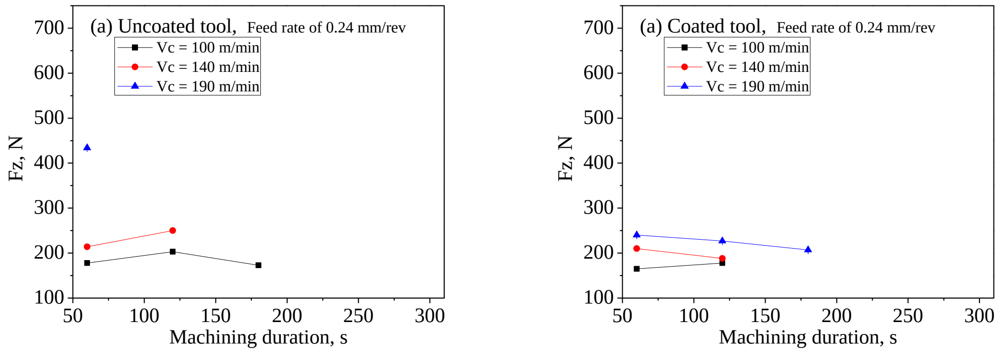


Fig. 41 Variation of tangential cutting force with progression of machining duration with variable cutting speed at feed rate 0.24 mm/rev for (a) Uncoated and (b) Coated tool

Figures 39,40 and 41 demonstrates the variation of tangential cutting force (Fz) with progression of machining duration with variable cutting speed under constant feed rates while machining 17-4 PH stainless steel with uncoated and CVD multi-layer coated tool. The cutting force data has been plotted for only few machining duration, as for further machining duration there was some problem with regard to dynamometer.

From the experimental it is seen that for the uncoated tool the tangential cutting force increased with increase in the feed rate. This can be attributed to increase in the tool wear with feed. However, the tangential force for machining 17-4 PH stainless steel with CVD coated tool the cutting force was high at initial feed rate due to high tool wear at this condition for low cutting velocity (Vc= 100 m/min). But for other cutting velocities with increase in the feed rate the tangential cutting force was comparable. Further increase in feed to 0.20 mm/rev for coated tool under low cutting speed the cutting force decreased. The cutting force at high feed rate was comparable with that of medium feed rate. This decrease in cutting force can be attributed to increase in the temperature with cutting velocity.

4.3 Effect of cutting velocity on machinability characteristics of 17-4 PH steel

4.3.1 Flank wear

Figures 42, 43 and 44 illustrate the variation of the flank wear with progression of the machining duration with varying feed rates at certain cutting speed when machining 17-4 PH stainless steel with both uncoated and coated type inserts.

It can be deduced from all figures that the flank wear rate increased with increase in cutting speed for both types of cutting tools. The generation of high cutting temperature at chip-tool interface at higher cutting velocities lead to softening of the tool, wearing the tool at faster rate than machining at the lower cutting velocity. The influence of increase in cutting speed was more prominent for the uncoated tool. It can be seen that with increase in cutting speed rate to 190 m/min increment of the flank wear for uncoated tool was more when machining under lower feed rate of 0.16 mm/rev as compared to its other lower cutting condition and as well as its coated counterpart at same cutting condition. A maximum increment of 55 % in tool life for coated was obtained at this cutting condition in contrast to uncoated tool when machining under cutting speed of 190 m/min and at lower feed rate of 0.16 mm/rev (Fig. 44).

For CVD coated tool machining at medium feed rate of 0.20 mm/rev and high feed rate of 0.24 mm/rev the increment in the flank wear with rise of cutting speed is not significant. But notable difference in flank wear at the lower feed rate can be clearly visible. The flank wear for the low cutting velocity (Vc =100 m/min) was more compared to medium cutting velocity (Vc = 140 m/min) due to poor performance of coating at low cutting feed of 0.16 mm/rev which has already been observed in earlier section. With increase in cutting speed from 140 to 190 m/min increase in flank wear was noted which can be ascertained to higher generation of temperature at tool-chip interface leading to more wear.

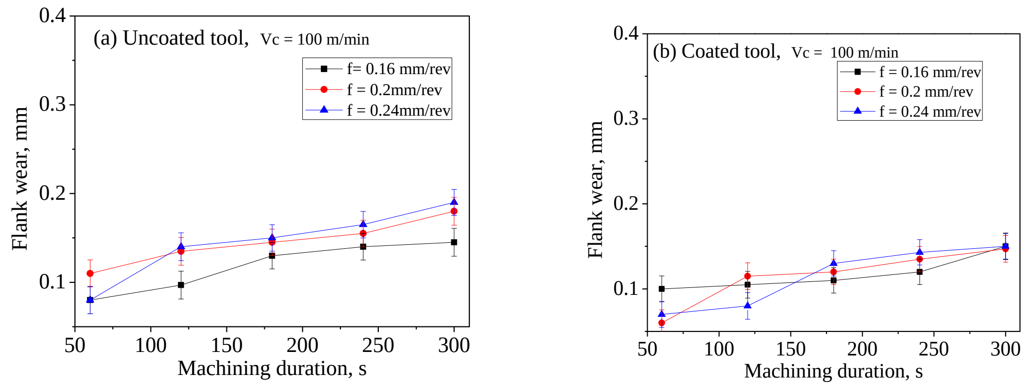


Fig. 42 Variation of flank wear with progression of machining duration with variable feed rate at cutting speed= 100 m/min for (a) Uncoated and (b) Coated tool

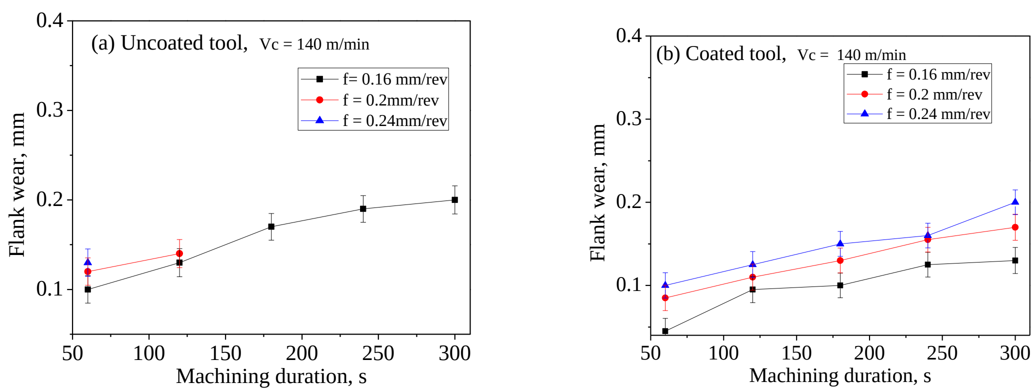


Fig. 43 Variation of flank wear with progression of machining duration with variable feed rate at cutting speed= 140 m/min for (a) Uncoated and (b) Coated tool

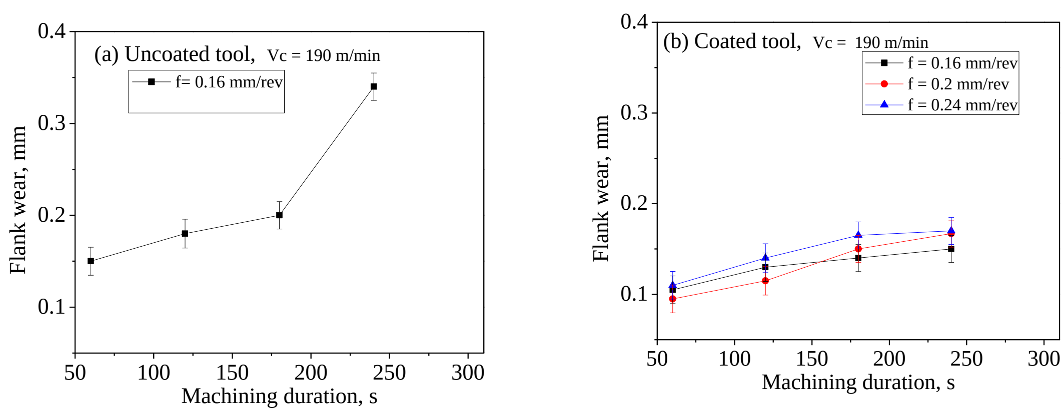


Fig. 44 Variation of flank wear with progression of machining duration with variable feed rate at cutting speed= 190 m/min for (a) Uncoated and (b) Coated tool

4.3.2 Nose Wear

Similar observations were noted for the progression of the nose wear as that of flank wear when machining 17-4 PH stainless steel with uncoated and CVD multi-layer carbide inserts. However, the nose wear for CVD multi-layer at lower feed rate for cutting speed of 100 m/min was found to be more than that of when machining 17-4 PH stainless steel at higher feed rates of 0.20 and 0.24 mm/rev at same constant speed of 100 m/min.

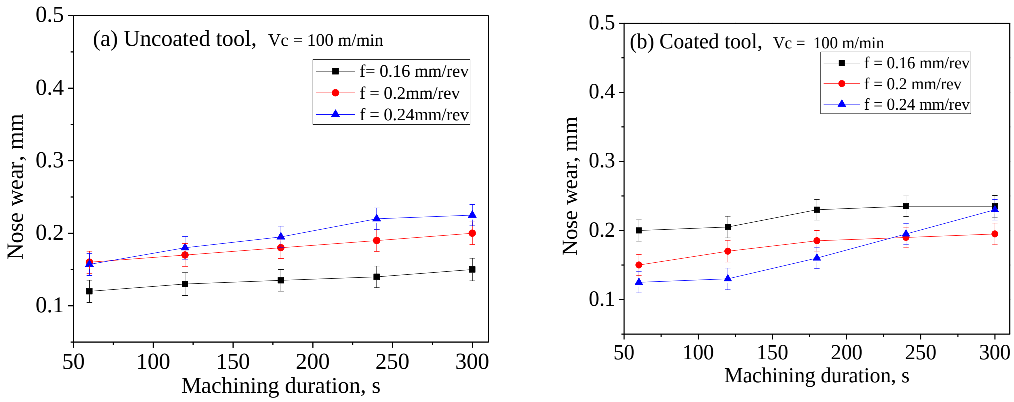


Fig. 45 Variation of nose wear with progression of machining duration with variable feed rate at cutting speed= 100 m/min for (a) Uncoated and (b) Coated tool

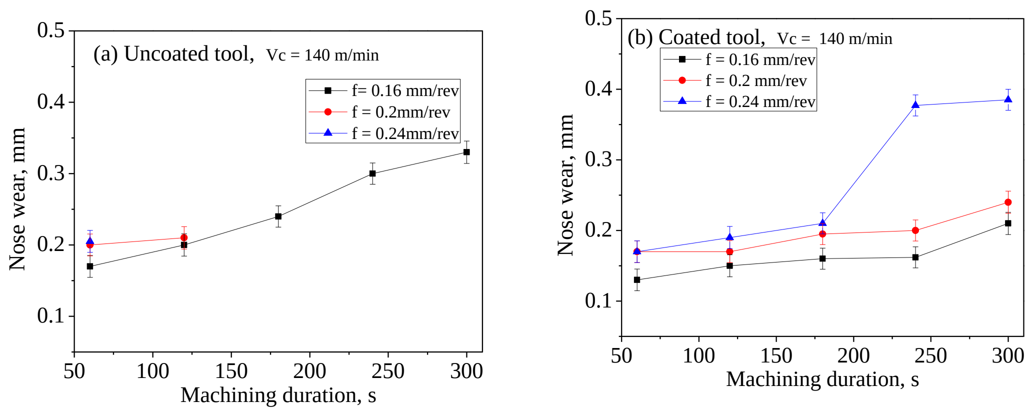


Fig. 46 Variation of nose wear with progression of machining duration with variable feed rate at cutting speed= 140 m/min for (a) Uncoated and (b) Coated tool

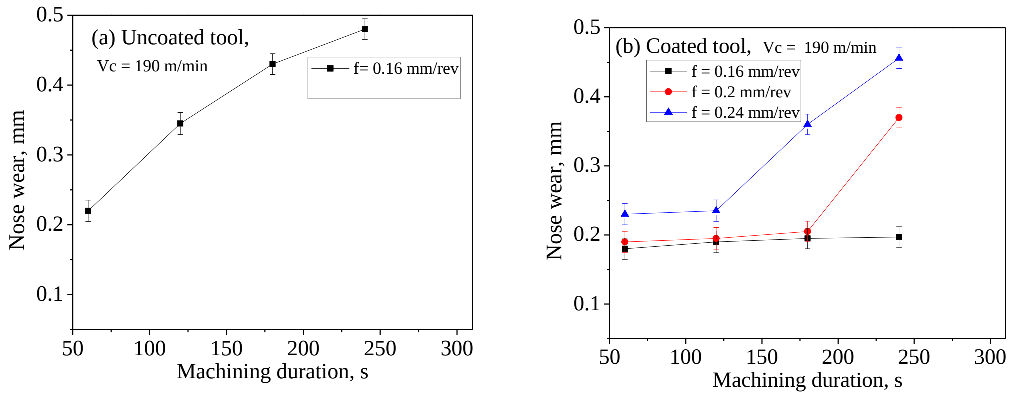


Fig. 47 Variation of nose wear with progression of machining duration with variable feed rate at cutting speed= 190 m/min for (a) Uncoated and (b) Coated tool.

4.3.3 Chip thickness

The chip deformation obtained during machining of 17-4 PH stainless with the uncoated carbide insert at constant cutting speed with variable feed rate was found to be more as compared to machining with CVD multi-layer coated tool. The high tool wear rate in case of the uncoated carbide tool resulted in higher amount of chip deformation than that of coated tool.

One can observe that the chip deformation at the lower cutting velocity with uncoated carbide inserts under lower feed rate of 0.24 mm/rev was found to be more in comparison with medium cutting speed of 140 m/min for same feed rate. The higher chip deformation at the lower cutting velocity can be assigned to the tendency of BUE formation on the cutting inserts at lower cutting speed during machining of 17-4 PH stainless steel. This BUE formation increases the friction along with slight reduction in the rake angle which aggravates the chip deformation, hence increasing the chip thickness.

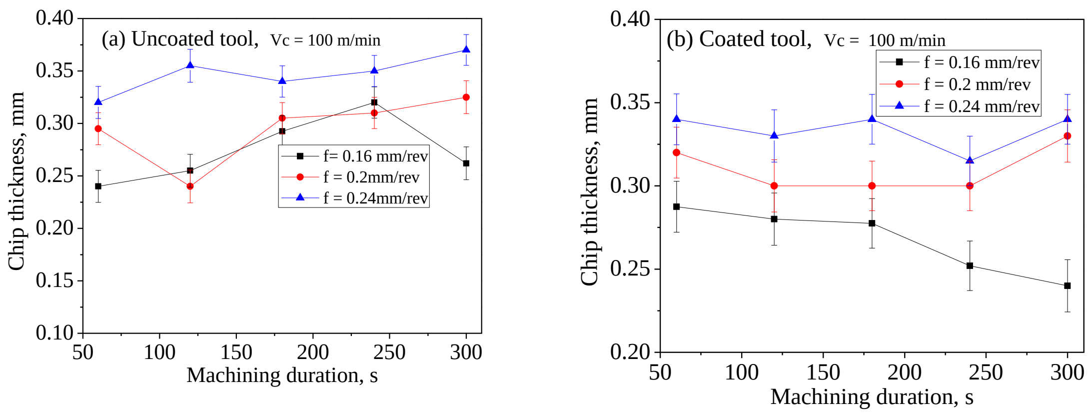


Fig. 48 Variation of chip thickness with progression of machining duration with variable feed rate at cutting speed= 100 m/min for (a) Uncoated and (b) Coated tool

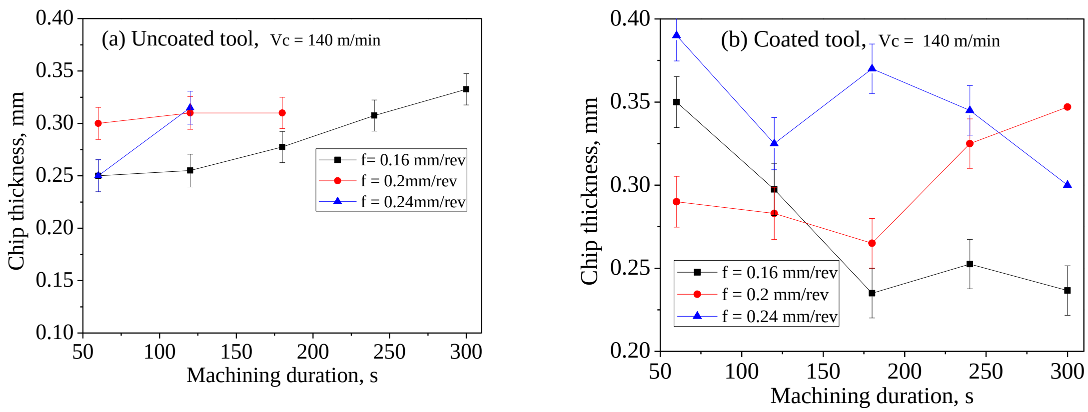


Fig. 49 Variation of chip thickness with progression of machining duration with variable feed rate at cutting speed= 140 m/min for (a) Uncoated and (b) Coated tool

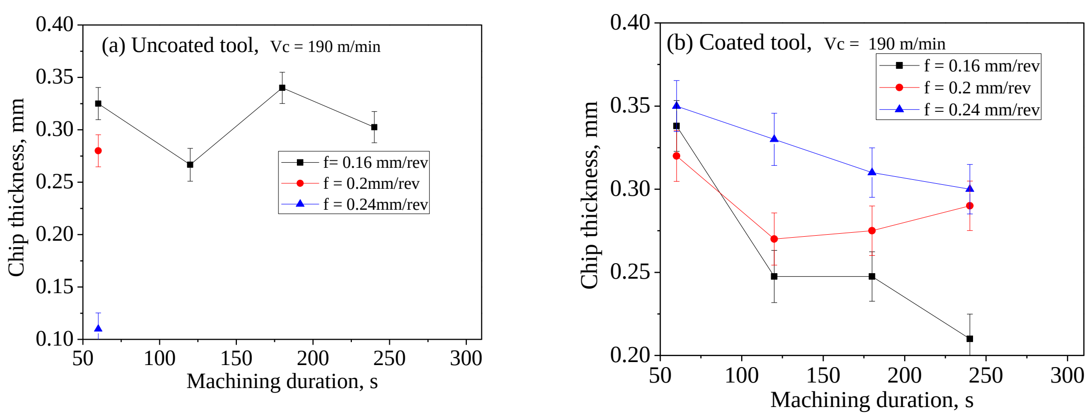


Fig. 50 Variation of chip thickness with progression of machining duration with variable feed rate at cutting speed= 190 m/min for (a) Uncoated and (b) Coated tool

Fig. 51 shows the BUE formation when machining 17-4 PH stainless steel with uncoated carbide inserts at lower cutting speed of 100 m/min for all feed rates. With increase in the cutting speed to 140 m/min there was almost no BUE for the uncoated tool when machining 17-4 PH stainless steel; hence there was reduction in the chip thickness with increase in speed from 100 to 140 m/min under feed rate of 0.24 mm/rev. But for lower feed rate of 0.16 m/min and at cutting speed of 140 m/min the chip deformation was comparable than at same feed but at lower cutting speed of 100 m/min. But when the cutting speed was raised to 190 m/min it was the high tool wear rate of uncoated tool at all feed rates which lead to large chip deformation than that machining at 140 m/min.

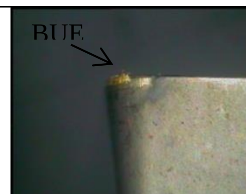
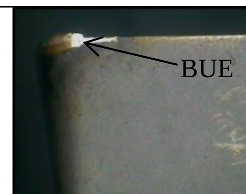
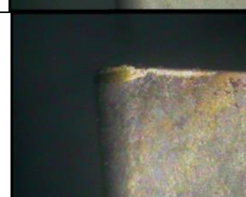
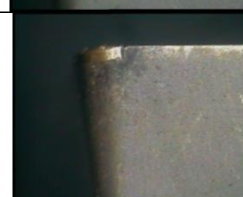
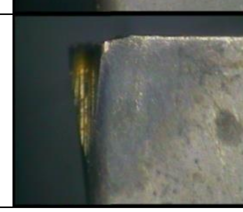
Machining condition	Uncoated carbide tool		
	0.16 mm/rev	0.20 mm/rev	0.24 mm/rev
Vc=100 m/min Machining duration = 60 s			
Vc=140 m/min Machining duration = 60 s			
Vc=190 m/min Machining duration = 60 s			

Fig. 51 Cutting tool condition for uncoated carbide tool at different machining condition

Chip deformation for CVD multilayer coated tool was comparable (slight increment) for all feed rates when cutting speed was raised from 100 to 140 m/min. This is due to reason that there is hardly any difference in tool wear when speed was increased. But when cutting speed was raised further to 190 m/min due to reduction in dynamic friction the chip deformation decreased.

4.3.4 *Surface roughness*

The surface roughness of the machined surface of the 17-4 PH stainless steel varied under a particular range with progression of machining duration when machining with uncoated and coated carbide inserts for all cutting speed condition. The variation of surface roughness between the uncoated and coated carbide inserts was comparable for low and medium cutting velocity. However, machining with uncoated tool under high cutting velocity of 190 m/min and at lower feed rate of 0.16 mm/rev the quality of machined surface highly deteriorated as machining duration progresses which can be accredited to very high flank wear rate of the uncoated carbide inserts (Fig. 54). Machining under same cutting condition maximum improvement of 76 % was noted for CVD multi-coated carbide tool.

For machining 17-4 PH stainless steel with CVD multi-layer coated tool the surface roughness was found to increase when cutting speed was changed from 100 m/min to 140 m/min (Fig. 52b and 53b). This increase in surface roughness can be intuited to increase in tool wear with cutting speeds. However at higher cutting speed of 190 m/min due to softening of the material the surface obtained was much better than machining at 140 m/min.

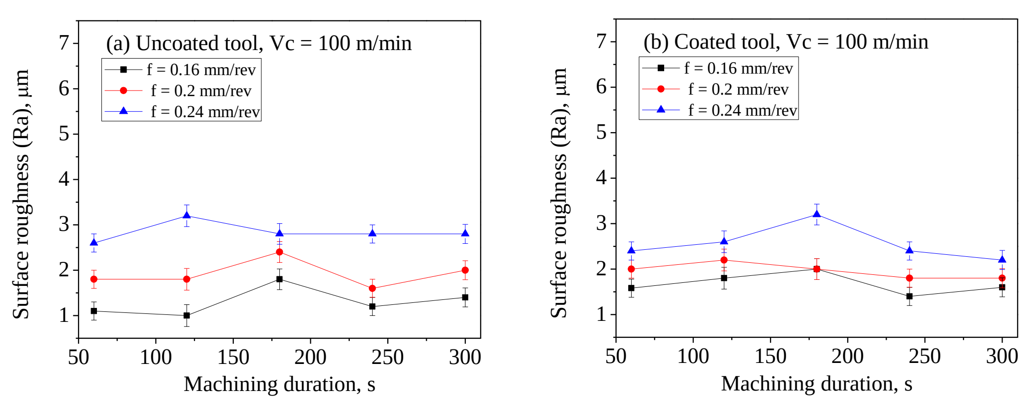


Fig. 52 Variation of surface roughness with progression of machining duration with variable feed rate at cutting speed= 100 m/min for (a) Uncoated and (b) Coated tool

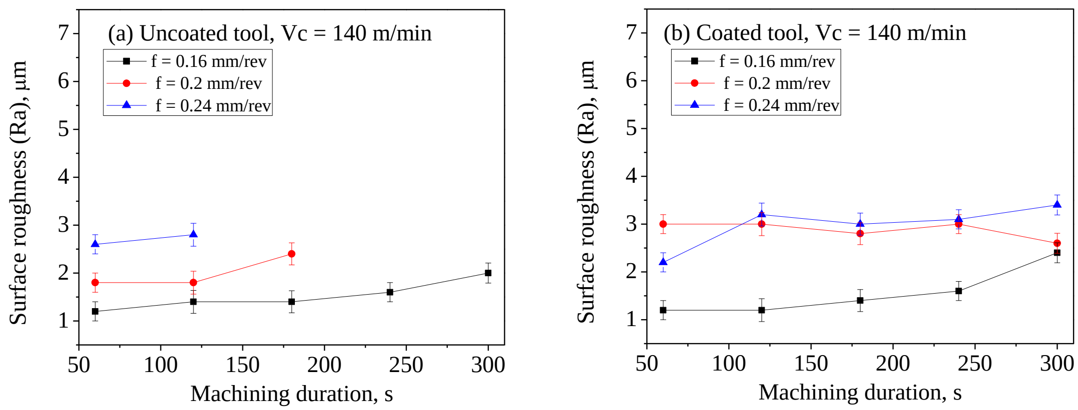


Fig. 53 Variation of surface roughness with progression of machining duration with variable feed rate at cutting speed= 140 m/min for (a) Uncoated and (b) Coated tool

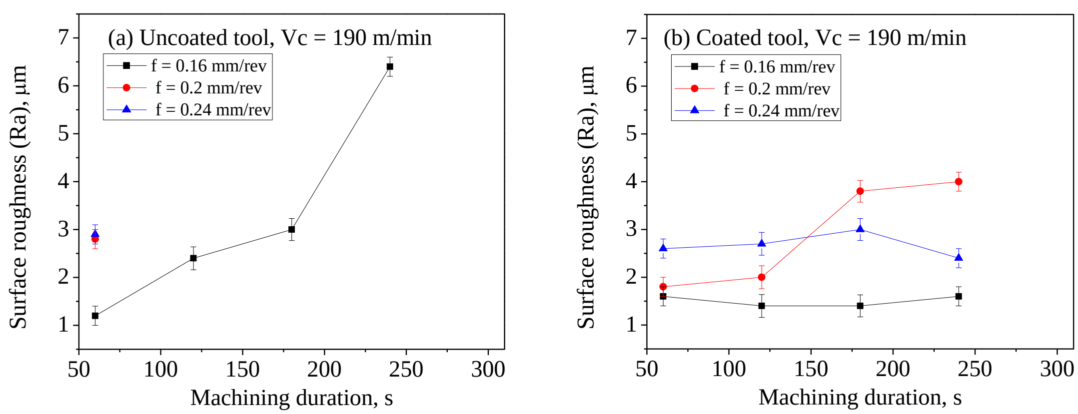


Fig. 54 Variation of surface roughness with progression of machining duration with variable feed rate at cutting speed= 190 m/min for (a) Uncoated and (b) Coated tool

4.3.5 Cutting temperature

Figures 55, 56 and 57 demonstrates the alteration of the cutting tool temperature with progression of machining duration with variable feed rate at constant cutting speeds for both uncoated tool and coated carbide tool. For all machining condition the cutting temperature for the uncoated tool was found less compared to the CVD multi-layer coated tool. This can be accredited to the difference in thermal conductive of both the tool, with thermal conductivity higher for the uncoated tool.

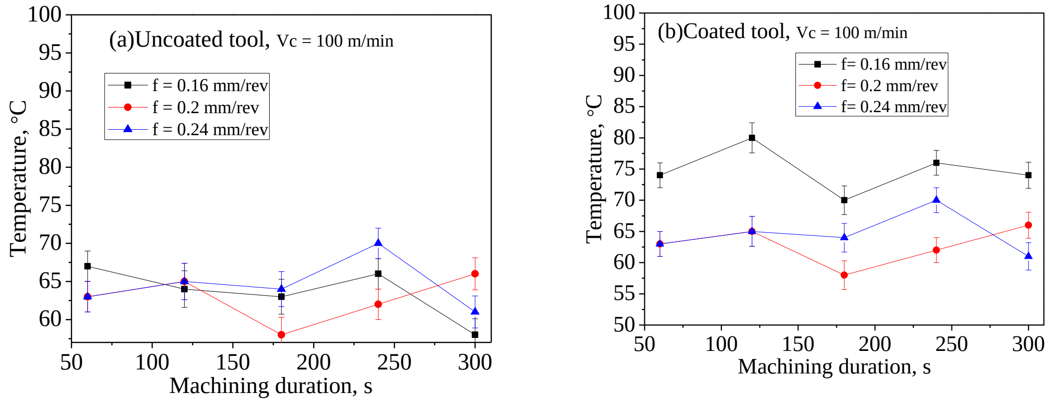


Fig. 55 Variation of cutting temperature with progression of machining duration with variable feed rate at cutting speed= 100 m/min for (a) Uncoated and (b) Coated tool

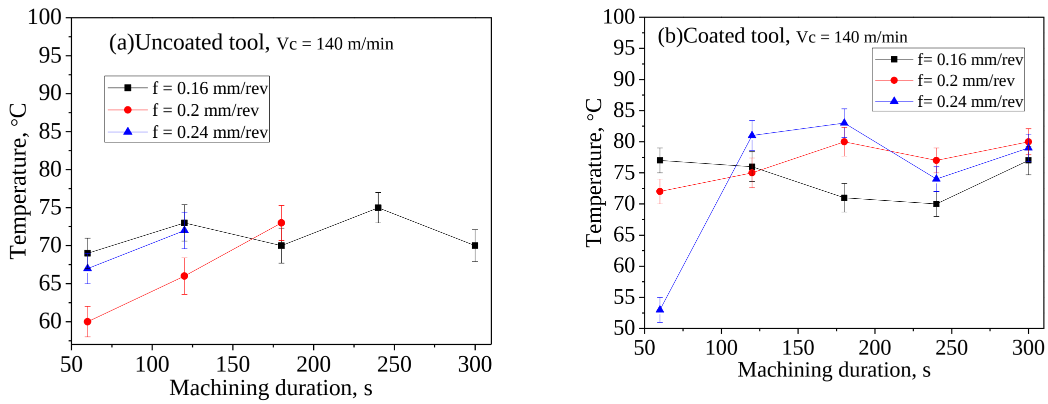


Fig. 56 Variation of cutting temperature with progression of machining duration with variable feed rate at cutting speed= 140 m/min for (a) Uncoated and (b) Coated tool

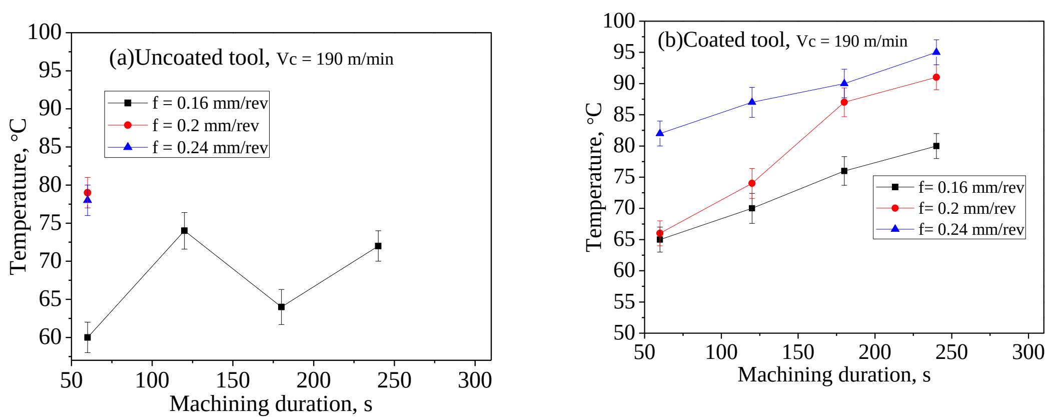


Fig. 57 Variation of cutting temperature with progression of machining duration with variable feed rate at cutting speed= 190 m/min for (a) Uncoated and (b) Coated tool

With increase in the cutting velocity the temperature noted for the cutting tool while machining 17-4 PH stainless steel increased for both type of cutting tools except for the lower feed rate of 0.16 mm/rev. It is due to inability of coated tool to perform well at low cutting condition which led to high tool wear, eventually resulting in generation of high temperature. But the decrease in cutting tool temperature for same feed rate of 0.16 mm/rev at higher cutting speed is due to lower chip-tool contact. However, machining under medium feed rate of 0.20 mm/rev and high feed rate of 0.24 mm/rev for CVD coated tool with increase in cutting speed increment in cutting temperature was observed. This can be attributed to dominance of tool wear. The dissimilarity of temperature between the uncoated and coated tool decreased under lower feed rate of 0.16 mm/rev with increase in the cutting velocity.

4.3.6 Cutting Force

Variation of the tangential cutting force with variable feed at constant cutting speed has been depicted in Fig. 58, 59 and 60. For uncoated tool the increment in the cutting speed had very insubstantial effect on the tangential cutting force for cutting at lower feed rate of 0.16 mm/rev. But for other feed rate of 0.20 and 0.24 mm/rev slight increase in the tangential cutting force was observed when cutting velocity was raised from 100 to 140 m/min.

Machining with coated tool at feed rate of 0.20 and 0.24 mm/rev the tangential cutting force increased with increase in the cutting velocity. However, for the lower feed rate of 0.16 mm/rev the tangential cutting force was highest under lower cutting speed of 100 m/min. It is due to inability of coated tool to perform well at lower cutting condition. Further increase in the cutting velocity led to decrease in the force, but it again increased slightly when cutting speed was increased from 140 to 190 m/min.

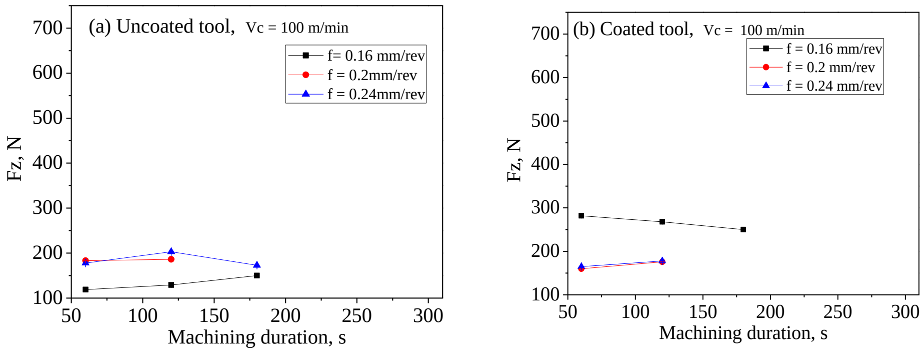


Fig. 58 Variation of tangential cutting force with progression of machining duration with variable feed rate at cutting speed= 100 m/min for (a) Uncoated and (b) Coated tool

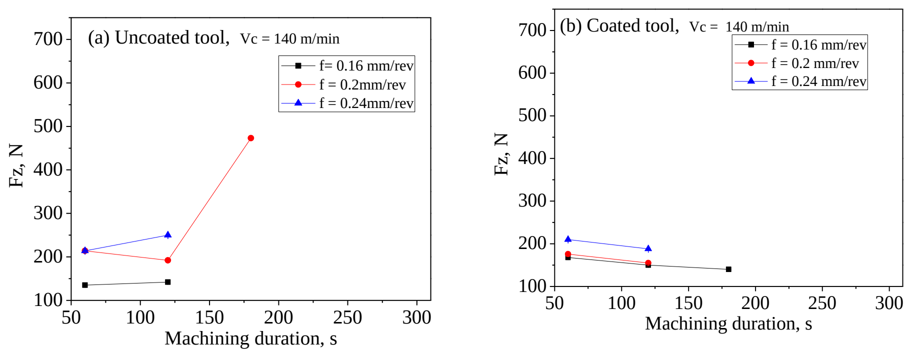


Fig. 59 Variation of tangential cutting force with progression of machining duration with variable feed rate at cutting speed= 140 m/min for (a) Uncoated and (b) Coated tool

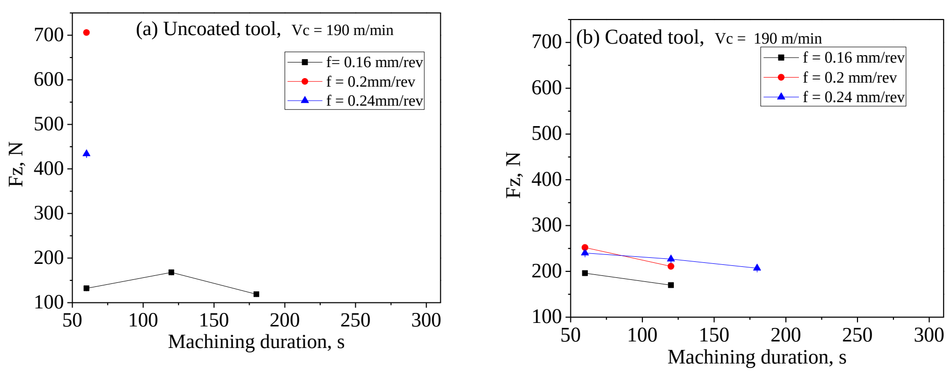


Fig. 60 Variation of tangential cutting force with progression of machining duration with variable feed rate at cutting speed= 190 m/min for (a) Uncoated and (b) Coated tool

CHAPTER 5: CONCLUSION

The current study aimed at investigating the influence of CVD multilayer (TiN/TiCN/Al_2O_3/ZrCN) coating and cutting parameters like cutting speed, feed rate and machining duration on various aspects of machinability characteristics of 17-4 PH stainless steel. Following conclusions can be drawn from current research work:

1) Nose wear was found to be prominent tool failure mode for the uncoated carbide inserts under high feed rates (0.24 mm/rev) and medium feeds (0.20 mm/rev) for cutting conditions of medium and high cutting velocity.
2) The chips obtained were mostly of long continuous and snarled type. The chips obtained at initial machining duration were of golden colour which later changed to silver light colour with progression of machining.
3) Flank wear and nose wear increased with progression of machining duration for both uncoated and CVD multilayer coated carbide insert for all cutting conditions.
4) Under minimum machining condition of minimum feed (0.16 mm/rev) and cutting speed (100 m/min), there was no improvement in average flank wear for coated tool as compared to its uncoated counterpart. However the improvement got more prominent with increase in feed rate and cutting speed.
5) The rate of flank wear for uncoated tool could also be brought down with the help of CVD multilayer coating under the medium and high feed condition. Improvement in tool life up to a maximum of 55 % for coated tool compared to its uncoated counterpart was observed under constant velocity of 190 m/min and for feed rate of 0.16 mm/rev at machining interval of 300 s.

6) Increase in both speed and feed resulted in increase in the temperature. CVD multilayer coated tool exhibited higher cutting temperature than its uncoated counterpart for all cutting conditions.
7) The anti-friction CVD multilayer coated tool resulted in less chip deformation as compared to uncoated carbide insert under any cutting condition.
8) The chip thickness for both uncoated and coated carbide insert increased with progression of machining duration with increase in feed rate for constant cutting velocity.
9) With increase in the cutting speed uncoated tool exhibited increase in chip thickness, whereas the average value of the chip thickness did not change significantly for CVD coated tool.
10) The quality of machined surface for 17-4 PH deteriorated with increase in feed rate. For obtaining better surface finish CVD multilayer coated tool is recommended with a feed rate of 0.16 mm/rev. Reduction of surface roughness up to a maximum of 76 % for CVD multilayer coated insert was noted during machining of 17-4 PH stainless steel under a high cutting velocity of 190 m/min and lower feed rate of 0.16 mm/rev.

CONTRIBUTION OF PRESENT RESEARCH WORK

The major contribution of the current study is to understand the effectiveness of CVD multilayer ($TiN/TiCN/Al_2O_3/ZrCN$) coated tool over the uncoated tool during dry machining of 17-4 PH stainless steel. The study also establishes various tool wear mechanism for both uncoated and coated tool during machining of 17-4 PH stainless steel.

The effect of cutting parameters such as cutting speed, feed rate and machining duration has been investigated for first time on machinability characteristics of 17-4 PH stainless steel such as cutting force, cutting temperature and chip thickness.

RECOMMENDATION AND SCOPE OF FUTURE WORK

Based on present investigation, prospective points are highlighted for improving machinability aspects of 17-4 PH stainless steel:

- It has been observed from the current study that the uncoated tool performed reasonably well under low cutting speed (Vc= 100 m/min) and feed rate (f= 0.16 mm/rev). It is recommended not to use uncoated cemented carbide insert beyond cutting speed of 100 m/min and feed rate of 0.16 mm/rev.
- For better productivity during machining of 17-4 PH stainless steel CVD multilayer consisting of $TiN/TiCN/Al_2O_3/ZrCN$ coatings is always recommended for improving the machining performance.

Future study as given below may be undertaken based on major findings of current research work:

- Since the current study indicated higher temperature of the coated tool, it is difficult to pin point chip-tool interface temperature. More careful study of measurement of cutting temperature which would depict the situation in chip-tool interface region more clearly. This may be carried out with high resolution thermal imaging camera.
- Attempt should be made to study the effect of lubrication with different application technique of cutting fluid i.e. minimum quantity lubrication (MQL) etc. on machining performance of 17-4 PH stainless steel.
- Future study should also be undertaken with different grades of CVD and PVD coated tools to recommend best coated tool for machining 17-4 PH stainless steel.

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