Effect of Cutting Parameters and Cutting Environment on Surface Integrity during Machining of Nimonic C-263

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By

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under the supervision of

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Supervisors Certificate

This is to certify that the work presented in this dissertation entitled "*Effect of Cutting Parameters and Cutting Environment on Surface Integrity during Machining of Nimonic C-263*" by "*Mahendra Singh*", Roll Number 214ME2334, is a record of original research carried out by him under our supervision and guidance in partial fulfilment of the requirements of the degree of *Master of Technology* in *Mechanical Engineering*. Neither this dissertation nor any part of it has been submitted for any degree or diploma to any institute or university in India or abroad.

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Declaration of Originality

I, Mahendra Singh, Roll Number 214ME2334 hereby declare that this dissertation entitled *Effect of Cutting Parameters and Cutting Environment on Surface Integrity during Machining of Nimonic C-263* presents my original work carried out as a masters student of NIT Rourkela and, to the best of my knowledge, contains no material previously published or written by another person, nor any material presented by me for the award of any degree or diploma of NIT Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the sections "Reference". I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation.

I am fully aware that in case of any non-compliance detected in future, the Senate of NIT Rourkela may withdraw the degree awarded to me on the basis of the present dissertation.

May 24, 2016

NIT Rourkela *Mahendra Singh*

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ABSTRACT

Nimonic C-263 has been widely used in hot portion of jet engine, submarine and chemical industries, gas turbine components, heat exchanger and ultra-supercritical power plant due to its ability to operate at elevated temperature for long period of time and higher resistance to corrosion and oxidation in acidic and aqueous environment. Properties such as high shear strength, low thermal conductivity, high tendency towards strain hardening, high hot hardness, and chemical affinity towards tool material poses greater challenge to the industries for achieving higher productivity and good surface quality of component with sustainable machining. Topographical, mechanical, metallurgical, chemical and thermal changes happen in the surface and sub-surface layer of material during machining which influences the functional performance of component. The study focuses on the effect of coating and cooling technique on surface integrity during machining of Nimonic C-263. Surface and sub-surface alteration such as surface damages, grain refinement, microstructural alteration, white layer and work-hardened layer during machining was examined using Field emission scanning electron microscopy (FESEM), X ray diffraction (XRD) system, XRD texture measurement and micro hardness tester. The effect of cutting speed and feed rate on surface integrity under these environments also has been analysed. The research demonstrated significant improvement in surface integrity with the use of minimum quantity lubrication (MQL) and flood environment during machining at low and medium cutting condition. High tool wear of uncoated tool and less cooling and lubricating efficiency of MQL and flood together deteriorate surface integrity at high cutting speed and feed. The PVD multilayer coated tool even under dry machining condition has given comparable result and sometimes even better than wet machining with uncoated tool. Surface damages in the form of micro cracks, voids, grooves, cavity and material transfer mainly observed in the surface. Deformed zones were intrinsic for all process conditions whereas their intensity and thickness increases with increases in tool wear and cutting parameter. The increase of feed rate had more influence on the plastic deformation. Overall it can be recommended that dry machining can be more beneficial than wet machining when PVD multilayer coated tool

used under high cutting speed and feed. This is particularly important for higher productivity in sustainable manner.

Keywords: Nimonic C-263; PVD multilayer coating; MQL; flood; machining; sustainable; surface integrity.

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CHAPTER 1

INTRODUCTION

Manufacturing can be simply defined as value addition processes in which raw materials of low utility and value are converted into high utility and valued products. The objective in manufacturing of any product should be less manufacturing time and high rate of production with reduced cost. Machining is used for achieving high dimensional and form accuracy and good surface finish for serving their purposes in better way. Machining is an essential process that imparts the desired dimensions and surface finish to a work piece by gradually removing the excess material in the form of chips or swarfs. Machining of work piece material is achieved with the help of cutting tool which moved past the work surface in different directions it may be manual or automatic. For material removal by machining system consists of cutting tool, work piece and machine tool, the work and the tool need relative movements. The machine tools need two types of relative tool work motions for machining flat or curved surfaces. Feed motion, cutting motion comes under formative motions those are assisting to get required target. Indexing motion, additional feed motion and relieving motion comes under auxiliary motions those are required to fulfil their assigned function such as clamping and declamping of the work piece. The understanding of chip formation mechanism during metal removal process is very important. Two shearing zone occur during chip formation and tertiary deformation zone occur between tool flank and work piece due to rubbing as shown in Fig.1. In primary shear zone, material removal takes place due to elasto-plastic deformation and majority of energy transferred into heat. High friction and heat generated in the secondary shear zone due to high movement of continuous chip on rake face which induces high crater wear and chipping. Generation of high cutting temperature take place in the cutting zone due to low thermal conductivity of super alloy. High temperature strength, hot hardness and high cutting temperature induces high tool wear resulting shorten tool life and poor surface integrity. Increase in cutting temperature and pressure at high cutting parameter adversely affect the tool condition and surface quality of machined component. In any machining system, for achieving higher productivity and good quality in less time a good selection of a cutting tool, cutting environment and cutting parameters is essential. Commercially available cutting tool materials can only be used at moderate speed machining. Superior tool materials such as reinforced ceramic, coated carbide and polycrystalline cubic boron nitride are used for high speed machining of exotic super alloys. Cutting fluid plays a significant role in reducing friction and minimising cutting temperature between chip-tool and work-tool interface resulting high tool life and good surface quality but it creates environmental pollution due to which trend move towards dry machining or near dry machining. Machining of difficult to cut material at high-speed conditions can be achieved by a combination of the appropriate coating of tool material, machining technique and the choice of a suitable cooling technology [1,2].

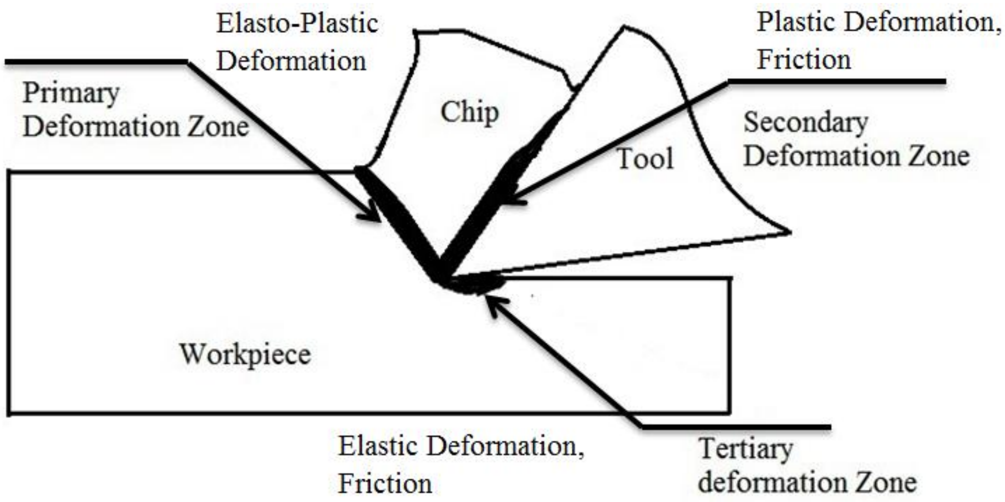


Fig.1: Schematic representation of cutting zone during machining [1].

1.1 Super alloys

Super alloys are also knows as high performance or high-temperature alloys. They contain a number of elements in a variety of combinations to maintain good characteristics like high mechanical strength and stability at elevated temperatures that make them different from other materials. Presence of more than 15 elements in a variety of combinations makes them a complex entity. The need for developing high performance alloy arises due to high demand of increasing energy production in power generation sector and more concern towards the environmental issues such as sustainability and CO_2 footprints. Super alloys are developed to possess good resistance to corrosion and oxidation, mechanical and thermal fatigue, creep, impact load, mechanical degradation over extended period of time at elevated temperature and at the same time maintain the characteristics like high strength to weigh ratio that ensure minimum fuel consumption. Among the aforementioned properties creep resistant properties at elevated temperature is very important in many application such as jet engines, heat exchangers, kilns and nuclear power plants because component failure normally occur due to creep [2]. Super alloy exhibits high corrosion resistance due to formation of protective oxide layer. Super alloys are mainly used in jet engines and gas turbines; other application of these alloys are in nuclear, marine, chemical, aeronautics, food processing unit, ultra-supercritical power plant, reciprocating engines, rocket engines, tool and dies for hot-working of metals and petrochemical industries. The mechanism behind high temperature strength of super alloy is solid solution strengthening (SSS). These alloys are referred to as iron-base, cobalt-base, or nickel-base super alloys. They contain nickel, chromium, cobalt, iron and molybdenum as major alloying element; other alloying elements are aluminium, tungsten, and titanium. Super alloys is mainly used in gas turbine and jet engine, therefore it is of utmost importance to understand the function of the various components of jet engine and gas turbine. An aircraft engine consists of three main subassemblies namely compressor, combustor and turbine. Turbine entry temperature is given more focus during the design of turbine. The efficiency of gas turbine is directly proportional to the pressure ratio and TET. To fulfil the ever increasing TET demand of gas turbine, the demand of use of new materials has been increase. These materials provide high temperature strength, high strength to weight ratio, good resistance to corrosion and oxidation etc. to ensure efficient fuel consumptions for economic operation and longer life of flight. There are numerous super alloys, available in cast or wrought forms. Super alloys have two-phase microstructure consisting of high volumes of L12 type precipitates known as gamma prime (γ') which serves to block plastic flow and is very stable at elevated temperature [2]. Three main categories that are jointly called super alloys are cobalt-based, iron-nickel based, nickel-based.

1.1.1Cobalt-based super alloy

Cobalt-based super alloys generally contain cobalt (35 to 65%), chromium (19 to 30%), and up to 35% nickel. These alloys possess excellent corrosion resistant at elevated temperature (980-1100^{o}C) because of their higher chromium contents which make them to be useful in the several parts of gas turbines such as vanes and combustion chamber. Cobalt-based alloys are not as strong as nickel-base super alloys due to less microstructural stability, but retain their strength at elevated temperature by the combined effect of carbides and solid solution strengthening. These alloys have very less high temperature strength compared to nickel based superalloy thus make it unsuitable for use in hot portion of gas turbine. Addition of tungsten increases its high temperature strength but decreases strength to weight ratio by increasing density abruptly. These alloys possess better weldability and thermal fatigue resistance as compared to nickel based alloy [3].

1.1.2 Nickel-based super alloys

Now-a-days, nickel-based super alloys find extensive applications primarily in critical components of aerospace engines and gas turbines due to their admirable properties such as high fatigue strength, thermal stability and good resistance to corrosion and oxidation under severe environment in the temperature range of 1024 to 1371°C. In fact, around 50% of the total material by weight of aero-engine is made up of nickel-based super alloys. The alloy continuous matrix (γ) is a face centred cubic (FCC) nickel-based austenitic phase. The solid solution elements present in the matrix are cobalt, chromium and molybdenum and aluminium and titanium are added in good proportions which contribute to the formation of gamma prime (γ') phase ($Ni_3(Al,Ti)$) and strengthen the material. The unique characteristic of this group of super alloys are their good application at elevated temperature up to melting point without compromising their integrity. Carbon (0.05-0.2%) is added which reacts with reactive and refractory element such as chromium, molybdenum and cobalt to form primary metallic carbide. These metallic carbides decompose and generate lower carbides such as $M_{23}C_6$ and M_6C, during processing which populate the grain boundaries and strengthen the material. Nickel-based alloys have little inherent resistance to high temperature oxidation and addition of chromium content in the range 15 to 30% forms adherent protective scale containing Cr_2O_3 on the surface of the material. During the development of super alloy, the amount of chromium content decreases in order to maintain microstructural stability and the amount of other γ' element, i.e. aluminium, titanium and niobium increases to obtain creep rupture properties [6,7,8]. Inconel, Nimonic, Udimet, Rene and Hatelloy mainly come under this category of super alloy. Some of popular grades of Nimonic are described in detail.

NIMONIC

(a) NIMONIC alloy 75

It has nickel (80%), chromium (20%) with the some controlled amount of carbon and titanium. Alloy 75 shows good resistance to oxidation at high temperatures. It has got wide applications in sheet-metal fabrications where high resistance to scaling and oxidation and mechanical strength required. Other applications of this alloy are in making of components of industrial furnaces, heat treating equipment and gas turbine engine.

(b) NIMONIC alloy 80A

It is an age hardenable nickel-chromium alloy. Some other element aluminium, titanium and carbon are added in the composition for precipitation hardening. Alloy 80A exhibits high resistance to oxidation and corrosion, high creep rupture property at temperature around 815°C. It is used in automotive industry, electrical component, marine bolts, gas turbine components and tube support in nuclear engine.

(**c) NIMONIC alloy 86**

It is a nickel-chromium-molybdenum alloy with the presence of rare-earth element cerium. It is a very rare material. It has good combined property such as better formability and weldability with high resistance to oxidation and scaling at elevated temperatures around 1050°C. It has been used being utilized in fabrication of afterburners, combustion chambers and industrial furnace.

(d)NIMONIC alloy 90

Nimonic alloy 90 consists nickel (55-63%), chromium (18-21%) and cobalt (15-21%) with the controlled amount of aluminium and titanium. It is a precipitation hardenable alloy and hardened by aluminium and titanium which makes precipitate. It has outstanding properties such as high stress-rupture strength and resistance to creep at high temperatures (up to 920°C). The other good property of this material is high resistance to corrosion and oxidation. The alloy is used in high stress application high temperature spring, turbine blades, and exhaust reheater.

(**e) NIMONIC alloy 105**

Nimonic alloy 105 is one of the precipitate-hardenable materials which consists higher percentage of nickel, cobalt and chromium with the addition of molybdenum. Presence of relatively high content of aluminium and titanium increases high temperature strength, creep rupture properties and resistance to corrosion and oxidation. It is used in making of shaft, blade and disc for gas turbine [3,4,5].

1.2 Nimonic alloy C-263

Nimonic C-263, one of the age-hardenable nickel based superalloys has high amount of cobalt, chromium and molybdenum in its composition which enhances the resistance to corrosion and oxidation. The elements Al and Ti forms coherent γ' phase which increases the mechanical property at elevated temperature by impeding the movement of dislocation. Presence of chromium and molybdenum strengthens the grain boundary with the formation of complex metallic carbide, such as MC, M_6C and $M_{23}C_6$ and further presence of high content of cobalt increases the strength of material by solution hardening make this material more heat and creep resistant. Precipitate hardening of metastable γ'' secondary phase together with work-hardening during machining contributes to the high tensile and yield strength of the material and the presence of carbide forming elements is useful in strengthening the matrix of material when present within a grain and aid high temperature strength by preventing the slippage of grain boundaries [6].

1.2.1 Properties of Nimonic C-263

- High mechanical strength at elevated temperature,
- Excellent tensile ductility, formability and weldability,
- High heat resistant,
- High resistance to thermal fatigue and creep,
- High resistance to oxidation and corrosion at elevated temperature,
- Good resistance to strain age cracking,
- Low thermal conductivity,
- Hot hardness,
- High work hardening tendency.

1.2.2 Engineering application of Nimonic C-263

- Hot section of gas turbine,
- Heat exchanger,
- Aerospace component,
- Ultra supercritical power plant,
- Submarine and chemical industries,
- Food processing equipment,
- Petrochemical plant,
- Exhaust value in reciprocating internal combustion engine,
- Compounding of industrial furnace.

1.2.3 Machinability of Nimonic C-263

The machinability of Nimonic C-263 is very less due to severe problem like high shear strength, presence of hard carbides particles, low thermal conductivity, high strain hardening effect, high hot hardness, chemical affinity towards tool material and formation of different phase at elevated temperature. Material poses greater challenge during machining compare to other grade of nickel based super alloy. The main problem during machining of this material is as follows [1,2,9,10,11]:

- Lots of heat and stresses generated during machining due to high mechanical strength and low thermal conductivity hampers machined surfaces and reduces tool life by inducing tool wear,
- High Strain hardening tendency of material deteriorates the quality of machined surface and reduces the tool life,
- Presence of hard metallic carbide particle like $Cr_{23}C_6$ in the microstructure of the material creates abrasive wear due to which tool life hampers,
- Formation of built-up-edges (BUE) and burrs hampers the tool life and surface integrity,
- Material shows high chemical affinity towards tool material thus induces high BUE formation,
- Problem of long continuous chip generation,
- High cutting force required which induces vibration.

1.3 Cutting tool

The selection of good cutting material is utmost important for achieving high productivity with good surface quality during hard machining of super alloy. The properties of work piece material such as high temperature strength, hot hardness, presence of high carbide particle, chemical affinity towards tool material creates lots of problem during machining. Cutting tool should possess following properties for machining these material:

- High wear resistance
- High hot hardness,
- Toughness,
- high chemical stability or inertness ,

- high thermal shock resistance,
- High thermal conductivity,
- High stiffness.

The high cutting temperature generated during machining softens the work piece as well as tool material thus reduces the strength and hardness resulting high tool wear. Cutting tool should retain their strength and be chemically stable at elevated temperature for achieving the benefit of work piece material softening. Coated carbide tool are widely used for machining super alloy. Different coating material and coating techniques have been used for increasing the property and life of carbide tool by protecting it from adverse condition such as high temperature and pressure. Normally used coating materials are shown in Fig.2 [1].

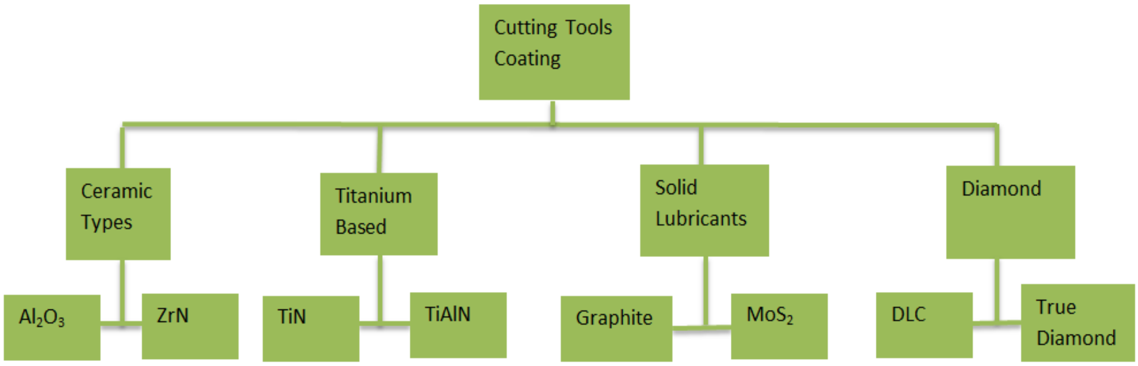


Fig.2 Classification of cutting tools coatings material with example.

Coated tool is used for improving productivity and quality of machined surface due to its higher resistance to wear and breakage, good antifriction properties. Coating layer deposited by PVD technique consists of very fine nano grain size particle and compressive residual stress. Coating layer thickness in this technique is less around 3-4μm and it is very suitable for intermittent cutting such as milling where chances of fatigue fracture of tool is very high.

1.4 Cutting fluid

Cutting fluid is also known as lubricant and coolants. It is widely used in machining process for increasing the surface integrity by reducing the cutting temperature and pressure. It lubricates all the contact region of tool, chip and workpiece resulting friction between mating surface reduces. There are lots of advantages of using cutting fluid as lubricant and coolant during machining [1,2]:

- Improve productivity and surface quality,
- Improve tool life and surface quality by reducing friction and wear between mating surface,
- Reduce the temperature of cutting zone thus avoid the detrimental effect of high temperature generation,
- Reduction in BUE formation by avoiding adhesion wear,
- Power consumption for doing the machining operation is reduced,
- Prevention of corrosion on machining,
- Wash away the chips from the cutting zone and preventing surface from corroding,
- Increases tool life by preventing adhesion, abrasion and diffusion wear and avoiding thermal softening of tool material.

There are lots of adverse effects of cutting fluid due to which trends move towards dry or near dry machining. Problems associated with the use of cutting fluid are as follows:

- Cost of cutting fluid is high around 20 to 30% of total manufacturing cost.
- Requirement of special care before disposal of waste
- Require regular maintenance for achieving optimum characteristics
- Hazardous to the environment
- Create breathing problem and skin cancer to operator.

Cutting fluids significantly influence the surface integrity thus selection of proper cutting fluid for different machining condition is very important. Cutting fluids having high lubrication capacity are mainly used in low speed machining of difficult-to-cut materials which reduces forces required for machining. However, Cutting fluids with less lubrication capacity give good result in high speed machining due to good capacity of heat removal from cutting zone. Cutting fluid classified on the basis of their miscibility in water as follow:

- Water miscible cutting fluid,
- Neat-oil cutting fluids,
- Gas-based coolant-lubricants.

There are lots of methods of cutting fluid application:

- Flood cooling (conventional cooling),
- Mist cooling (MQL),

➢ High-pressure cooling,
➢ Cryogenic cooling.

1.5 Environmentally conscious machining

The cutting fluid becomes major problem during machining due to previously mentioned disadvantage. By seeing these entire problems with cutting fluid and strict government rule towards environmental issue, industries move towards dry machining. Dry machining creates problem at high cutting condition due to excessive tool wear which deteriorates surface quality. A new technique known as minimum quantity lubrication (MQL) has been used for penetrating the cutting fluid with high flow rate into the machining zone. Although fluid quantity reduces by using it in the mist or droplet form and at high speed, there are the chances of health hazard to the operator. Cryogenic cooling is used as good alternative for avoiding these problems. Cutting zone temperature reduces with the use of liquefied gas such as liquid nitrogen and liquid helium which does not creates pollution.

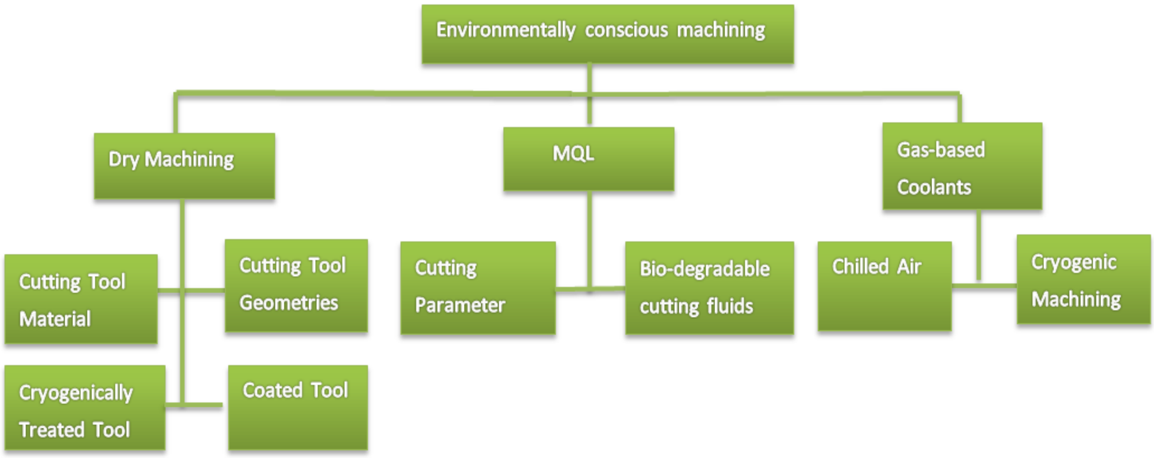


Figure.3: Schematic representation of different environmentally conscious machining techniques [1].

1.6 Surface integrity

Surface integrity is the term which describes all the feature of surface produced by the manufacturing process. Surface integrity affects not only the geometric features of surface, but also their mechanical, chemical, metallurgical and thermal characteristic as well such as fatigue life and corrosion resistance. Topographical, mechanical, metallurgical, chemical and thermal changes happen in the surface and sub-surface layer of material during machining which influences the functional performance of component by effecting tribiological characteristics such as friction, wear and lubrication. The machined surface properties during intended application are highly influenced by surface integrity. Surface integrity covers the entire element which describes the condition of machined surface layer exist at or on the top and in cross-section of round bar both in cutting speed and feed direction of machining. Several layers exist in the machined surface such as layer of contaminant on the outermost surface followed by oxide layer and plastically deformed or hardened layer and the last one is bulk material as shown in Fig.(4). Surface integrity largely affected by temperature and pressure generated during machining process. The built-up edge formation during machining has the greatest effects on surface finish. Surface integrity aspects can be categorized as follows: Surface Topography Sub-surface metallurgy.

1.6.1 Surface Topography

Surface topography covers the condition of machined surface which is in directly contact with or interfaces environment such as surface roughness, lay, waviness and surface damages. Surface roughness and surface damages are considered as the important aspects which highly affect the component performance during intended application by influencing wear resistance, fatigue life and other reliable function. These two aspects of surface topography are explained in detail as follows:

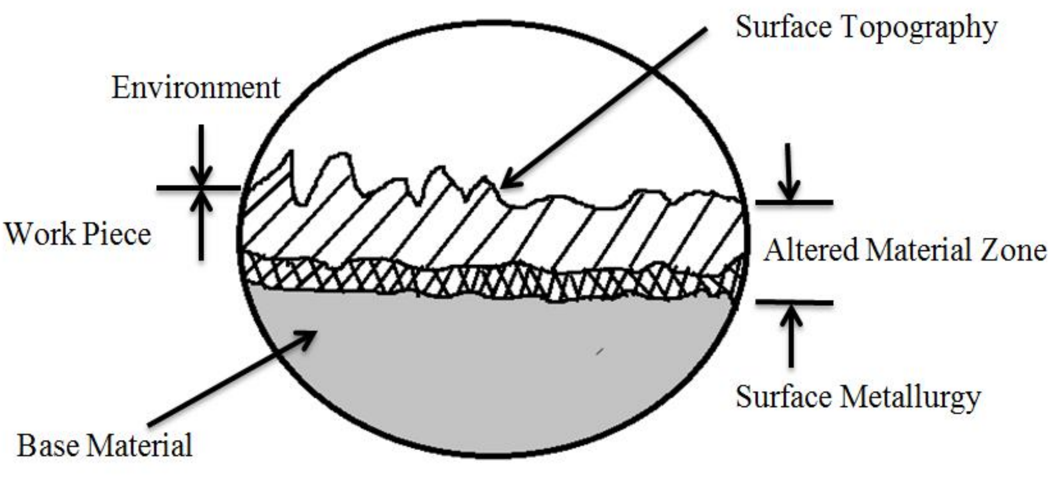


Fig.4. Schematic representation of alteration in the machined surface [3].

(a) Surface roughness

It is measured as deviation of normal vector on surface from its original form. These deviations tell whether surface is rough or fine. High magnitude of deviations indicates surface is rough and less magnitude indicates surface is smooth. It is necessary to know the amplitude and frequency of deviation for ensuring that surface is fit or not. Smooth surface shows less friction and wear compare to rougher one. The inherent surface roughness of turned component is highly dependent on cutting parameter, cutting environment and tool geometry of the cutting tool. High feed rate, BUE formation increases surface roughness while increase in cutting speed decreases surface roughness. Use of cutting fluid reduces adhesion between tool and workpiece resulting less formation of BUE and surface finish increases. Coated tool increases surface roughness compare to uncoated one due to high cutting edge radius. The most common method of measuring surface roughness is centre line average method.The roughness measurement can be done by using straight edge, surface gauge, optical flat, tool marker’s microscope, profilometer, profilograph and talysurf [3]. The presence of micro and macro irregularities on the surface can also be detected by measuring surface roughness.

(b) Surface damages

High stresses and temperatures generated during machining create lots of surface damages in the workpiece. These defects are usually influenced with the metal properties, processing technique and parameter used. Common surface damages observed during machining of superalloy are micro and macro cracks, burrs, adhered chip particle, surface tearing, groove, smeared material, metal debris, adhered material fragments, cracked carbide particles, surface plucking, smeared material, chatter marks, feed marks, carbide particle ploughing etc. Some of the major surface damages produced during machining is explained as follows:

- **Cavity, cracks or micro voids:** Presence of carbide particle and precipitates in the microstructure are the main cause of cracks formation. Plastic deformation opposed by these particles available in the microstructure resulting in formation of cracks of voids for relaxing with high stresses.
- **Seams or folds or laps:** These surface defects result from overlapping of the material during processing.

- **Grooves**: Grooves formed on the surface due to rubbing or ploughing action of worn tool.
- **Metal debris:** Machining with worn tool at high cutting condition and chip fragmentation are the main cause of metal debris formation.
- **Plucking:** Dragging by worn tool on the workpiece create pile of material thus material plucking takes place.
- **Smeared material:** Smearing happen in tertiary zone of machining due to plastic deformation caused by extrusion between flank and workpiece material with the progression of machining.
- **Redopisted material:** Adhesion of chip segment or break tool material during machining on workpiece surface is known as redopisted material.

1.6.2 Sub-surface metallurgy

Sub-surface metallurgy covers the nature of altered layer beneath the machined surface compared to bulk material.

(a) White layer

White layer formed in many manufacturing processes and the dominant factors of its formation is temperature variation in cutting zone and tool wear due to which phase transformation, microstructural changes and activation of plastic strain happens in the machined adjacent layer. White layer is hard, brittle and consists of tensile residual stress. It is detrimental to the component performance and reduces fatigue life of component up to high extent (around 50 times). It seems white under microscope and featureless in SEM. White layer formation occurs in many manufacturing processes like grinding, hard turning, reaming, drilling, milling, blanking, and electrical discharge machining [2,12,13,14]. The primary heat source for WL is flank wear rubbing. The two key mechanisms of white layer formation termed as mechanical and thermal effect on surface during hard machining are explained as follows:

- High phase transformation resulting from rapid thermal variation in cutting zone,
- Refinement of grain due to high severe plastic deformation.

White layer formed during hard machining is varying in nature and it shows less adhesion to the substrate material and normally flaked off from it. White layer resists etching and its grain boundary does not visible in the microstructure because small grains do not scatter light. It has nanocrystalline structure due to high grain refinement associated with dynamic recrystallization and high strain deformation.

(b) **Work Hardening**

Work hardening is the strengthening of machined layer due to high plastic deformation. Grain size of material influences work hardening such as material with small grain size work hardened rapidly compared to material with large grain size. Work hardening occurs in the ductile material. Work hardening reduces the ductility thus chances of brittle failure increases. The mechanism behind high plastic deformation as follows:

1. Presence of dislocation in the material increases the shear stress of material required for machining by interfering and entangling with each other. Increase in dislocation density increases work hardening.

2. Impeding of dislocation movement by grain boundary or impurities such as metallic inclusion increase the cutting forces required for machining thus high plastic deformation generated.

Pile up of dislocation density takes place just underneath the machined surface due to high plastic deformation thus work hardening occur in the machined surface region. Below the machined surface, neutralization of heat and strain took place which reduces the hardening effect. Both elastic and plastic deformation involved during chip formation. One layer has been removed from the material in the forms of chip and the remaining layer of the material being hardened by the severe plastic deformation. The degree and depth to which the machined surface is hardened depend upon many factors such as geometry of the cutting edge, the degree of tool wear, cutting environment, and the properties of workpiece material. Thermal softening effect at high cutting condition has been observed near the machined surface due to high temperature which soften the material. In these conditions micro hardness value goes below the bulk material hardness in the vicinity of machined surface and it start increasing as we moved towards the center of workpiece. The term micro hardness is generally applied where measurement of hardness is done with low applied load around 200gf. Micro hardness testing method is used for measuring the material's hardness in a very small region. In this technique, indentations of around 50μm are made by using a diamond indenter. The most commonly used method for measurement of micro hardness are Vickers and knoop hardness test.

(c) Residual Stress

Some latent stresses remains within the workpiece after the machining due to non-uniform plastic deformation and phase transformations. These stresses are known as residual stress. It may be tensile or compressive depending upon the deformation either it is mechanical induced deformation or thermal induced deformation. High strain deformations induced by mechanical or thermal load generate residual stress because mechanical and thermal stresses generated during hard machining due to high plastic deformation and lots of variation in temperature does not relieve from machined surface and persists even after machining. Generation of compressive residual stresses in the machined surface is the consequences of plastic deformation influenced by mechanical load and of tensile stresses is the consequences of plastic deformation influenced by thermal load. Depending upon the nature of residual stress it can be concluded that whether it is detrimental to the performance of the component. Compressive stresses which are opposite to the applied load are beneficial in increasing the fatigue life and resistance to stress corrosion cracking and crack propagation while tensile residual stresses reduces the fatigue life and are detrimental to the product life. Additional plastic deformation can occur as a consequence of local heating of the machined surface area if the temperature dependent yield strength of the material is exceeded. XRD-texture measurement is used for measuring residual stress.

(d) Phase transformation and grain refinement

Material stress-rupture properties is highly influenced by microstructural features such as grain size, distribution, size and volume fraction of γ' phase in the γ matrix and distribution grain boundary precipitates such as carbide. Ordered distribution of γ' in the γ matrix provides high strength and stability at elevated temperature. Coarse γ' particles are in the shape of cuboidal whereas fine γ' particles are seen in the shape of spherical. Titanium and aluminium used to generate γ' phase during heat treatment process [6,7,8]. Other phase γ'' generated at elevated temperature during machining which is the result of coarsening and nucleation of γ' phase. XRD analysis is used finding any metallurgical transformation in the machined surface such as phase transformation and variation in grain size. Any change in phase and crystal structure can be identified with variation in position of peak and any change in grain size is identified with variation in intensity and width of peak.

CHAPTER 2

LITERATURE REVIEW

2.1 Influence of machining condition on white layer and sub-surface deformation

Three or four distinct zones have been observed with decreasing trend of intensity of deformation from machined surface to bulk material during microstructural examination of machined surface and sub-surface region [2,12,14,15,16,19]. The first zone is heat affected or white layer zone. It was characterized by nanocrystalline grain structure which is the effect of both high mechanical and thermal deformation. The possible mechanisms of white layer formation was found to be phase transformation due to rapid variation in temperature during machining and grain refinement due to high plastic deformation. The main reason behind the formation of severe plastic deformation in the subsurface layer was found to be the deformations and slip in grain boundaries, and elongation of grains. TEM and AFM analysis of the white layer divulged that white layer composed of uniformly and continuously distributed nano crystalline grains [14]. Presence of severely deformed layer with equiaxed ultra-fine nano sized grained microstructure was observed in this zone. Highly deformed sub grain boundary in random orientation dispersed over the grains in the region beneath the surface due to large deformation. The machining affected grains also were found to be aligned and bend towards the cutting speed direction. Highly strained grains with undefined grain boundaries consists of plastic slip band were found in the second zone. This morphology varied as the depth increases. In the slight deformation zone, the presence of only some slip bands was observed. The declination of intensity of the plastic deformation took place from the surface to the bulk material. This was attributed to decrement of mechanical and thermal load towards the bulk region from the machined surface [15,19]. Severe plastic deformed layer was visible in the very near surface up to 100µm, third a zone of less deformed grains than previous but with defined grain boundaries and at last was the bulk material [16]. Different zone such as white light zone, dark gray zone and gray zone observe in the subsurface region. In the cross section of machined surface grain refinement and presence of crack was seen [18]. Deformed zones are intrinsic for all process conditions whereas their intensity and thickness increases with tool wear, feed and lessen with cutting speed [2,12,13,18,20]. The depth of white layer and its hardness decreased at higher cutting velocity due to the fact that at higher velocity much of the heat is taken by the chip rather than the surface it is as evident from the increase of temperature of chip along with slight reduction in temperature of machined surface. Another primary reason for the decrease of white layer depth is due to decrease in the plastic deformation at high cutting speed and thus reduction in the cutting forces [12,18]. With increase in feed rate and cutting speed the strain rate in cutting region increased which resulted in higher plastic deformation and thickness of white layer. The increase of feed rate had more influence on the deformed layer thickness [20].With a new tool small plastic deformation generated in the subsurface which is the result of low cutting force and temperature. Apart from the cutting parameters the tool wear had a great significant effect on the change of subsurface deformation depth and the microstructure alterations. White layer and plastic deformation increases with increase in tool wear due to high tool/workpiece contact area and reduction in clearance angle of the tool which increases the cutting force and temperature [2,12,14,15,19]. Multilayer CVD coated tool reduced the thickness of deformed layer over its uncoated counterpart due to less severity in shear deformation and good anti-friction properties at low and medium cutting speed [13].

2.2 Influence of machining condition on surface morphology

During machining at high cutting speed the machined top surface showed the formation of surface defects like surface plucking, material smearing, surface cracking, tears, laps,debris and re-deposited materials. This was explained by the occurrence of high cutting temperature, high plastic deformation and tool wear. Due to presence of lower thermal conductivity of Al_2O_3 coating, coated tool could not improve machined surface morphology in better way. Presence of material re-deposition and debris was found during machining at high speed with coated tool. The surface machined with coated tool showed good micro-morphology with less plastic flow compared to uncoated tool. [15,21]. The effects of edge preparation of coated carbide cutting insets on surface defects was observed during machining of age hardened Inconel 718. Surface damages in the form of flash, grooves, smeared material, streak and metal debris were observed on surface machined by sharp cutting edge tool due to dominance of thermal effect. Good surface with only some light feed marks were found in case of honed and the chamfered cutting edges due to less temperature generation in the cutting zone [28]. Surface machined with coated carbide tools showed no significant tearing due to good antifriction properties and less adhesion of material on tool surface. High plastic deformation was observed during prolonged machining. This was attributed to combined effect of high pressure and temperature generated between tool and workpiece during long period machining [30]. Adherence of some protuberances resulted from surface plucking, deformation of grain, cavity, slip line were found on machined surface induced from higher plastic deformation and presence of carbide particle. High surface plucking was observed when surface turned at low cutting speed of 60m/min and high feed of 0.25mm/rev compare to high cutting speed of 100m/min and low feed of 0.15mm/rev. Very less surface plucking with only some scratch and reduced slip zones in terms of intensity and depth was observed at high cutting speed of 100m/min and low feed due to reduction in cutting force and plastic deformation at this condition. With more increase in cutting speed of 140m/min surface plucking increased due to high temperature generation. Mechanism of crack formation during machining was attributed to presence of carbide particle which when removed from the material left some residual crack behind it. Enlarging of these cracks was associated with rise in shear stresses which promotes plucking of [26]. Surface defects such as feed marks, smeared surface, and adhered chip particles at high feed rate and low cutting speed were found in the surface. These surface defects at a lower cutting speed are generally attributed to adhesion of chip on the tool surface which can randomly start plucking and scratching the machined surface due to high pressure between tool chip interfaces. Increasing in cutting speed results in the high temperature in the machining zone which reduces the cutting force and thus generation of good surfaces [32].

2.3 Influence of machining condition on surface roughness

Study of different aspects of surface integrity has been done during turning with PVD coated tool in MQL 50ml/hour and MQL 100ml/hour environment. Higher surface roughness value observed at cutting speed of 90m/min compare to cutting speed of 150m/min. At lower and medium cutting speed (90 and 100m/min) MQL 50ml/hour showed lower surface roughness but at high cutting speed the MQL 100ml/hour showed lower surface roughness. This was attributed to high penetration of cutting fluid and improved lubrication effect between tool chip interfaces which reduces the forces and temperature thus induces lower surface roughness compare to dry and MQL 50ml/hour environment [34]. Less surface roughness variation achieved with coated carbide and PCBN tools when new tools were employed. Worn coated carbide produced more surface roughness compared to worn PCBN. This was attributed to less notch wear of secondary cutting edge of PCBN inserts even in the presence of severe flank wear at high cutting speed. Notching of secondary cutting edge was substantial for coated carbide inserts thus poor surface generated [31]. The multilayer CVD coated tool produced higher machined surface roughness due to the rounding of cutting edge as compared to its uncoated counterpart. Surface deteriorates gradually due to frictional rubbing of tool on machined surface and BUE formation [15]. The machined surface roughness decreased with increase of the cutting speed due to reduction in plastic deformation, built up edge (BUE) and burr formation. Better surface roughness was achieved at high cutting speed range of 400-600m/min during facing operation [23]. Surface roughness increased with increase in cutting time and decrease in cutting speed during machining of Nimonic C-263 with whisker-reinforced ceramic insert. Increase in feed rate increased surface roughness. Significant variation has been shown at feed rate of 0.051mm/rev due to the fact that high resistance of material to plastic deformation produce built-up-edge on surface [33]. The influence of insert shape, rake type, nose radius, cutting edge preparation and coolant were examined on surface roughness during machining of age hardenable Inconel 718. Round inserts produced a lower surface finish since due to large contact length of the tool is compared to a square insert for both dry and wet machining. Sharp or chamfered cutting edges produced a better surface finish when compared with honed cutting edges due to excessive chipping of the sharp cutting edge at entry and while cutting. Further it was conclude that square shape carbide insert with positive rake angle, having honed cutting edge and high nose radius produces good surface finish when facing Inconel 718 with coolant [28]. Good surface finish has been achieved with ceramic inserts compared to CBN. The cutting feed rate was found most influential input parameter on the surface roughness compared to speed and depth of cut. This was attributed to more influence of feed rate and depth of cut on flank wear compared to cutting speed. The optimal input parameter combination for minimizing surface roughness was high cutting speed (210 m/min), feed rate (0.05mm/rev), and depth of cut (0.75mm) [35]. Optimization of cutting parameters in the machining of Nimonic C-263 alloy was done by using Taguchi's method. Optimization result done by using Taguchi's method on cutting parameter showed more predominant influence of feed rate followed by cutting speed and depth of cut on surface roughness. Combination of cutting speed (54 m/min), feed rate (0.051

mm/rev) and depth of cut (1.00 mm) was found optimum setting for obtaining good surface finish. Increase in cutting speed and depth of cut decreased surface roughness, whereas increase in feed rate increased surface roughness. This was attributed to the fact that the rubbing action took place between the work piece and the cutting tool due to friction at high feed rate and low cutting speed [36]. The influence of feed rate on surface roughness has dominant effect compared to other parameter. Surface roughness increases with increase of feed rate and decrease with increase of cutting speed and depth of cut [37].

2.4 Influence of machining condition on work hardening

Gradual decrement of micro hardness from the machined surface to the centre took place due to pile of dislocation density near the machined surface which is the result of high plastic deformation during machining of difficult to cut material [2,18]. Micro hardness decreased with increases of speed from 51 to 84 m/min and it increased when speed increased from 84 to 124 m/min at surface machined with coated tool. The multilayer CVD coated tool reduced the work hardening at high cutting speed due to its good tribiological properties. Coated tool could not help in reducing work hardening tendency at low cutting speed due to its low performance at this condition. Thermal softening was observed on the surface machined with uncoated tool at high cutting speed. This was attributed to the generation of high temperature associated with high cutting speed and tool wear [18]. The machined surface hardness was found more than that of bulk material. The ratio of micro hardness value HV0.05max/HV0.0 increased with increase of both feed rate and cutting speed. Material reached a higher surface hardness and a deeper hardness variation at higher cutting speed and feed rate [22]. The effects of cutting edge preparation and geometric modifications on work hardening tendency of INCONEL 718TM during turning at high cutting speeds were studied. Microhardness values were slightly lower at the depth around 125μm for all cutting speed. Microhardness values at the top surface were slightly higher than that of bulk material. This was attributed to formation of stressed layer resulted from strain hardening of the material during machining. Increase in the cutting speed lower down the micro hardness due to less contact time [27]. The effects of coated and uncoated WC tools were studied on the tendency of work hardening during turning of Inconel 718 at various cutting conditions by using Knoop indenter. The worn tools produced harder surfaces (maximum 500HK0.05) with a high depth penetration around 200µm compare to new tool due to rapid heating and cooling and high mechanical deformation of workpiece. The large difference in microhardness was found during machining with worn tool at different cutting speed. The thermal softening effect was also observed during machining with worn tool. The noticeable difference in microhardness was not found during machining with multilayer coated WC (TiCN/Al_2O_3/TiN) at different cutting speed. This can be probably due to difference in the co-efficient of friction in both types of tools. The complex chip breaker geometry present at the multilayer coated tools induced high chip curling generating which induces high degree of work hardening [28]. Effect of machining parameters and cutting edge geometry on work hardening of machined surface was done. Chamfered plus honed cutting edge geometry induced the highest depth of work hardening in the machined sub-surface compare to other two cutting edges. This was attributed to additional ploughing along the honed. The high level of work hardening was found at high cutting speed, feed and depth of cut but least extent of work hardening was found at medium cutting speed [29]. [E.O. EZUGWU et.al] studied the effect of different coated tool such as multi-layer CVD (TiC/Al_2O_3/TiN), single layer PVD (TiN) and multi-layer PVD on different surface integrity aspects during machining of Inconel 718. Surface machined with sharp edged multilayer PVD coated carbide inserts showed higher hardness compare to other two tools. This was attributed to smaller contact area, high temperature generation and high compressive stress between tool and workpiece due to sharp edge of cutting tool. Prolong machining also increased the surface hardness due to increase in tool wear which increases temperature and pressure thus increases the depth and intensity of plastic deformation [30]. Low cutting speed (60m/min) and high feed (0.25mm/rev) generated high deformed layer up to 90-100µm below the machined surface compared to other combination of cutting speed and feed. Nano micro-hardness of the machined surface was always more than that of the bulk material. At cutting speed (100m/min) and feed (0.15mm/rev) low deformed layer up to 40-50µm was found due to low cutting force [21]. The micro hardness measurement on the machined surface after machining with PVD coated tool under MQL and dry environment. Surface machined under dry condition showed higher hardness value thus indicate high work hardening tendency due to severe microstructural alteration compared to MQL environment [34]. The micro hardness value tends to increase with both feed rate and cutting speed [33].

2.5 Influence of machining parameters on grain size and phase transformation

The occurrence of grain refinement or dynamic recrystallization was not found at low cutting speed. With increase in speed nucleation sites or grain refinement increases on machined surface and at high cutting speed more grain refinement was seen as a result of dynamic recrystallization. The grain growth observed with uncoated tool was more compare to coated tool due to generation of high cutting temperature resulting from combined effect of severe plastic deformation as well as tool wear [15]. Different phases such as $(Ni, Co)_3(Ti, Al)$ generated in the machined surface due to generation of high temperature. Grain refinement take place in the machined zone and nanocrystalline structure with severe plastic deformation has seen in the surface. White layer shows poor crystallinity, more hardness and brittleness due to occurrence of grain refinement. Xrd analysis of white layer showed presence of ceramic γ-alumina phase at high cutting speed. Presence of thermal resistant alumina phase encouraged intensive cratering on the rake surface of the cutting tool [18]. Grain size variation from machined surface towards the center of workpiece was observed and depth of affected zone increased with increase of both cutting speed and feed rate. The influence of cutting speed was more predominant when feed rate above 0.075 is used. At higher cutting speeds and feed, grain refinements in the machined surface were observed [22]. Analysis of phase change and grain refinement during the formation of white layer on machined FGH95 superalloy was done by using XRD technique. The result showed that white layer has poor crystallinity and significantly different microstructures than bulk material. At higher cutting speed, the more serious grain refinements were observed. This was attributed to the generation of more dislocations within the material at high speed [42]. Severities of the deformation zone more predominantly depend upon the tool wear rather the cutting speed. Cutting speed showed only marginal effect. High strain was observed with worn out tool rather new one. The SC maps showed high strain near the machined surface with decreasing trends towards the bulk [21]. The increased in the hardness of the white layer than the bulk material is due reduction in the grain size in the layer [26].

2.6 Influence of machining parameters on residual stress

The tensile residual stress at the surface is comparable for both types of inserts when in new condition but it tend to increase with progress of tool wear, the PCBN tool insert showing larger percentage increment [21]. Residual stresses generated in the machined surface were all of compressive nature but modified honed edge tool resulted in higher compressive stress than others [27]. The influence of insert shape, rake type, nose radius, cutting edge preparation and coolant were examined on residual stress during machining of age hardenable Inconel 718. Positive rake inserts generated a tensile residual stress whereas the negative rake type produced compressive residual stresses due to higher degree of plastic deformation of surface machined by negative rake inserts. The stresses in the machined zone shift from compressive to tensile with the increase of cutting duration due to the high heat production. Sharp cutting edge generated high tensile residual stresses in the machined surface compare to honed cutting edge, while chamfered cutting edge produced compressive residual stresses on. Machining under wet environment with round inserts generated compressive residual stresses while square inserts produced surface consists of tensile residual stresses. Further it was conclude that round shape carbide insert with negative rake angle, having chamfered cutting edge and small nose radius produces compressive stress when facing Inconel 718 with coolant. Coolant reduced cutting zone temperature thus induces compressive stresses or lower magnitude of tensile residual stresses [35]. Increase in cutting speed reduced tensile residual stress and increase in feed increased tensile residual stress. Machining with multilayer coated insert induced higher tensile residual stress in the machined surface compared to uncoated inserts due to presence of thermal barrier Al_2O_3 layer in multicoated insert which increases cutting zone temperature [39]. Slight increment in tensile residual stress was observed with increase of speed from 125 to 300 m/min. At higher cutting speed of 475 m/min, compressive residual stress found in the machined surface. At lower feed rate tensile residual stress was observed in the surface but at high feed decrement in tensile residual stress was seen. Increase in depth of cut increased compressive residual stress [39]. High tensile residual stress on the machined surface observed during machining with uncoated tool. Compressive residual stress found below the machined surface after 10-20 µm distances. The thickness of tensile residual stress in the sub-surface region increased with the use of coated tool [43]. Peak tensile stress reduced with increase of cutting speed due to high chip flow rate which reduces the cutting zone temperature. At low cutting and medium cutting speed coolant reduced tensile residual stress but at high cutting speed there was no variation in dry and wet machining due to less efficiency of cutting fluid in reducing cutting zone temperature [44].

2.7 Motivation

It has been observed from the literature review that there is not much valuable information on surface integrity characteristics of Nimonic C-263 material. Influence of uncoated tool, coated tool such as PVD and CVD coated cemented carbide, whisker reinforced ceramic tool have been studied under different machining condition on different machinability characteristics such as tool wear, cutting temperature, chip morphology, surface roughness, residual stress and tendency of work hardening have been reported so far. The effect of cutting tool and cutting environment on surface integrity have been analysed by many researchers on the nickel based super alloy with particular emphasis on Inconel 718 during machining by using different cutting parameter such type of researches on Nimonic C-263 material has been rarely reported. Moreover, the effects of coolant in MQL and flood mode with uncoated tool and dry machining with PVD coated tool on different surface integrity characteristics such as surface roughness, white layer formation, phase transformation, grain refinement, residual stress and work hardening tendency have not been analysed on Nimonic C-263 at all.

2.8 Objective

The major intention of the present research is comparative study of different surface integrity characteristics i.e. surface roughness, microstructural changes, phase transformation, white layer formation, and work hardening tendency by using PVD multilayer (TiN/TiAlN) coated and uncoated cemented carbide inserts under different machining condition. The impact of cutting parameters such as feed rate on different surface integrity characteristics also studied. The following objectives are included as follow:

- Influence of coolant (MQL and Flood) using uncoated tool over best performing PVD coated tool on the following aspects has been investigated on the machined samples turned at different cutting condition.
    - ➢ Surface roughness
    - ➢ Macro and micro morphology
    - ➢ Formation of white layer
    - ➢ Variation in micro hardness
    - ➢ XRD analysis of machined surface
    - ➢ Residual Stress
- Effect of cutting parameters such as cutting speed and feed rate on the aforementioned aspects using PVD coated tools and uncoated tool (in dry and wet condition) have been investigated.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

In this section, characteristics of work piece material and cutting tool, procedure of preparing the samples for studying the different aspects of surface integrity, details of equipment used experimental set up, cutting parameter and cutting environment has been explained.

3.1 Work piece material

In this experiment, round bar of Nimonic C-263 with dimensions of 60 mm diameter and 180 mm length was used as a specimen. Nimonic C-263 is one of the age-hardenable nickel based super alloy with higher amount of chromium, cobalt and molybdenum in its chemical composition. Chemical composition of Nimonic C-263 is shown in Table 2.

Table 1: Chemical composition of Nimonic C-263

Element	Ni	Cr	Co	Mo	Ti	Fe	Mn	Al
Content	49-53%	19-21%	19-21%	5.6-6.1%	1.9-2.4%	0.7%	0.6%	0.6%

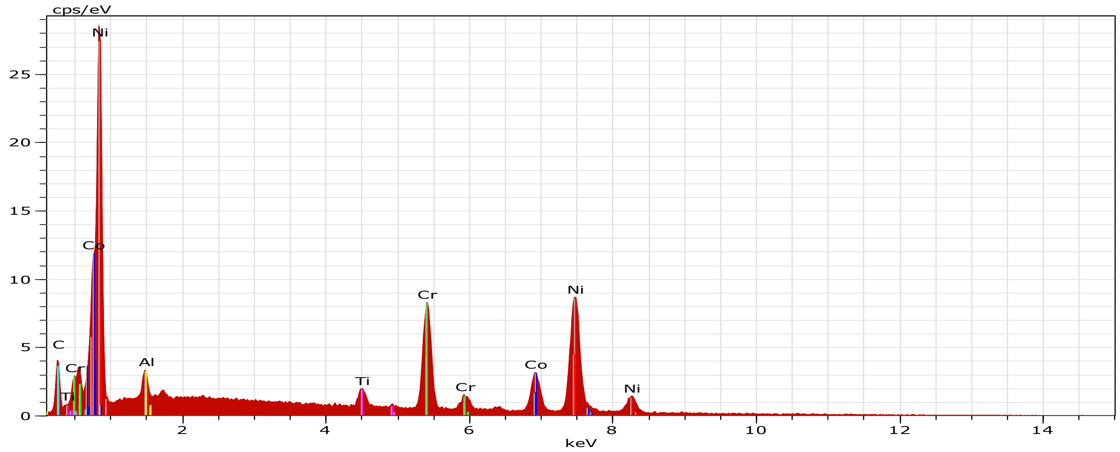


Fig. 5: EDS spectrum of Nimonic C-263.

Table 2: Properties of Nimonic C-263

Material	Nimonic C-263
Thermal conductivity	11.75 W/m.K
Yield strength	350 – 550 MPa
Density	8.36 g/cm^3
Tensile strength	650 – 940 MPa
Young's modulus	200 – 2000 GPa
Melting temperature	1450-1510°C
Poison ratio	0.3

3.2 Cutting tool

PVD multilayer coated tool consists different phase over the substrate material. Inserts used in the experiment made by SECO, India and tool holder made by WIDIA, India. PVD multilayer (TiN/TiAlN) coated and uncoated cemented carbide inserts with ISO insert designation of SNMG 120408 were used during the experiment. The each inserts were clamped in a standard holder with ISO designation PSBNR2020K12. The characteristics of different phase used in coating is shown in Table 3.

Table 3: Characteristics of different phase present on PVD multilayer coated tool.

Phase	**Characteristics**
TiN	Lower chip tool interface friction
TiAlN	Higher hot hardness and resistance to oxidation

3.3 Machining operation

The turning of Nimonic C-263 was carried by using heavy duty center lathe (Model: NH26) made by Hindustan Machine Tools (HMT) Ltd., Bangalore, India with the progression of time. The center lathe machine was equipped with flood and MQL cooling setup. PVD multilayer coating (TiAlN/TiN) used for machining in dry environment. The cutting environment and cutting tool combination used during machining operation was dry with multilayer PVD coated tool, and MQL and flood with uncoated tool. MQL setup used mixture of coolant and highly compressed air (6bar). High pressure air from compressor went through air filter which purifies the air by removing all the impurities. Oil controls valve guide the flow of coolant in the mixing chamber. Oil and compressed filtered air mixed together and form oil-mist in mixing chamber. Nozzle was used for supplying the oil mist to the cutting zone in proper way. Machining was carried out at cutting speed of 54, 84 and 124m/min, feed rate of 0.1, 0.14 and 0.2mm/rev and constant depth of cut of 1mm. Experiment run for each condition was 150s.

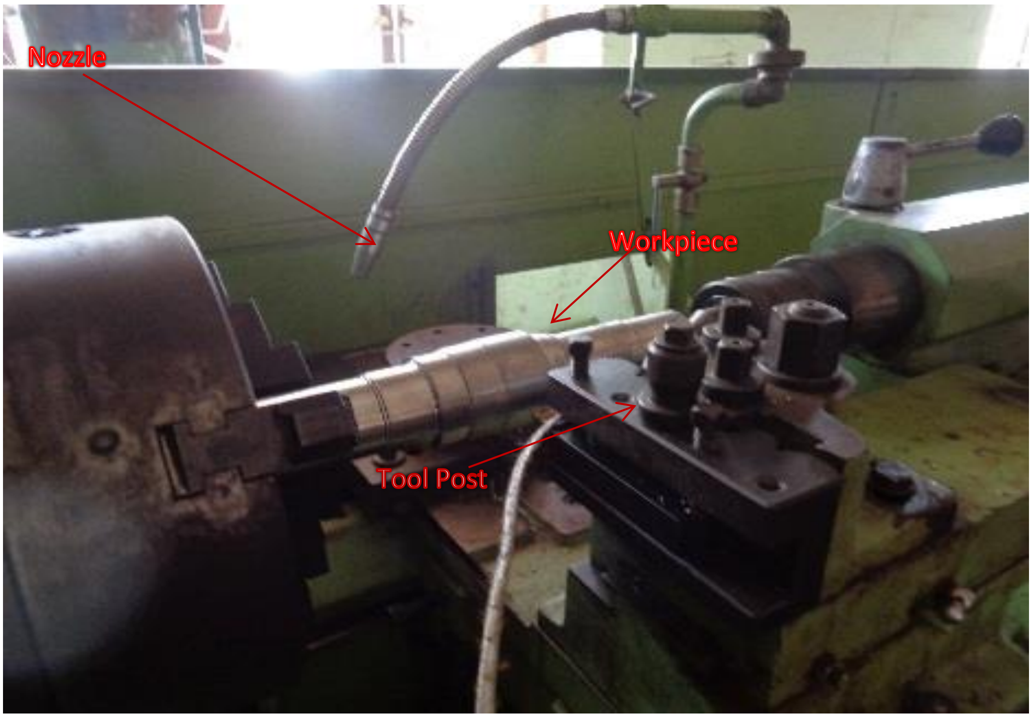


Fig.6: Experimental setup for turning.

3.4 Sample preparation for microstructural examination

Mould was made by using cold setting compound by embedding the samples into epoxy resin for holding the specimen in proper way during microstructural and micro hardness measurement. The cross sectional plane of machined samples was then metallographically prepared by initially grounding with waterproof SiC grinding paper of grit 250, followed by 400, 800 and finishing it with 1000. Mirror like surface finish was obtained by polishing with diamond paste before etching. The polished surfaces were then etched with etchant consists of 2% of diluted (40%) hydrofluoric acid, 8 % hydrogen per oxide, 40% of concentrated hydrochloric acid and 50 % of de-ionised water (by volume).

3.5 Study of surface integrity characteristics

3.5.1 Surface roughness measurement

Measurement of surface roughness has been done by using talysurf (Model: Surtronic 3+) made by Taylor Hobson. For achieving good accuracy in result, surface roughness value calculated at four different locations in the same machining area. R_a, R_t and R_z value has been noted during measurement.

3.5.2 Surface morphology

Samples were cut out from the different place of machined round bar machined at different cutting condition and time duration using wire electro-discharge machining (WEDM) along a plane perpendicular to the rotational axis. Samples were put in Scanning electron microscopy (SEM, model: NOVA NANO SEM-450) for study the surface micro and macro morphology. Images were taken at high and low magnification on different area of samples for explaining the mechanism of forming surface defects.

Fig.7: Scanning electron microscope

3.5.3 XRD analysis and residual stress measurement

Multipurpose X-ray diffraction (XRD) system (model: Ultima-IV) made by Rigaku, Japan is used for identification of different phase and grain refinement in the machined surface. Samples were positioned accordingly into the center of X-ray goniometric for ensuring correct beam irradiation. The aim of XRD analysis is to find the effect of variation in cutting parameter and cutting environment on change in phase, crystal structure and grain size. The 2θ scans on different samples machined at different feed rate were carried out between 30° and 90° diffraction angle. The step size was 0.05. Anode material of this XRD system was copper. High score software is used for analysing the result. Residual stress measurement on the machined surface was done by using XRD-texture measurement (Model: D8 Advance design) made by BRUKER. The value of 2θ during measurement was between 109.3^0-117.0^o and step size was 0.02. Time/step was 1sec. Anode material of this XRD system was cobalt. X'Pert stress software is used for analysing the result.

Fig.8: Set-up for XRD-texture measurement.

3.5.4 Formation of white layer and microstructural alteration

Field emission scanning electron microscopy and FESEM (model: FEI) made by Nova NanoSEM were used for analysing the formation of white layer and microstructural alteration in the sub-surface. White layers seen in the FESEM are varying in nature. The average thickness of white layer was measured by using ImageJ software. By dividing the white layer area with the length of FESEM images, thickness of white layer calculated.

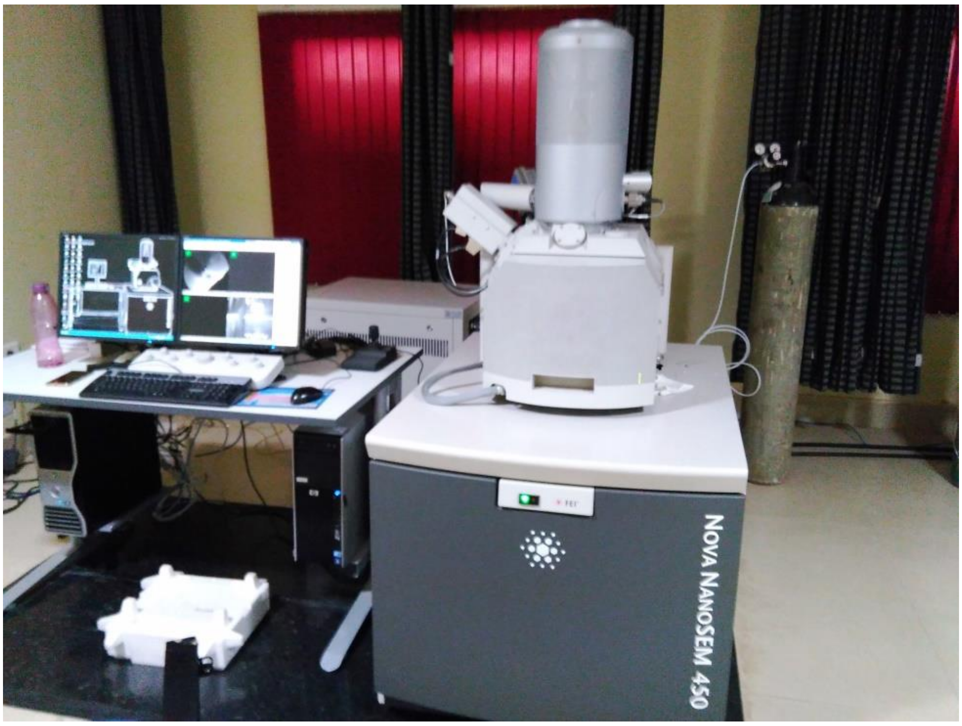


Fig.9: Field emission scanning electron microscope

3.5.5 Micro hardness measurement

Vickers microhardness test method was used for studying the hardness and thickness of work hardened layer formed in the surface and subsurface region. The measurement was done with Vickers hardness tester made by LECO, USA on the cross-section of machined surface. Indentations were done on the shining polished surface for creating good square shape. The indenter moved from the edge point of circumference to the centre along a straight line. Measurement was done at a load of 50 gmf, dwell time of 10s and distance of separation from indentations was 50μm. Optical microscope was used for seeing the exact shape.

Fig.10: Vickers micro hardness tester

Fig. 11: Optical microscope

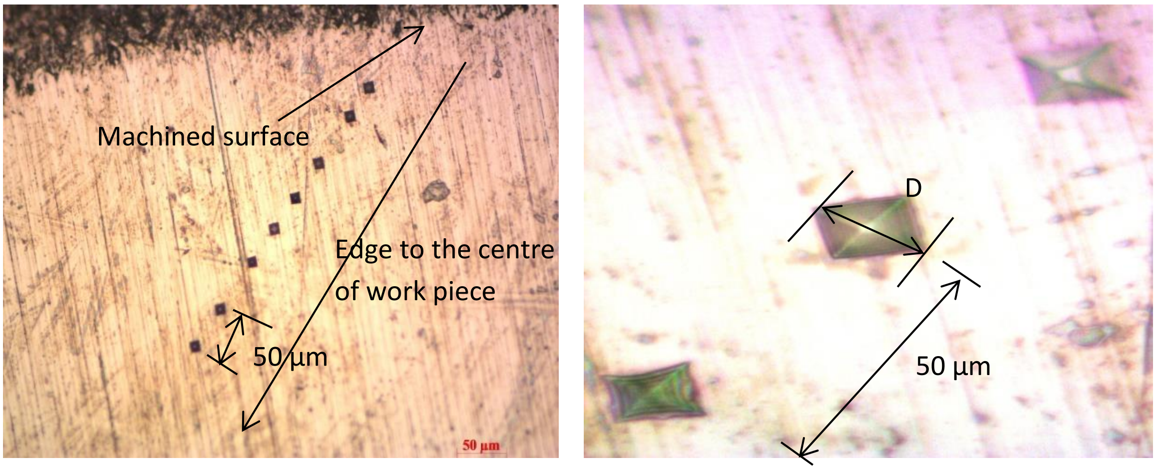


Fig.12: Images of micro indentation on cross-sectional surface of machined work piece.

CHAPTER 4

RESULTS AND DISCUSSION

The present investigation dealt with the influence of cutting parameter and PVD multilayer coating on several aspects of surface integrity such as surface roughness, machined surface morphology, XRD analysis of machined surface, residual stress white layer formation and microhardness during dry and wet turning of Nimonic C-263.

4.1 Surface roughness

Surface roughness is an important parameter which characterizes the surface topography. It is an important aspect of surface integrity of machined component because it has direct relation with tribological properties such as wear, friction and lubricant retention of material. At low cutting condition low surface roughness have been observed at all cutting condition due to good anti friction properties of TiN coating and good lubrication properties of cutting fluid. Surface roughness increases with increase in feed rate and cutting speed. Surface roughness decreases with increase of cutting speed at low feed rate as shown in Fig.13. This is attributed to reduction in cutting force along with vibration due to softening of material at high speed. Built-up edge formation also reduces at high speed which is another reason for reducing surface roughness. There is no such trend at medium and high feed rate due to predominant tool wear phenomena at this condition which increases extrusion and friction between mating surface resulting high burr formation and plastic deformation. Enhanced cutting load and presence of high feed mark are also valid reason for achieving high surface roughness. Surface machined with uncoated tool exhibited higher surface roughness around 4.4 µm due to increase of tool wear and less capacity of heat removal at high cutting condition. PVD coated tool produces high surface roughness at low cutting parameter compare to other uncoated tool due to high edge radius. MQL and flood cutting environment provide proper lubrication between tool-chip and too-work interface which reduces force and detrimental built-up edge formation resulting low surface roughness at low and medium cutting parameter. Flood cooling does not penetrate inside the cutting zone due to formation of vapour blanket and thus induces high surface roughness resulting from high tool wear. MQL gives good result in lowering down surface roughness due to high penetration of liquid in the cutting zone at medium cutting speed which lowers down the frictional rubbing. At high cutting condition lots of heat and pressure generation reduces the efficiency of MQL and flood resulting high tool wear and deterioration of surface finish. Flood coolant gives little bit good result compare to MQL due to high heat removal capacity. PVD coated tool circumvent thermal influences up to some extent due to its good tribiological property such as high hot hardness, high wear resistant etc. thus less surface roughness generated compared to MQL and flood cutting environment with uncoated tool at high cutting condition. This type of result has been shown by previous researches on nickel based super alloy [34].

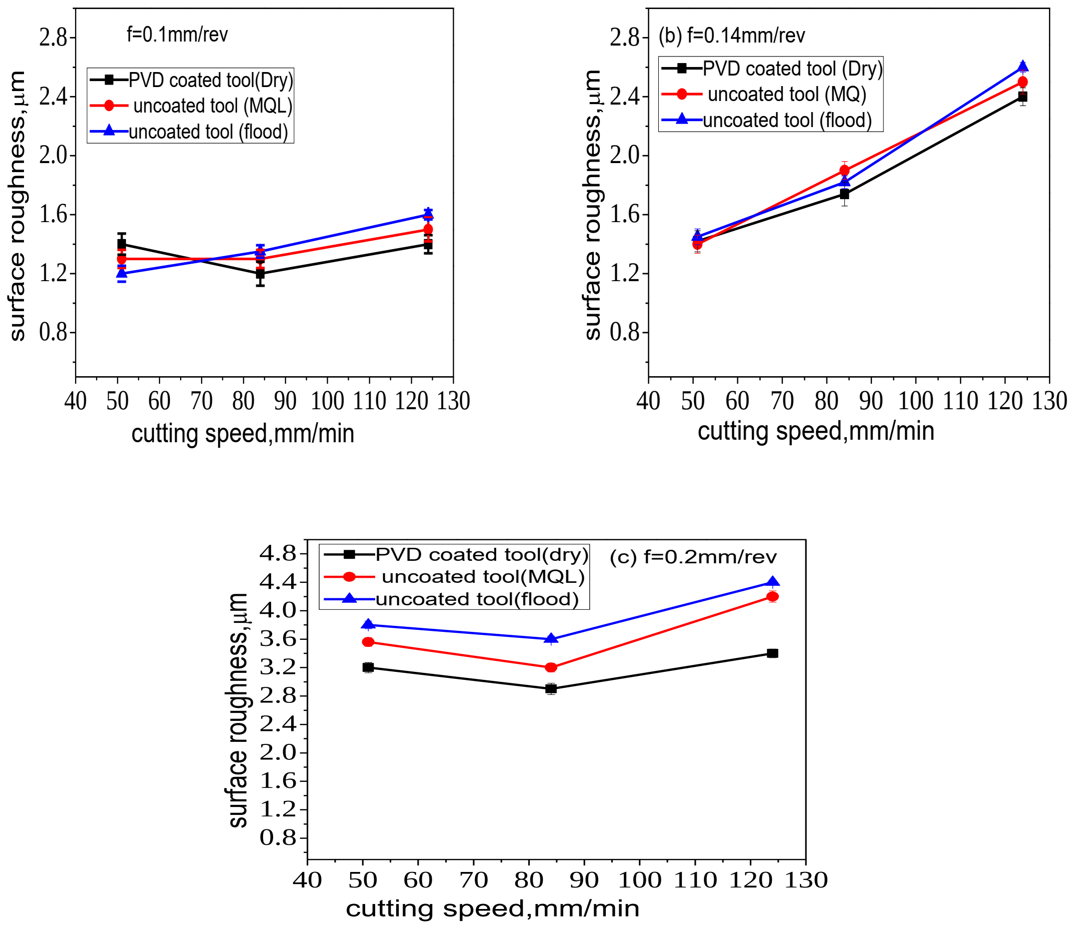
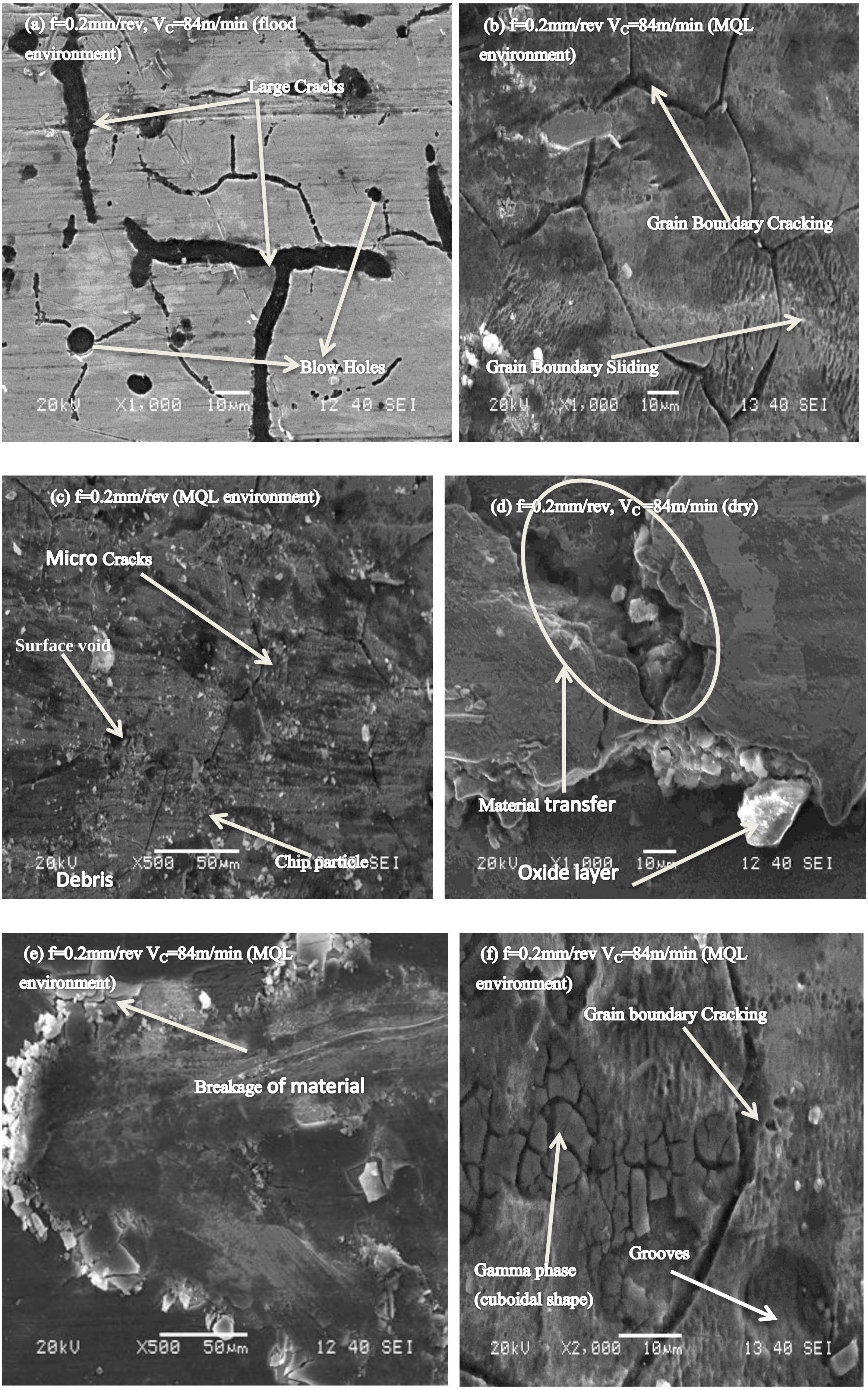


Fig. 13 Variation of surface roughness with cutting speed (a) f=0.1mm/rev (b) f=0.14mm/rev and (c) f=0.2mm/rev.

4.2 Morphology of machined surface

Some visual defects generated during machining have detrimental effect on surface quality. Surface damages like grooves, cavity, material breakage, surface voids, tearing, chip particles, smeared materials, high feed mark, material side flow has been observed during machining at medium cutting speed and high feed rate as shown in Fig.14 (d-f).This is attributed to the dominance of high stresses between tool and work piece, higher plastic deformation and formation of built-up-edge (BUE) due to which more rubbing and vibration take place. Surface damages such as micro cracks, grain boundary sliding, voids, grooves and cavity formation have been observed on surface machined under MQL environment at high feed rate as shown in the Fig.14 (b,c,f). The mechanism behind crack formation is presence of lots of carbide particle in the microstructure. Carbide particle when moved from the workpiece during machining leave some residual crack behind it and enlarging of these cracks associated with application of high shear stress. Creep failure at elevated temperature occurs mainly due to grain boundary sliding [31]. Surface machined with PVD coated tool shows less tearing and grain refinement due to good antifriction property and less adhesion of material on tool surface. Surface damage in the form of flash, long grooves, streak, smeared material and metal debris has been observed on surface machined by sharp cutting edge of coated tool at high speed and feed due to dominance of high thermal effect as shown in Fig.14 (g,h). With increase in cutting speed feed marks, BUE and cutting force reduces due to thermal softening of material resulting from generation of high temperature at cutting zone during dry machining. Fig.14 (d,g,h) depicts material transfer from the surface at high cutting speed and feed in dry machining. This is attributed to high temperature generation due to low thermal conductivity of coated tool. At low cutting speed and low feed very less surface plucking with some scratches and tearing has been observed as shown in Fig.15 . This can be explained by reduction of cutting force and plastic deformation at this condition. Flood machining reduces the surface damages by reducing the cutting force, temperature and adhesion wear at low cutting parameter. High tool wear and less penetration of cutting fluid in cutting zone induces defects in the form of large cracks, blow holes and cavity as shown in Fig.9 (a).


(a) f=0.2mm/rev, V_C=84m/min (flood environment)
Large Cracks
Blow Holes
20kV X1,000 10µm 12 40 SEI
(b) f=0.2mm/rev V_C=84m/min (MQL environment)
Grain Boundary Cracking
Grain Boundary Sliding
20kV X1,000 10µm 13 40 SEI
(c) f=0.2mm/rev (MQL environment)
Micro Cracks
Surface void
Chip particle
Debris
20kV X500 50µm SEI
(d) f=0.2mm/rev, V_C=84m/min (dry)
Material transfer
Oxide layer
20kV X1,000 10µm 12 40 SEI
(e) f=0.2mm/rev V_C=84m/min (MQL environment)
Breakage of material
20kV X500 50µm 12 40 SEI
(f) f=0.2mm/rev V_C=84m/min (MQL environment)
Grain boundary Cracking
Grooves
Gamma phase (cuboidal shape)
20kV X2,000 10µm 13 40 SEI

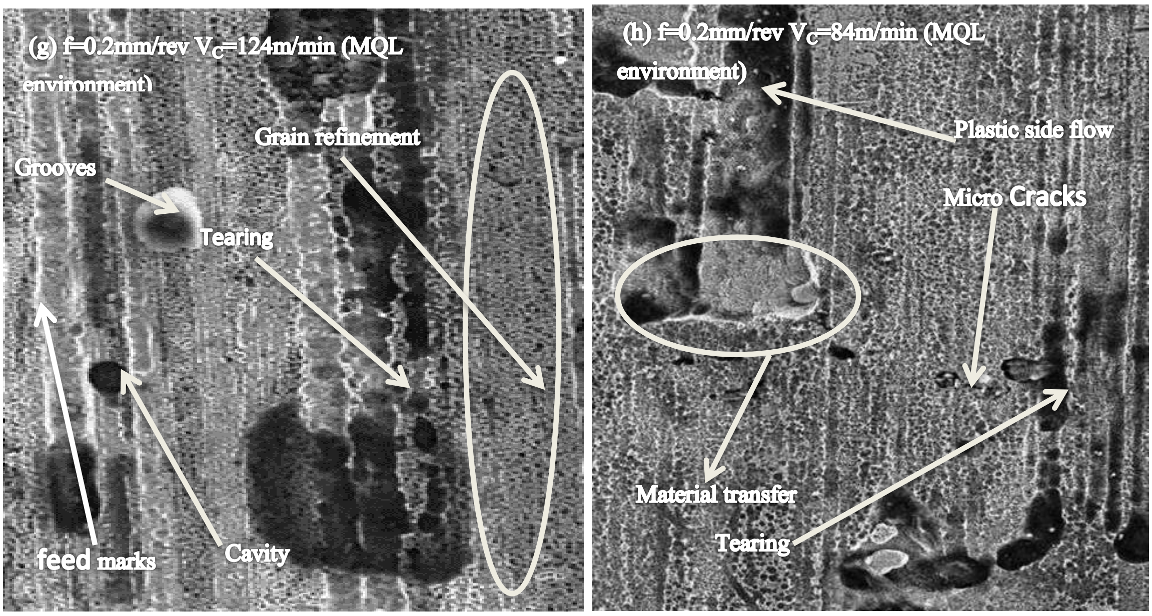
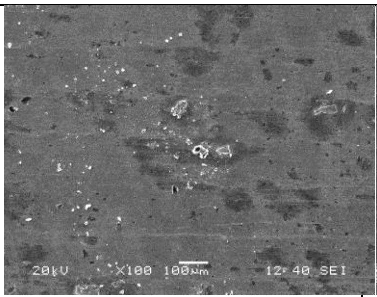
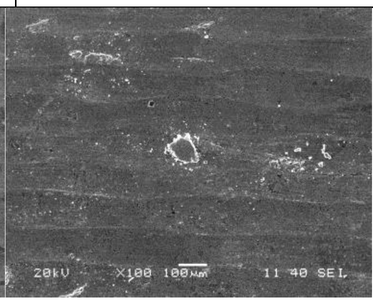
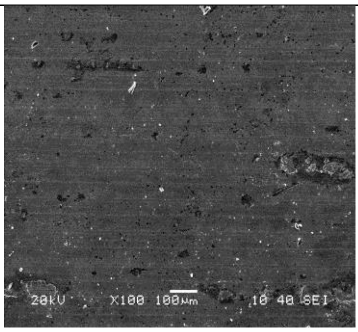
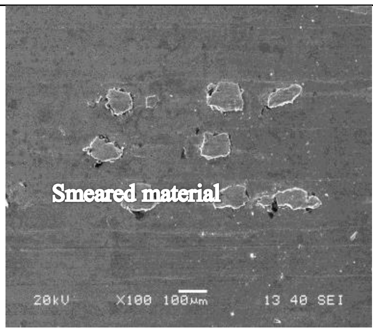
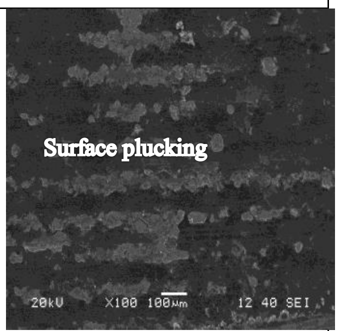


Fig.14 SEM micrographs of the surface machined at different condition.

	f=0.1mm/rev	**f=0.14mm/rev**	**f=0.2mm/rev**
Dry			
MQL			

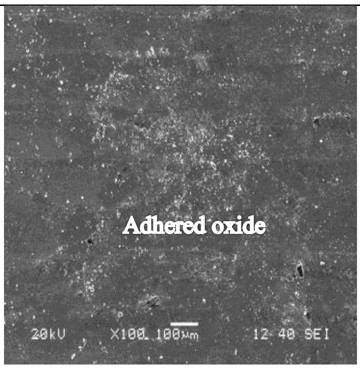
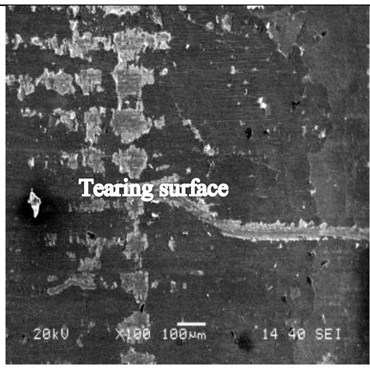
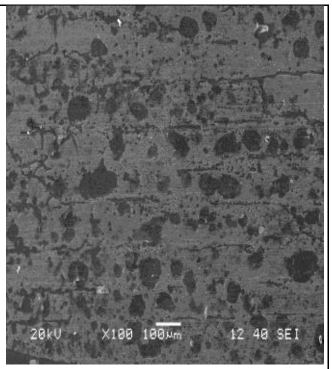
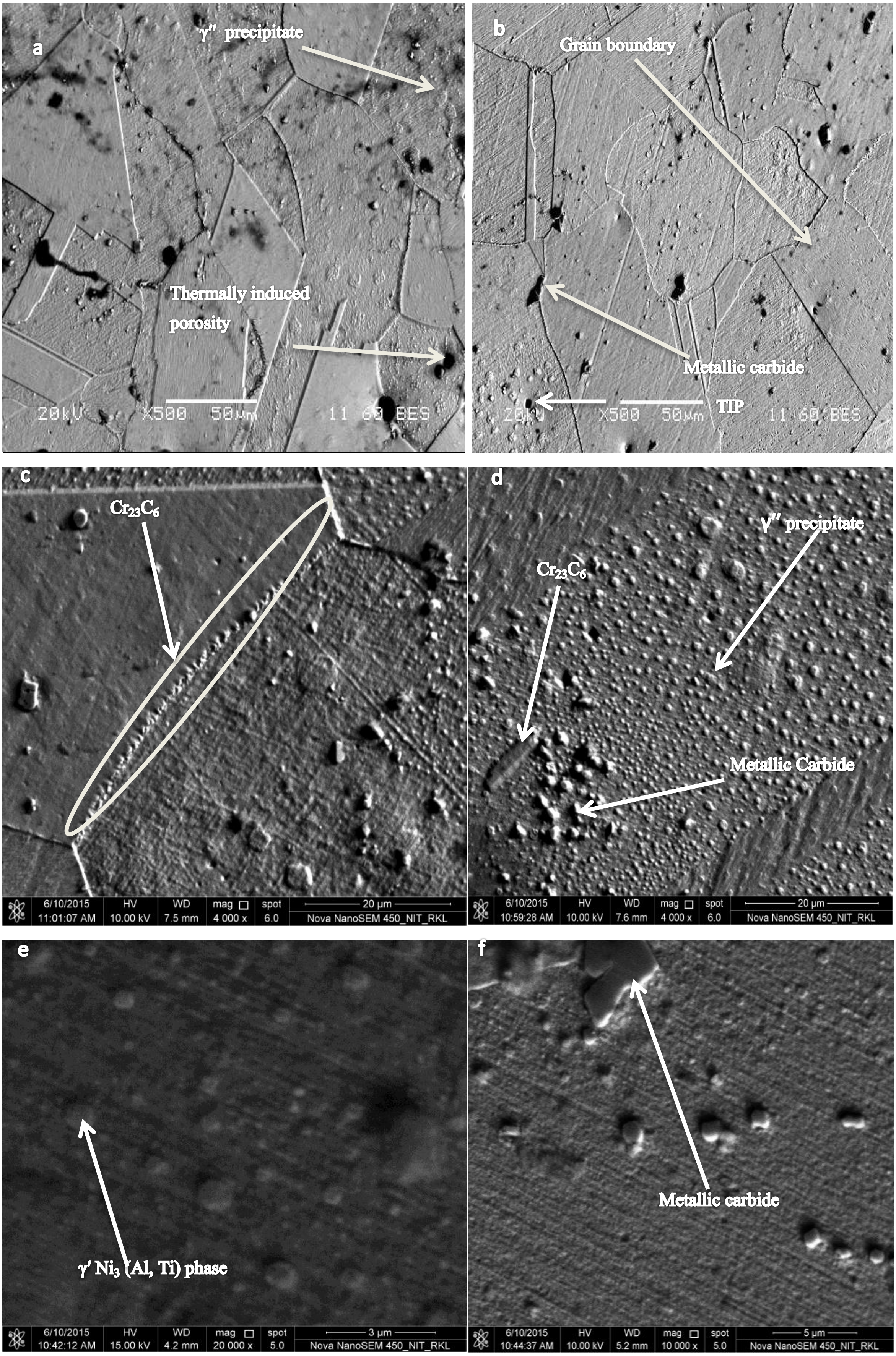
flood			

Fig.15 Images of machined surface at magnification (×100).

4.3 Microstructural examination of work piece

Nimonic C-263 is precipitation hardening nickel based super alloy which possess high amount of chromium, cobalt and molybdenum. The Nimonic C-263 material has two phase microstructure which consists of coherent γ' precipitates embedded in disordered face centred cubic crystal structure known as γ matrix. The presence of high amount of precipitates impedes the plastic flow and increases the stability and yield strength of material at high temperature. The mechanical properties highly related with size, fraction, distribution and morphology of γ' precipitates. The fine γ' precipitates exhibited nearly spherical shape and dispersed in the grains as shown in Fig.16 (e,g,h,i). However the coarse γ' precipitates are in cuboidal shape with round corner and mainly present at grain boundary. We can see from the Fig.16 (c,d,e), blocky and rods like $Cr_{23}C_6$ carbide particle at the grain boundary and in grain interior. Blocky $Cr_{23}C_6$ is identified more compare to needle-like mostly at grain boundaries. Carbides particles improve structural refinement at the time of fabrication and heat treatment of material by helping in control of grain size. The presence of carbide particles is useful in strengthening the matrix of material when present within a grain thus increase high temperature strength and stability of material by preventing the slipping of grain boundaries. Carbides can be source of dislocation and thus increases the chance of fatigue failure. Carbides particles poses problem during machining by inducing abrasive wear of the tool. Some defects such as thermally induced porosity (TIP) can be seen in the microstructure of Nimonic C-263 from the Fig.16 (a,b). These defects in the microstructure will become the crack sources and decrease the mechanical properties of material.


a
γ″ precipitate
Thermally induced porosity
20kV X500 50μm 11 60 BES
b
Grain boundary
Metallic carbide
TIP
20kV X500 50μm 11 60 BES
c
$Cr_{23}C_6$
6/10/2015 11:01:07 AM HV 10.00 kV WD 7.5 mm mag 4 000 x spot 6.0 20 μm Nova NanoSEM 450_NIT_RKL
d
γ″ precipitate
$Cr_{23}C_6$
Metallic Carbide
6/10/2015 10:59:28 AM HV 10.00 kV WD 7.6 mm mag 4 000 x spot 6.0 20 μm Nova NanoSEM 450_NIT_RKL
e
γ′ Ni_3 (Al, Ti) phase
6/10/2015 10:42:12 AM HV 15.00 kV WD 4.2 mm mag 20 000 x spot 5.0 3 μm Nova NanoSEM 450_NIT_RKL
f
Metallic carbide
6/10/2015 10:44:37 AM HV 10.00 kV WD 5.2 mm mag 10 000 x spot 5.0 5 μm Nova NanoSEM 450_NIT_RKL

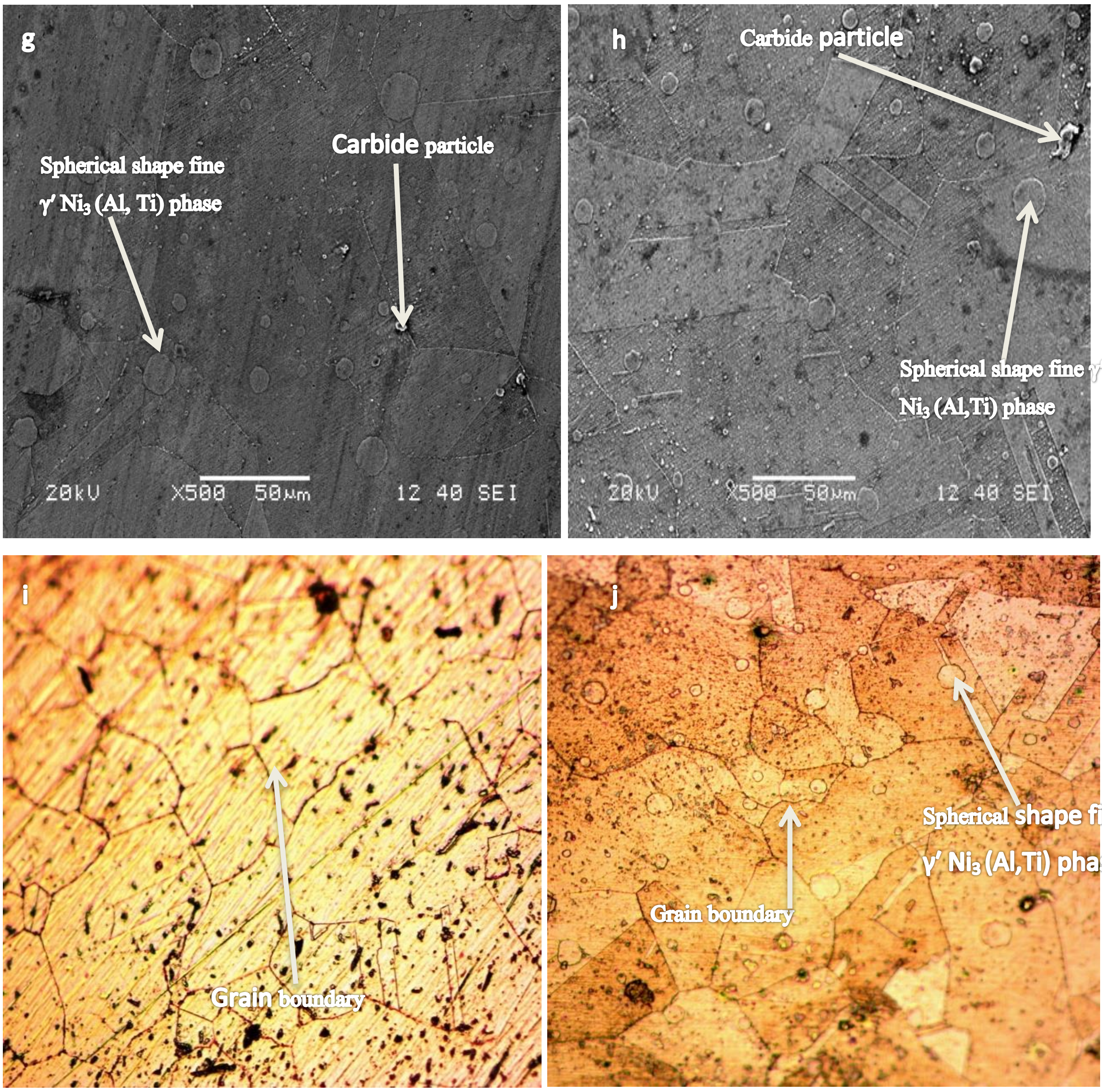


Fig.16 Images of microstructure of Nimonic C-263.

4.4 XRD analysis

The properties of material is strongly depends on microstructural features such as presence of carbide particles in the grain boundary and their distribution, variation in grain size (coarse or fine) and the size, shape and distribution of gamma prime (γ') in the ɤ matrix. The high temperature strength and stability of material for long time is governed by these features. The mechanical properties of nimonic are largely influenced by the size, distribution and morphology of γ' precipitates in the γ matrix. Ordered γ' precipitates increase mechanical properties such as high temperature strength and long term stabilities of component. Gamma prime structure such as Ni_3 (Al, Ti) has been found in greater proportion during xrd analysis of machined surface of Nimonic C-263. Gamma prime structure (Ni_3Ti) and metallic carbide ($Cr_{23}C_6$, TiC) has been found in greater proportion in the machined surface at all cutting condition. At medium and high feed rate a different phase (Co_7Mo_6) has been seen on the machined surface which is the result of high pressure and temperature. Grain refinement associated with dynamic recrystallization rate has been noted at high feed rate.

It is known that cutting forces increases with feed rate. Accordingly plastic deformation, compressive stress, tendency of dynamic recrystallization also goes up. From Table 4 it is evident those different peaks always appear at higher angle, followed by gradual shift towards lower angle with increase in feed. At higher feed rate reversal of trend has been noticed. This can be explained by the fact that compressive stress increases with the feed rate. On the other hand, at high feed rate (0.2mm/rev), because of increase in temperature there is fall in compressive stress. Similarly grain refinement at high feed also noted which is attributed to possibility of dynamic recrystallization during machining at high feed rate. Effect of dynamic recrystallization under the condition of low and medium feed rate has been observed.

Table 4: Variation of peak position and FWHM with feed rate (mm/rev).

Peak	Position (°2Θ)			FWHM (°2Θ)		
	f=0.2	f=0.14	f=0.1	f=0.2	f=0.14	f=0.1
1	44.2797	44.0395	44.4139	1.44	0.96	0.96
2	51.6068	51.4053	51.6605	0.96	0.96	0.96
3	75.6865	75.4545	75.7333	1.44	1.2	0.96

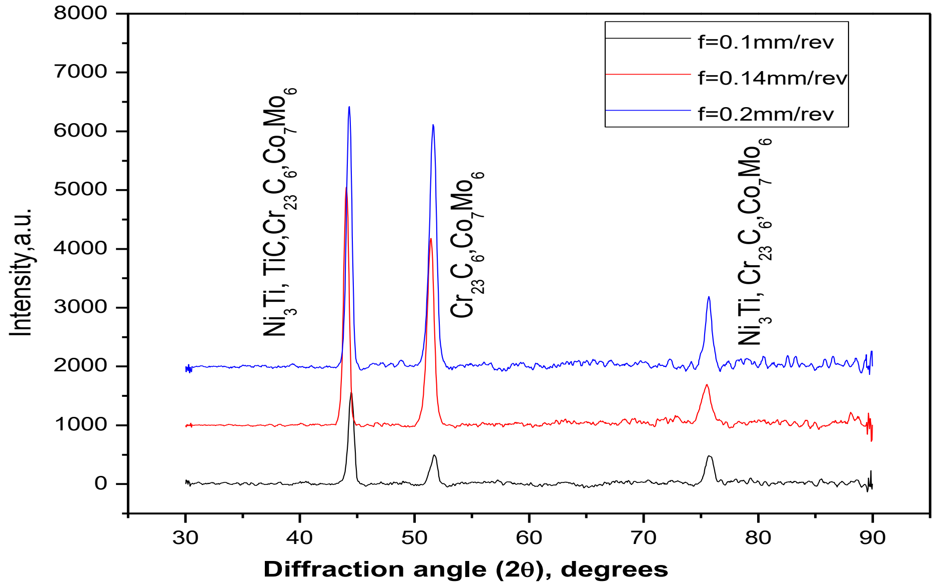


Fig. 17: XRD spectra of machined surface at different feed rate.

In dry machining cutting temperature increases, therefore tendency of grain growth is high. On the contrary, under MQL and flood cooling environment cutting temperature is reduced by the cooling action of cutting fluid. Therefore, tendency of grain coarsening also decreases. In the other word, finer grains obtained in wet machining compare to dry. This mechanism has been established from FWHM value under machining as shown in Table 5. In XRD analysis, shifting of peaks towards lower angle is indicative of either generation of compressive stress or reduction in tensile stress vice versa. During dry machining, tensile stress at the surface region of the machined work piece is predominant owing to higher cutting temperature. This tensile stress can be reduced by application of cutting fluid. It is evident from Table 5 that different peaks appear at lower angle during wet machining compare to dry machining. It can also be concluded from the table 5 and 6 MQL is more effective in reducing detrimental tensile stress obtained during machining. On the other hand flood cooling is not that effective characterized by insignificant variation in peak position compare to dry machining. In fact under low feed condition second peak appeared at higher angle under flood cooling condition. This clearly shows that MQL is more beneficial in reducing cutting zone temperatures as well as surface tensile stress.

Table 5: Variation of peak position and FWHM with different cutting environment at feed rate of 0.2mm/rev.

Peak	Position (°2Θ)			FWHM (°2Θ)		
	Dry	MQL	Flood	Dry	MQL	Flood
1	51.5354	51.5205	51.5456	1.2096	0.8064	0.8064
2	60.4240	60.3939	60.4062	1.2096	1.0080	1.0080

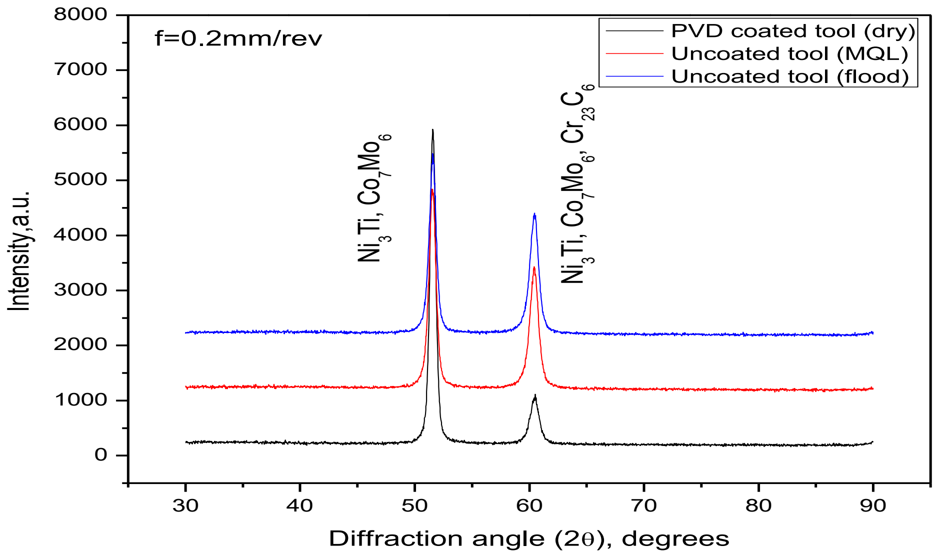


Fig.18: XRD spectra of machined surface under different cutting environment at feed rate of 0.2mm/rev.

Table 6: Variation of peak position and FWHM with different cutting environment at feed rate of 0.1mm/rev.

Peak Sequence	Position (°2Θ)			FWHM (°2Θ)		
	Dry	MQl	Flood	Dry	MQl	Flood
1	51.5597	51.4901	51.5327	0.8064	1.2096	1.2096
2	60.4927	60.3956	60.5527	1.0080	1.2096	1.2096

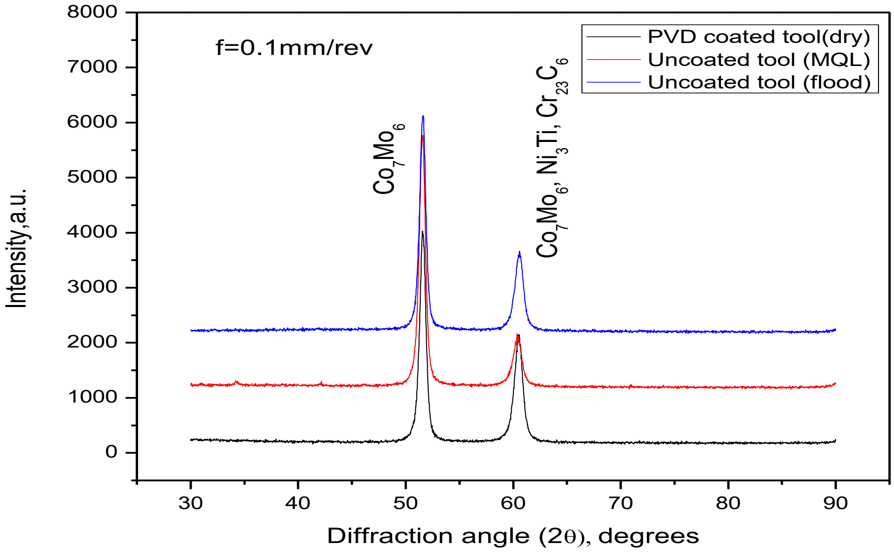


Fig.19: XRD spectra of machined surface under different cutting environment at feed rate of 0.1mm/rev.

4.5 Residual Stress

Residual stress formed during hard machining because of mechanical and thermal stresses generated due to high plastic deformation and lots of variation in temperature during machining does not relieve from machined surface and persists even after machining. Compressive stresses which are opposite to the applied load are beneficial in increasing the fatigue life while tensile residual stresses reduces the fatigue life and are detrimental to the product life. It is evident from the Fig.20 lower tensile residual stress was obtained while using lower feed rate (0.1mm/rev) under MQL and flood environment both in cutting speed and feed direction.. Higher frictional drag force under low feed condition might result in early coating failure. Therefore coated tool was not effective in reducing friction under low feed. However, when feed was increased frictional force reduced, but at the same time, it is more difficult for the cutting fluid to penetrate into the chip-tool interface. As a consequence, coated tool under dry machining recorded lower friction heat in the cutting zone hence lower tensile residual stress observed in the machined surface.

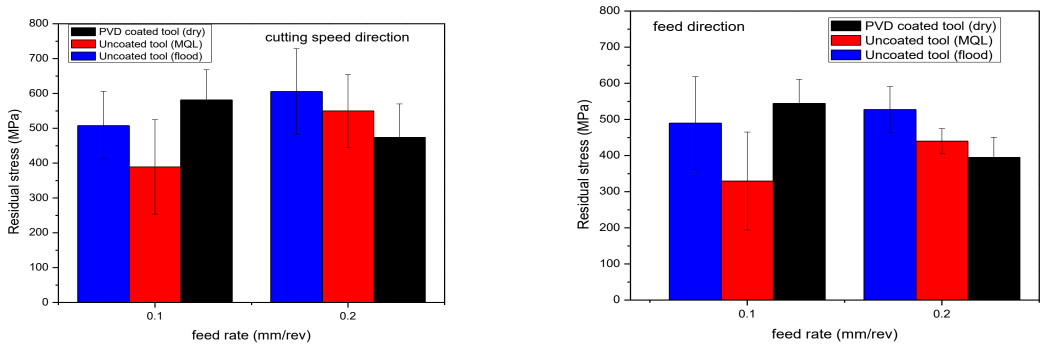


Fig. 20: Variation of residual stress with feed rate at different cutting condition (a) cutting speed direction and (b) feed direction.

4.6 Surface and Sub-surface deformation

Three to four distinct zones have been observed in terms of formation of white layer, microstructural changes, grain refinement and work hardened layer in the sub-surface region during the machining. The depth of deformation and their intensity increases with the increase of cutting parameter and tool wear. Cutting temperature and mechanical load increases with increase in cutting speed and feed rate which induces higher amount of plastic deformation in the machining zone resulting in high deformation. Three different regions have been seen in microstructural analysis of cross-section of machined round bar. The region shown in Fig.21 (a) is white layer, transition and bulk material. The variation of white layer thickness is highly irregular in nature and it shows poor adhesion to the work piece material and almost flacked off from the bulk material as shown in Fig.21 (b). Dynamic recrystallization has been observed on surface during machining at high feed rate and medium cutting speed with uncoated tool under flood condition. This is attributed to high temperature generation due to high plastic deformation and tool wear at this condition [2,15].

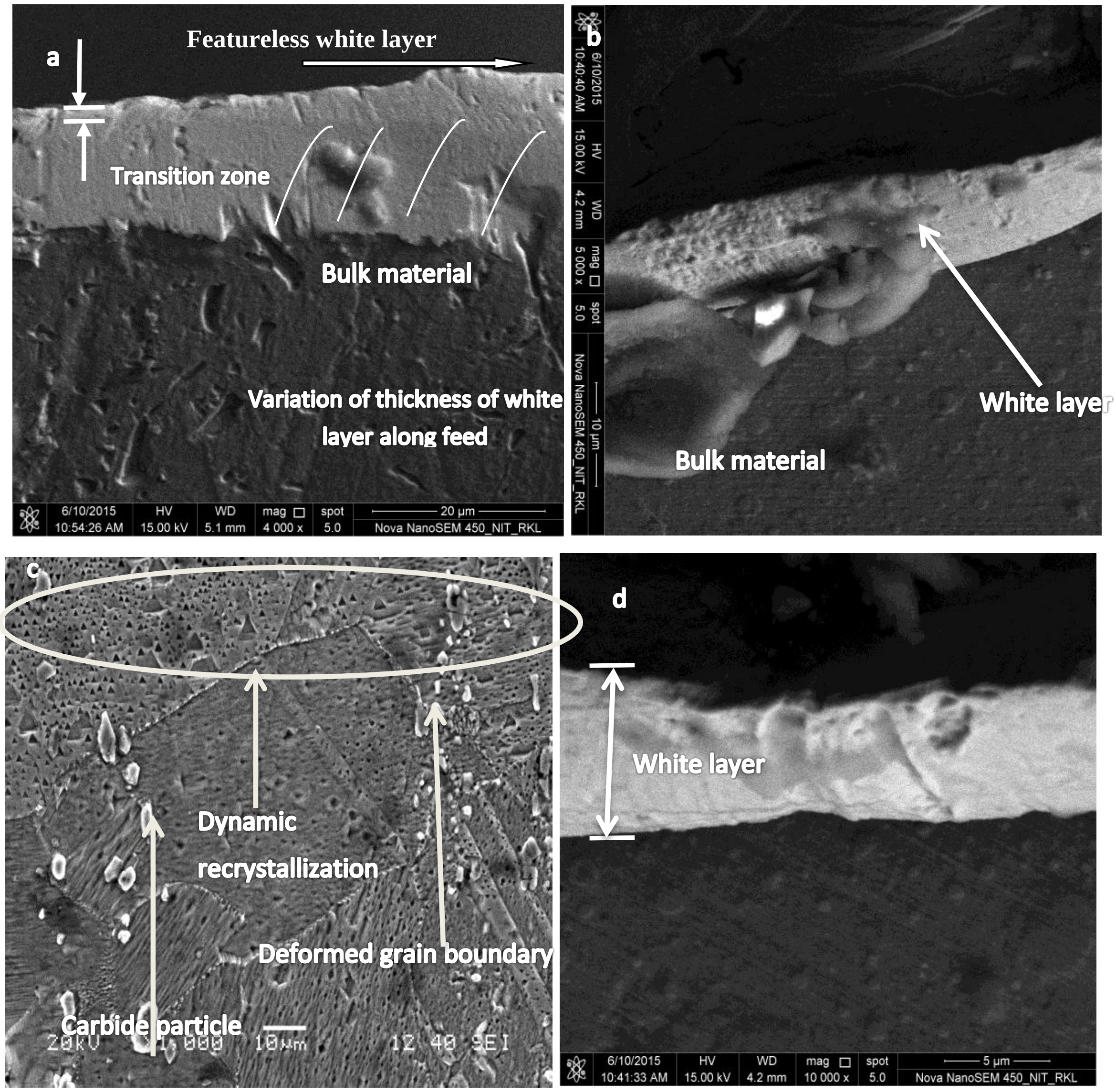
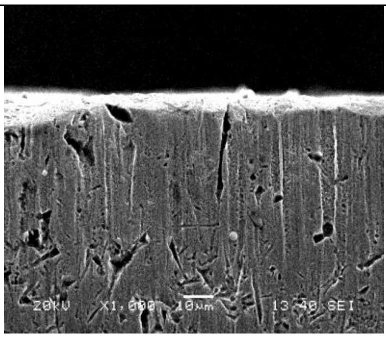
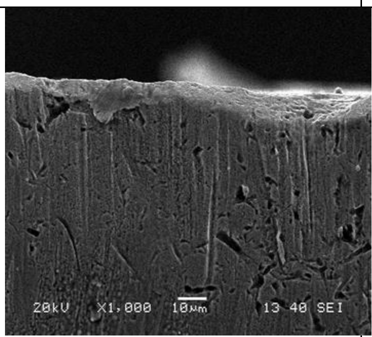
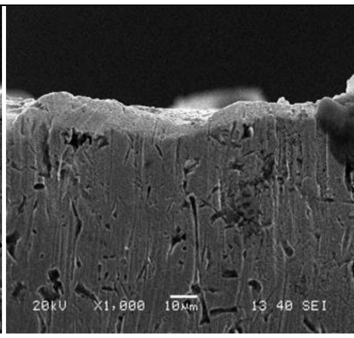
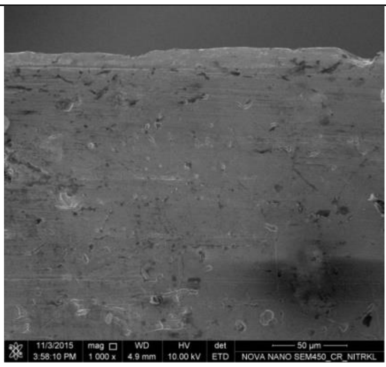
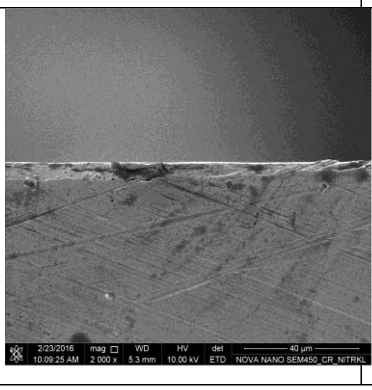
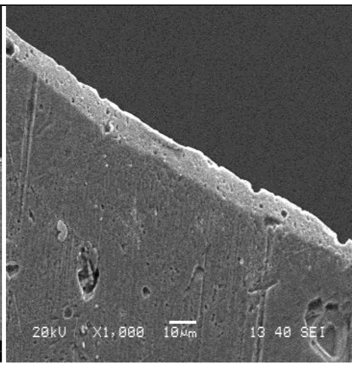


Fig. 21: Images of machined sub-surface region showing white layer, plastic deformation zone, dynamic crystallization and deformed grain boundary.

4.7 White layer

White layer thickness highly depends on the temperature generation during machining and tool wear. White layer thickness increases with increase in cutting speed and feed due to high cutting temperature, pressure and low thermal conductivity of material which induces high plastic deformation [13]. White layer thickness decreases with increase of cutting speed up to 84m/min at constant feed and depth of cut due to less relaxation time although tool tip temperature is very high resulting less plastic deformation area as shown in Fig.25. PVD coated tool reduces the white layer thickness at cutting speed of 84m/min and feed rate of 0.14mm/rev due to good stability at high temperature and good antifriction property of TiN layer. At cutting speed of 124m/min and feed rate of 0.2mm/rev, white layer generated with the coated tool. This could be attributed to the generation of high temperature due to lower thermal conductivity of coating and enhanced mechanical load on workpiece which promote high plastic deformation [2]. Coolant also reduces the thickness of white layer at low and medium cutting condition due to its good capability to circumvent thermal influences generated during machining. Flood cooling does not give good results in lowering temperature due to formation of vapour blanket which prevent the penetration of coolant to the higher temperature zone. White layer generated at very high cutting condition due to high flank wear of uncoated tool and low heat dissipation capacity of workpiece and coolant. MQL does not give satisfactory result at very high cutting condition compare to flood due to less quantity of coolant. At medium and high cutting speed MQL gives good result by reducing temperature and shear stress due to high penetration of cutting fluid between cutting zone.

	f=0.1mm/rev	**f=0.14mm/rev**	**f=0.2mm/rev**
Flood			
MQL			

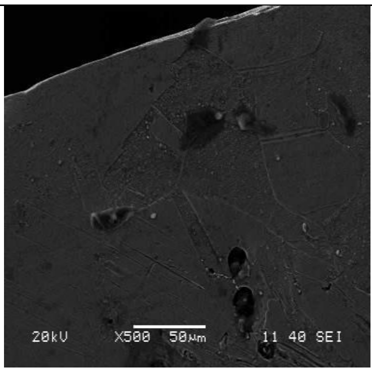
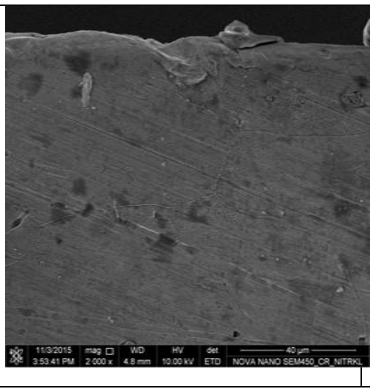
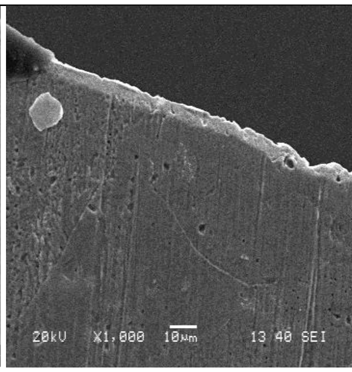
Dry			

Fig. 22: White layer images on surface machined at different feed rate, constant cutting speed of 54m/min and constant depth of cut of 1mm under different cutting environment.

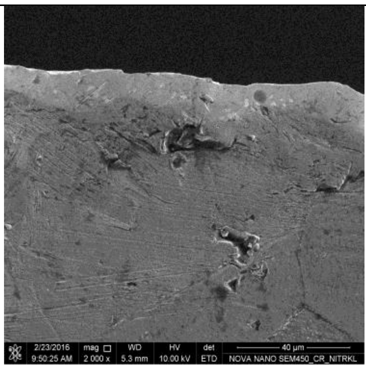
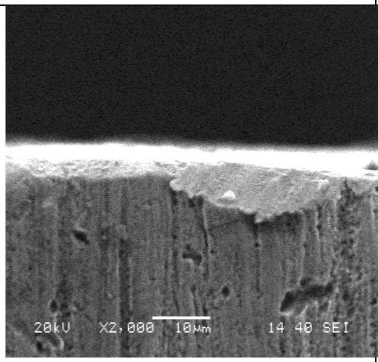
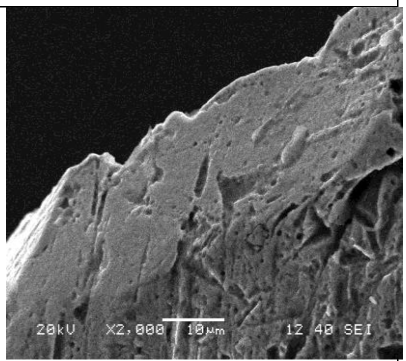
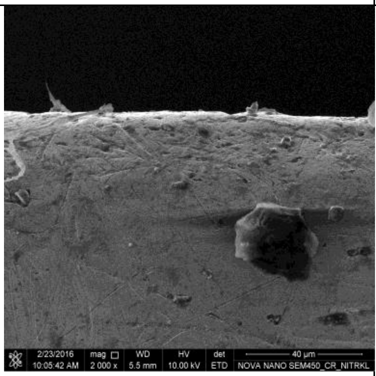
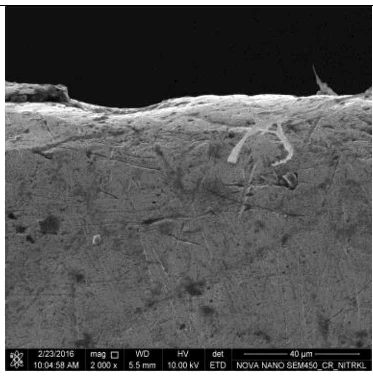
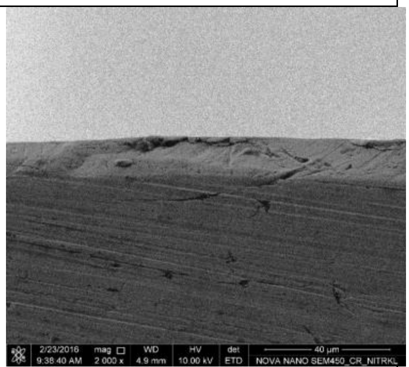
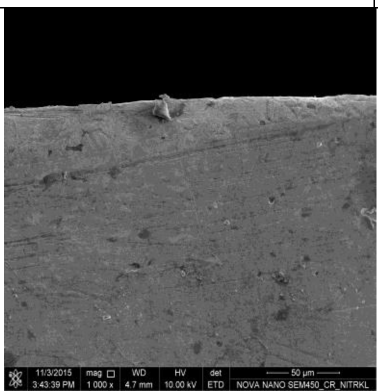
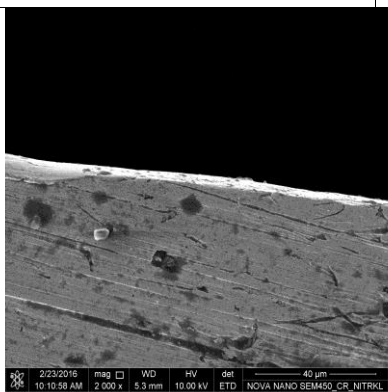
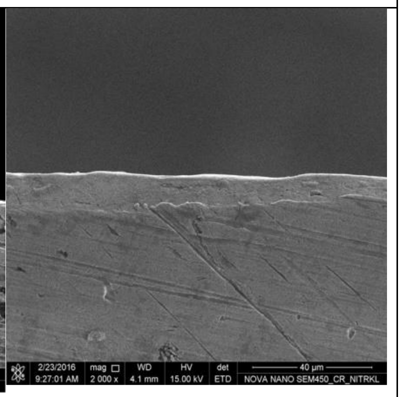
	f=0.1mm/rev	**f=0.14mm/rev**	**f=0.2mm/rev**
Flood			
MQL			
Dry			

Fig. 23: White layer images on surface machined at different feed rate, constant cutting speed of 84m/min and constant depth of cut of 1mm under different cutting environment.

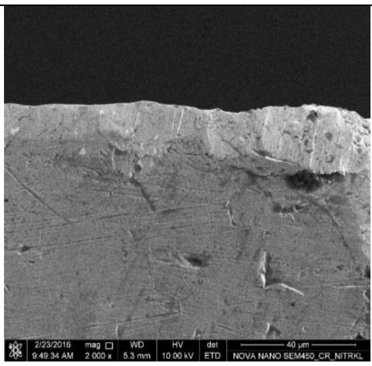
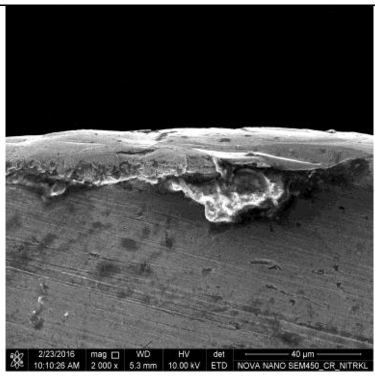
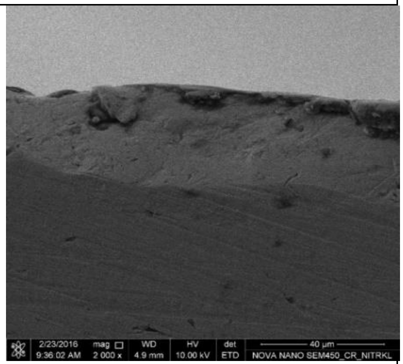
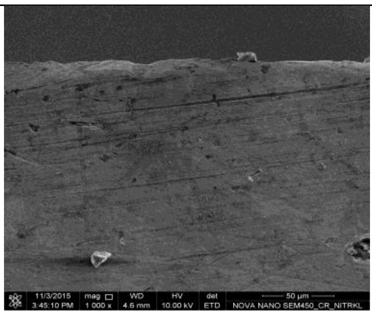
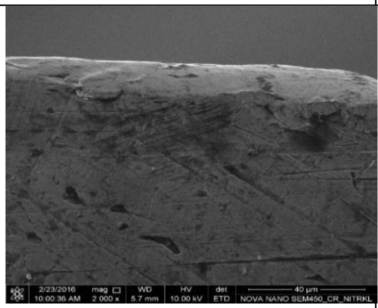
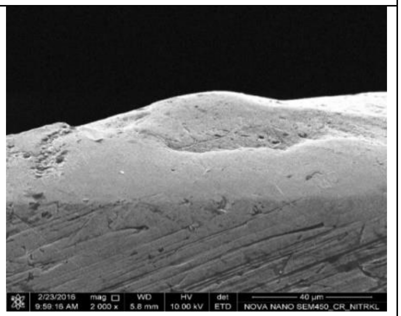
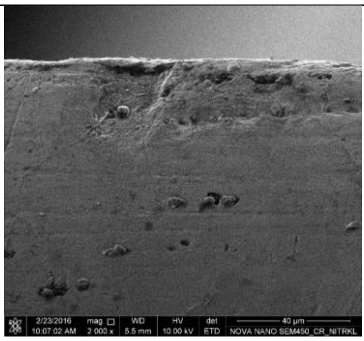
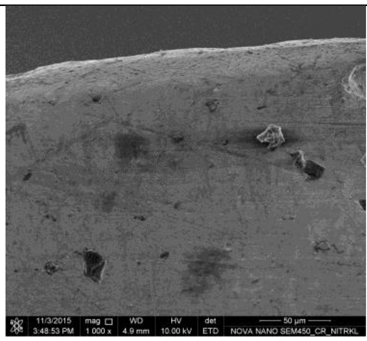
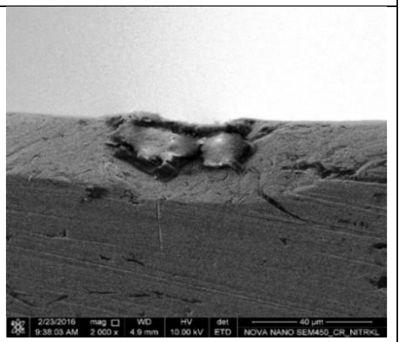
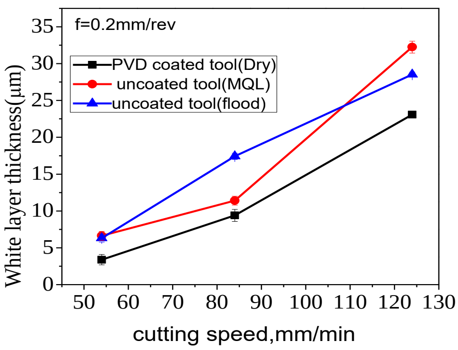
	f=0.1mm/rev	f=0.14mm/rev	f=0.2mm/rev
Flood			
MQL			
Dry			

Fig. 24: White layer images on surface machined at different feed rate, constant cutting speed of 124 m/min and constant depth of cut of 1mm under different cutting environment.



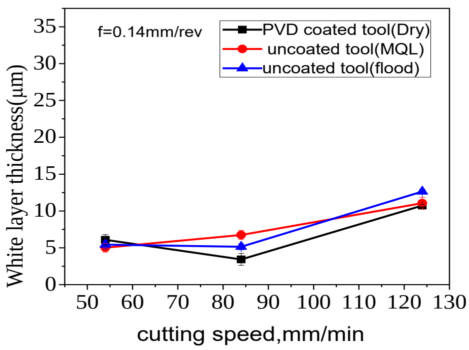


Fig. 25: Variation of white layer thickness with cutting speed at constant feed rate of (a) 0.2mm/rev and (b) 0.14mm/rev.

4.8 Micro hardness

The high stresses and pressure generated between tool and inserts during hard machining of nickel-based super alloy and requirement of more number of passes for achieving good quality of desired component and high productivity induces high work hardening tendency. The degree and depth of work hardened layer formed during machining depends on the properties of work material, condition of tool, cutting environment and the geometry of cutting edge. The machined surface subjected to severe plastic deformation which created work hardened layer. White layer formed on machined surface shows high micro hardness value due to presence of fine grains [26]. Micro hardness value near the machined surface is higher as shown in table due to formation of high stressed layer and decrease in hardness value below the machined surface towards centre could be attributed to the neutralization of strain and heat. Thickness of work hardened layer and hardness of surface and sub-surface increases with increase of cutting speed parameter and tool wear due to high strain rate and high cutting temperature. Generation of high hardened layer is highly influenced by cutting environment and coating of tool. Comparative study has been done between micro hardness value on surface machined with dry environment using PVD coated tool, and MQL and food environment using uncoated tool for finding the effect of cutting environment and coating on work hardening of the material. Dry machining with PVD coated tool reduced the work hardened layer thickness at high cutting parameter due to less deformed region below the machined surface. MQL or wet machining with uncoated tool gives satisfactory result due to reduced friction and temperature between tool-work. Micro hardness value for PVD coated tool at very high cutting speed and feed shows higher value compare to other two cutting condition. This is attributed to at high cutting condition more prominent thermal effect takes place due to lower thermal conductivity of coated tool leading to more work hardening compare to other condition in which cutting fluid plays significant role in reducing cutting temperature by reducing friction. At low cutting speed and feed rate, there is not much deviation in micro hardness value on machined surface thus less stressed layer formed with dry environment with PVD coated tool, and MQL and flood environment with uncoated tool due to low temperature generation during machining between tool and work piece and good antifriction property of coating layer and coolant. Coating provides good resistance to wear and high thermal stability and thus less mechanical deformation, and cutting fluid reduces the pressure and temperature which is the major reason of formation of less work hardened layer at high cutting speed and feed. At very high cutting speed and feed, higher value of micro hardness with high depth beneath the machined surface around 400µm with coated tool as shown in Fig.26. Low thermal conductivity of coating layer could be the reason for this high deformation zone which increases the temperature to high level near the machining zone [2]. At very high cutting condition due to less cooling efficiency of MQL, less thermal conductivity of work piece material and high wear of uncoated tool creates high temperature around the machining zone induces thermal softening as shown in Fig.

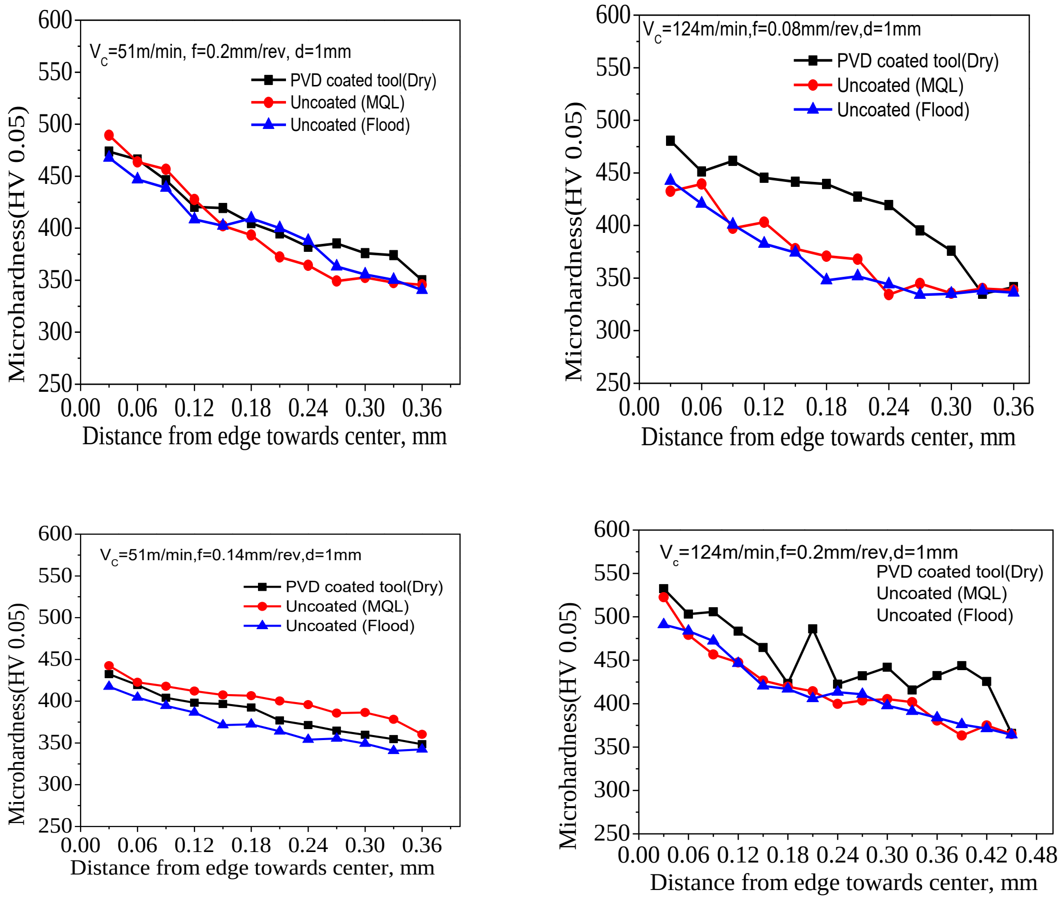


Fig. 26: Variation of micro hardness with distance from edge towards centre of machined sample at different feed rate and cutting condition.

CHAPTER 5

CONCLUSIONS

The current research work investigated the influence of PVD multilayer coating and cutting fluid in the form of MQL and flood on surface integrity at different cutting parameter during machining of Nimonic C-263. The following conclusions can be drawn from this research work.

1. PVD multilayer coated tool even under dry machining condition resulted in lower surface roughness compare to wet machining (flood &MQL) by using uncoated tool under condition of high cutting speed and feed.

2. Overall surface damages could not be improved by using PVD coated tool under dry machining compare to uncoated tool under wet machining. Dry machining showed dominance presence of surface plucking and tearing while wet machining resulted grain boundary cracking, breakage of material, material transfer, debris and grooves at high cutting speed and feed rate.

3. Grain refinement associated with dynamic recrystallization has been noted at high feed rate. Microstructural damages in the material during machining consisted of deformed grain boundary and cracked carbide particle.

4. MQL and flood cooling showed good result in reducing tensile residual stress at low feed. Coated tool was more effective under high feed in bringing down frictional heat hence lower tensile residual stress compare to wet machining using uncoated tool.

5. Under low feed rate white layer thickness is comparable under all machining environment. However, when feed was increased PVD coated tool exhibited minimum white layer thickness.

6. Coating and MQL both have significant influence in reducing micro hardness at low and medium cutting speed. At high cutting condition PVD coated tool could not give satisfactory result.

Overall it can be recommended that dry machining can be more beneficial than wet machining when PVD multilayer coated tool is used under high cutting speed and feed. This is particularly important for higher productivity in sustainable manner.

CONTRIBUTION OF PRESENT RESEARCH WORK

The major contribution of the current research work is to compare the effectiveness of wet machining (MQL and flood) with the uncoated tool and dry machining with the PVD multilayer (TiN/TiAlN) coated tool in improving the surface integrity of. Such type of comparison between dry and wet machining with coated and uncoated tool has been done for first time for improving surface integrity in sustainable manner.

The effect of feed rate has been observed on surface integrity characteristics of Nimonic C-263 such as residual stress, white layer, surface morphology and microhardness first time.

RECOMMENDATION AND SCOPE OF FUTURE WORK

Based on current research, expected points for improving surface integrity of Nimonic C-263 in future have been explained as follows:

- Uncoated tool fail in lowering down the surface damages due to inefficiency of MQL and flood in reducing temperature and force at high cutting speed and feed. It is recommended that machine the Nimonic C-263 material at cutting speed of 84m/min and feed of 0.14mm/rev with uncoated cemented carbide insert.
- PVD multilayer coating is always recommended for achieving better surface quality and high productivity in sustainable manner.

Future work based on current work may be undertaken on Nimonic C-263 as given below.

- Comparative study on surface integrity characteristics of Nimonic C-263 with the use of CVD and PVD coated tools under conventional cooling (flood) and MQL should be perform in detail.
- Effect of cutting parameters on surface integrity aspects should be done in great detail with the use of CVD and PVD coated tool under different cutting environment.

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