INVESTIGATIONS ON THE INFLUENCE OF HIGH PRESSURE COOLANT JET IN TURNING HARDENED STEELS UNDER VARIABLE MACHINING CONDITIONS

By

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It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

Mozammel Mia

This work is dedicated to my
Loving Parents

Late Kala Mia
and
Amena Begum

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ABSTRACT

The energy dissipated in hard machining operation is converted into heat which raises the temperature in the cutting zone. With the increase of cutting temperature; tool wear, surface roughness, dimensional inaccuracy increases significantly. Various researchers worked on various techniques to effectively control the increased cutting temperature as well as tool wear rates, and surface integrity. The cutting temperature, which is the cause of several problems restraining productivity, quality and hence machining economy, can be controlled by the application of high-pressure coolant (HPC) jet. High-pressure coolant (HPC) jet cooling is a promising technology in high speed machining, which economically addresses the current processes, environmental and health concerns. The benefits of reduction in machining temperature are reduction in cutting force, tool wear and surface roughness. This benefit of HPC cooling depends on the process parameters and cutting tool.

In this research work turning of AISI 1040 hardened steels (40 HRC, 48 HRC, 56 HRC) with HPC condition has been investigated and its performance is evaluated on the basis of chip morphology, surface finish, flank wear and cutting temperature. An effort is made to investigate the effect of cutting parameters (cutting velocity, feed and depth of cut) and the cutting environment on cutting performance. The cutting oil has been delivered through a specially designed and developed nozzle in such a way so that it can deliver oil jet at critical zones during hard turning. An investigative comparison with dry and HPC under same conditions has been done to evaluate the relative performance of hard turning with HPC jet. A model of tool wear was also developed for specific working condition. The model is developed to estimate the amount of principal flank wear with machining time for any one of the tool-work combinations and cutting environments. The experimental results indicate that the performance of the machining under HPC condition is quite good and more effective compared to machining under dry condition. With the help of the experimental results, model of principal flank wear has been developed to understand the basic phenomenon in metal machining. Finally the model was validated with experimental results to make it an acceptable model.

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Introduction

1.1 Introduction

In the recent era of manufacturing when the market is very competitive, the manufacturer constantly strive to produce parts with the highest quality possible without sacrificing the quality of that part but with the lowest possible cost. When it's about cost and quality then it's definitely vigorously related to time which should be the shortest. At the same time, manufacturers have to keep a sharp eye on the side effects, specially the effects on environment of that very used manufacturing process as environmental regulations are being emerged and imposed *i.e.* green environment. The detrimental waste, produced during machining *i.e.* cutting fluid, vapor, fume, chip and worn out cutting tools must be eliminated or at least reduced to ensure a healthy and green environment.

Shortest time, green environment, best quality and lowest cost all are possible to achieve but not to some specific value rather within a range of the values. The overall quality of the part depends on its dimensional accuracy, form accuracy and surface quality. To attain those qualities, the part needs to have some machining operations followed by grinding. The grinding operation itself is very time consuming as the Material Removal Rate (MRR) is comparatively smaller than other machining processes. But today's competitive market demands for fast product release which in turn depends on rapid removal of material *i.e.* higher MRR. So, machining and/or grinding operations must ensure high MRR but without shortening the cutting tool life. Otherwise, alternative method should be searched for so that this time consuming grinding process is eliminated.

Hardened steel is frequently used in the automotive industry to manufacture bearings, gears, shafts and cams requiring tight geometric tolerances, longer service life and good surface finish [**Dawson and Kurfess 2001, Kundrak et al. 2008**]. The conventional approach for the production of these parts involves a sequence of forming, annealing, rough cutting and heat treatment followed by a final grinding operation to obtain the desired surface roughness. Thanks to the advancement of material science and practical realization of cubic boron nitride (CBN) cutting tools, two procedures from the conventional processes can be eliminated by applying Hard Turning (HT) process, that is, annealing and grinding [**Grzesik 2011**]. But machining of hardened steel is a very complex phenomenon which results in poor surface finish, high tool wear, premature failure of the tools etc.

There are three major factors influencing surface alterations, namely high temperature, plastic deformation and chemical reactions. In hard turning, white layer is believed to be detrimental to the part performance and can affect its tribological performance, corrosion resistance and fatigue life [**Umbrella and Filice 2009**]. White layers are hard, brittle and normally associated with a tensile stress and hence has the ability to reduce the fatigue life of machined components. Griffiths reported that white layer formation as a dimension of surface integrity was first discovered on the surfaces of used steel wire rope by Stead as early as 1912. He described a white layer as a hard surface formed in a variety of ferrous materials under a variety of conditions and this layer resists etching compared to the bulk material. This surface layer was found to be high hardness compared to bulk and featureless when observed under a low power microscope. This high hardness white layer is brittle and often possesses a tensile compressive stress which influences engineering properties such as fatigue life, stress corrosion and wear resistance. In general, there are three cases where white layers can be formed *i.e.*, materials in engineering service, laboratory pin on disk wear experiments and material removal processes. The three main mechanisms of wear layer formation are plastic flow, rapid heating and quenching and surface reaction.

There are several causes those are directly and indirectly related to poor surface finish of the product and short cutting tool life among which generation of huge amount of heat at the chip-tool interface during hard turning is most prominent. This heat is not only concentrated at the chip-tool interface but also distributed around this contact point creating a Heat Affected Zone (HAZ). In practice, the magnitude of the heat gets bigger in the high production machining with high cutting velocity, feed and depth of cut. This higher tool temperature has inverse effect on the tool life and its performance. The elevated temperature soften and weaken the tool, the tool tip become blunt and in result, produce poor surface finish, dimensional deviation, surface and sub-surface defects including micro-cracks and shorten the tool life. When the tool material becomes soft, there exists greater amount of abrasion and adhesion which in turn remove material from the tool rake surface, principle flank surface and auxiliary flank surface and the performance of tool deteriorates. The ups and downs of chip-tool interface temperature create natural heat treatment and induce thermal distortion into the produced part. This high temperature cause corrosion as there is cutting fluids and oxidation as elevated temperature facilitate rapid oxidation in open environment. As a result, it’s important to investigate the work piece-tool behavior during machining of different materials under variable machining conditions.

The amount of heat generated at the chip-tool interface is related to the tool-work material combination. Proper selection of tool-work can reduce the heat amount significantly. It is also dependent on the cutting speed, feed rate and depth of cut. So combination of optimum machining parameters (cutting speed, feed, depth of cut) along with tool-work material and application of effective cutting fluid can trim down the heat generation. Partial control of the temperature can be achieved by using heat resistant tools like coated carbides, PCD, CBN, PCBN etc. Among these, use of diamond and CBN tools are not wide spread due to their high price. In turn, coated carbide tool can be used to attain this partial temperature controlling. Unlike other tools with which poor surface finish occurs at high cutting velocity, these tools also facilitate high speed machining with higher cutting speed, feed and depth of cut without sacrificing the surface integrity and tolerance of the produced parts.

Reduction of friction between the chip and tool is very important in cutting operation as reduction in kinetic coefficient of friction not only decreases frictional work, but also decreases the shear work as well due to a resulting increase in the shear angle. Application of water soluble cutting fluid although mainly reduces temperature but it also serves some other benefits *i.e.* create lubrication, handles chip to clean cutting zone, protect from oxidation by creating coating on the nascent finished surface from contamination by the oxygen. Al lower speeds, the cutting fluid application are ‘friction reducing’ through a process of chemical action whereby the cutting ratio is increased reducing the cutting forces. At higher speeds, the action is mostly ‘cooling’ by reducing the bulk temperature of the chip. Such chilling may improve tool life but will not improve cutting ratio or reduce the cutting force. Due to the above limitations, cutting fluid and it's method of application should be so chosen that it will react at the interface zone to form a low shear strength solid lubricant.

When the fluid is applied in the form of flood, the large fat molecules constituting the cutting fluid encounters difficulty in entering into the chip tool interface. Also, in high speed machining the cutting fluid may cause premature failure of the cutting tool by fracturing due to close curling of the chips and thermal shocks. For this reason, water based cutting fluids are avoided in machining steels by brittle type cutting tools like carbides and ceramics. The more serious problems associated with oil-based type cutting fluid are the pollution of the working environment, water pollution, soil contamination and possible damage of the machine tool slide ways by corrosion. So it is obvious, in carrying out only two objectives of friction reduction and cooling, many problems may arise due to the method of application of cutting fluid. Therefore, the fluid must have some auxiliary properties such as it must be stable, non-volatile, odorless, no tendency for gum, foam or smoke formation, anti-corrosive, anti-bacterial agent, etc.

To ensure the above mentioned two benefits the conventional cutting fluid is applied in the flood form where the cutting zone is inundated into cutting fluid which most of the times fails to fulfill specific process requirements. Investigations have shown that the application method has significant influence on the product quality and tool life. It is suggested that the application method should be such that the cutting fluid must enter into the chip-tool contact point so that the contact area between chip and tool is reduced. Although some operations may be performed without cutting fluids (such as machining gray cast iron, pure aluminum and magnesium alloys), in many processes its application is vital for the success of operation.

Machining without the cutting fluid would be most appropriate if the cooling and friction reduction *i.e.* lubrication were not necessary. But as that is not the real case and manufacturers are compelled to use cutting fluid then it leads to only one solution, dry and pollution free machining. Use of proper lubrication is one the ways of taking care of the heat generation at the chip tool interface. Over the past few decades, the lubrication technology has been significantly changed because of a combination of environmental, health, economic, and performance challenges. To address these challenges, it is essential to develop and implement lubrication process. Some of the alternative approaches are using biodegradable and cryogenic coolants [**Cakir 2007, Dhar and Kamruzzaman 2007, Grzesik and Zak 2014, Sashidhara and Jayaram 2010**]. Typically the high cutting temperature is controlled by profuse cooling [**Kurimoto and Barroe 1982, Wrethim et al. 1992, Alaxender et al. 1998**]. But such profuse cooling with conventional cutting fluids is not able to solve these problems fully even when employed in the form of jet or mist. The more efficient cooling has become essential with the advent of modern machining processes and harder material as the demand on the control of machining temperature is of highest priority. The use of tribologically modified carbide inserts has reduced cutting forces and temperatures. It is considered as one of the alternative ways of reducing cutting temperatures without using cutting fluids. To lower the heat generation and tool wear during the machining process, it is necessary to reduce the shear stress at the secondary shear zone. To achieve that a thin stable interfacial layer is deposited as coating on the tool with low shear strength between the chip and tool, using coating techniques such as Physical Vapor Deposition (PVD) or Chemical Vapor Deposition (CVD) [**Silva et al. 2013**]. This coating technology improves dry lubrication under normal cutting conditions. Minimum Quantity Lubrication (MQL) is an established alternative of the traditional flood cooling method but it over come the negative side of flood cooling as MQL is a near dry lubrication process. So, cost for coolant and environment pollution may be reduced. With the application of MQL cutting and feed force, variation of cutting force, cutting zone temperature, tool wear, dimensional inaccuracy, chip-tool contact length are reduced and surface finish, tool life are increased [**Dhar et al. 2005, 2006, 2007**]. Here the manner of lubricant supply is more important than amount of lubricant supplied. That means the amount actually reaches in the chip-tool interface to reduce temperature. Cryogenic machining with liquid nitrogen and machining with Minimum Quantity Lubrication (MQL) has improved machinability of steel to a certain extent under normal cutting conditions. It has also been reported that though the machining of steel with liquid nitrogen improves the machinability index; it is not used in industrial practices due to high cost of liquid nitrogen and sharp increment of notch wear under nitrogen rich atmosphere.

Another emerging cutting fluid application technology to control the cutting temperature is High Pressure Coolant (HPC) method. If the coolant is applied at the cutting zone through a high speed nozzle, it could reduce the contact length and coefficient of friction at chip-tool interface then cutting force and temperature may be reduced and tool life can be increased. The HPC uses 3000 psi (205 bars) to deliver a high velocity jet of coolant to the cutting zone. When a fluid is applied at this pressure it become easier to get to the target so it can cool, lubricate, and sometimes perform its third function-breaking chips that do not break neatly with ordinary machining processes [**Mazurkiewicz et al. 1989**]. These broken chips are also rapidly flushed from the cutting edge so that they are not cut again by the tool, providing longer tool life and better finish. The high pressure and high volume delivery of clean coolant to the cutting surface provide increased tool life and higher rotational speeds with reduced cycle time. High pressure coolant injection technique not only provided reduction in cutting force and temperature but also reduced the consumption of cutting fluid by 50% [**Wrethim et al. 1992, Umbrella and Filice 2009**]. Concern for the environment, health and safety of the operators, as well as the requirements to enforce the environmental protection laws and occupational safety and health regulations are compelling the industry to consider a high pressure coolant machining as one of the viable alternative instead of using conventional cutting fluids.

The application of HPC over conventional fluid in hard turning may be beneficial in terms of surface finish, tool wear, white layer formation, tool life, cutting zone temperature etc. The overall success of implementing HPC in the realm of metal removal industries therefore depends on increased research activities providing credible data for sound understanding of high pressure coolant supplies at the chip-tool interface and integrity of hard turned machined components. In this regard, the present research work is carried out to experimentally investigate the role of high-pressure coolant jet in respects of average chip-tool interface temperature, chip reduction coefficient, white layer formation, tool wear, and surface roughness in machining hardened steel at different level of hardness (40 HRC, 48 HRC, 56 HRC) by coated carbide inserts (SNMM and SNMG) at different speeds and feed rates combinations. Also a model of tool wear based on abrasion and adhesion wear model is developed and validated with the experimental data. The outcome of the present work is expected to show the effects of different hardness of hardened steel on machining responses with different process parameters which will help to select different parameters in finish hard turning.

1.2 Literature Review

In comparison with conventional approach of turning, hard turning of softer materials exhibits several distinct characteristics which are found by different researchers. As in hard turning the material is harder, specific cutting forces are larger than in conventional turning, and thus the engagement between cutting tools and the workpiece must be limited. Otherwise, tool break may occur due to greater engagement of tools and workpiece. At the small cutting depths, cutting tools must possess proper amount of hardness even at elevated temperature that are developed when machined hardened steels. Nose radius of cutting tools plays a vital role in machining and the tools are typically prepared with chamfered or honed edges to provide a stronger edge geometry that is less prone to premature failure. Cutting on a chamfered or honed edge equates to a large negative effective rake angle, while neutral or positive rake angles are typical in conventional machining. The large negative rake angles yield increased cutting forces compared to machining with positive rake tools, and also induce larger compressive loads on the machined surface. This large compressive force generates significant amount of heat which may cause tool break. This elevated temperature also produce poor surface finish and induces residual and thermal stresses in the machined workpiece.

1.2.1 Research on Hard Turning

In the hard turning processes, the high hardness of materials creates large cutting forces when turned with carbide inserts. For this reason, rigid and precise machine tools are required to expel any vibration and chatter. Tonshoff et al. [**1986**] found that the large negative rake angles (from the edge chamfer) on tools used for hard machining yield large dynamic thrust forces that require adequate machine rigidity, spindle power, damping characteristics, and accuracy of motion along the axes of the machine. Bosssom [**1990**] found that tools with chamfered edges produced cutting forces twice as large as non-chamfered tools. Chryssolouris [**1982**] showed that when machining in a poor stiffness setup, tools failed quickly due to edge fracture. These needs have led to recent machine tool designs that improve stiffness and damping by several methods. New machines have incorporated polymer composite materials in the machine base, reduced the number of joints in the machine, and developed improved slide ways such as hydrostatic designs

[**Sheehy 1997, Devitt 1998**]. Advances in the control capabilities have also improved the accuracy of the machines.

Hard turning and grinding both operations are time consuming as well as not very efficient. So, the ideal case is elimination of all machining operations. But as the market competition demands for producing parts with certain dimensional accuracy, which was previously done using grinding processes are now gradually replaced by hard turning if and only if the hard turning can produce parts with similar dimensional characteristics, geometric precision, and quality surface. Several studies have investigated the capability of the process to compete with grinding, and most have concluded that at proper conditions with a good machine, hard turning can produce dimensional accuracy and surface finishes acceptable for most applications. Matsumoto et al. [**1986**] were able to hard turn parts with surface finish ranging from 0.045-0.197 µm, and surface waviness from 0.775-1.26 µm. They had determined that requirements for a ball bearing surface were less than 0.2 µm for R_a surface finish and less than 1.5 µm for waviness. Similar results were found by Jochmann and Wirtz [**1999**], who produced consistent peak-to-valley finishes below 1.0 µm, roundness below 0.2 µm, and cylindricity below 1.0 µm. Abrao and Aspinwall [**1996**] were able to produce a surface finish with roughness value R_a as low as 0.14 µm.

If hard turning is to replace any grinding operation, it must be capable of producing surfaces of acceptable quality. This includes both the surface topography (surface finish) and surface integrity, which is achieved when "the surface of a component meets the demands of a specific stress system and environment" [**Field et al. 1972**]. Ramesh et al. [**1999**] defined an "extended surface integrity data set" which includes: surface finish, microstructure, microhardness, fatigue resistance, residual stress state, and frictional characteristics.

To discuss the effects of hard turning on residual stresses, the surface influences of hard turning compared to grinding should be mentioned. Compared to grinding, the force components are large, particularly the thrust force, which is generally larger than the cutting force in hard turning. If the tool loading is thought of as a Hertzian contact, the maximum compressive stress induced in the workpiece occurs at a depth approximately 0.7 times the contact area of the tool. Because the contact area is larger than grinding (a single grit) and load is increased, larger residual compressive stresses that penetrate deeper below the workpiece surface result in hard turned components. This was verified by Brinksmeier et al. [**1982**] and Konig et al. [**1993**]. As expected, the magnitude and depth of residual stresses are a function of tool geometry and process conditions [**Matsumoto et al. 1986, Tonshoff et al. 1995, Brinksmeier et al. 1982 and Thiele 1998**].

Unlike residual tensile stress, reasonable levels of compressive stress are desirable. Based on the residual stress caused by mechanical loading only, hard turned surfaces should exhibit increased fatigue life compared to ground surfaces. However, the undesirable tensile stresses generated by heat are superimposed on the compressive stress [**Tonshoff et al. 1996, Konig 1993**]. As tool flank wear increases, so does the frictional energy between the tool flank and workpiece, as well as the depth of the compressive stress induced by mechanical loading. Thus, increasing tool wear results in larger tensile stresses near the surface, which is then followed by steep stress gradients with a larger compressive stress further below the surface. The stress pattern with less overall change was generated by a tool with very little flank wear compared to the other stress pattern, which was generated with a significantly worn tool.

In addition to tool wear, tool edge geometry has an effect on the residual stress profiles that are generated. Kishawy and Elbestawi [**1998**] investigated the effect of the edge preparation in combination with cutting speed on the residual stresses of hardened D2 tool steel. Thiele et al. [**Thiele et al. 2000**] reported the effects of edge geometry, feed, and workpiece material hardness on subsurface deformation and residual stresses when finish machining hardened AISI 52100 steel.

1.2.2 White Layer Formation in Hard Turning

Hard machining has several potential advantages over grinding including the ability to be carried out dry, greater flexibility in producing complex geometric forms, lower machine tool cost, and comparable surface finish [**Konig et al. 1993**]. Unfortunately, hard turning is yet to find widespread industry acceptance as a viable finishing operation primarily due to the formation of undesirable microstructural artifacts in the near-surface layers after machining. There are two major types of artifacts in the form of surface damage that can be caused by hard turning. The first is white layer, which has generally been assumed to result from temperatures generated at the workpiece surface that exceed the austenitizing temperature of the material, followed by rapid cooling. The second type of damage is the formation of undesirable residual stress profiles at, and just below, the workpiece surface. Mechanical loading, plastic flow, and phase transformation can affect residual stresses, but negative effects are primarily due to the elevated temperatures during machining. Thus, the two types of damage (white layer and tensile residual stress) are related and have generally been investigated together. The white layer is known to be function of the cutting conditions and its thickness ranges from a few microns to a few tens of microns. Abrao et al. [**1995**] reported that at a range of test conditions, the thickness of the transformed layer was below 3 µm.

It is generally believed that generation of white layer requires both excessive heat at the workpiece surface and subsequent rapid cooling. Heat generation is attributed to large amounts of energy generated in the shear region during chip formation and to the frictional energy between the tool flank and workpiece surface. However, experimental results disagree about the source of rapid cooling. Tonshoff et al. [**1995, 1996**] performed hard turning experiments with and without coolant and found the white layer magnitude was identical, indicating that workpiece self-cooling, and not coolant, must be responsible for quenching of the workpiece surface. This argument is reasonable because the heat-affected zone is small in hard turning, and because the cutting velocities are large enough that the contact time between the tool and workpiece is minimal. Therefore, it is possible that the bulk workpiece material acts as a heat sink and draws heat from the surface to create a self-cooling effect. However, Konig et al. [**Konig et al. 1990**] found that cutting with a worn tool produced white layer, but that similar cutting conditions with the application of coolant resulted in undamaged surfaces.

Many researchers have paid considerable attention to the generation of white layer because it appears similar to thermal damage generated in grinding that is referred to as "grinding burn." To determine the structure of white layer, Tonshoff et al. [**1995**] used an X-ray technique to determine the separate structures of the bulk workpiece material and the white layer region. The results showed that for 16MnCr5 steel hardened to 60-62 HRC, the bulk material was composed of approximately 75% martensite and 25% austenite. The white layer consisted of only 30% martensite and almost 70% austenite. However, inspection of chemical concentrations when machining ASTM 5115 showed no difference between the surface layer and bulk [**Tonshoff et al. 1995**]. Apparently, the crystallographic structure may change, but there is not sufficient time for diffusion. It is commonly thought to be composed of un-tempered martensite. Furthermore, based mainly on knowledge of thermal damage or "burn" in grinding processes, white layers are generally considered to be detrimental to fatigue life since they are known to be hard and brittle and can be associated with tensile surface residual stresses [**Brinksmeier and Brockhoff 1999, Griffiths 1987**].

Besides machining and grinding, white layers have been reported in other operations such as rubbing, rail-wheel contact and under a wide range of process conditions. Griffiths [**1987**] reported three situations where white layers have been generated: surfaces subjected to significant rubbing and wear (railroad tracks as an example), surfaces that see similar conditions resulting from pin-on-disk testing, and surfaces that undergo certain machining processes. Brinskmeier and Brockhoff [**1999**] presented evidence that in addition to machining conditions, material properties affect white layer generation. They attributed formation of all white layers to heating and quenching of the material, and concluded that chemical composition of the material affects the transformation. Griffiths [**1987**] did not agree that all white layers are caused by a transformation, and suggested that other causes may be surface reactions with the environment and plastic flow that causes grain refinement. Several publications have proposed that white layers may have increased hardness relative to the bulk material [**Brinksmeier and Brockhoff 1999, Tonshoff et al. 1995, Akcan et al. 1999**]. Others have reported nearly identical hardness in the white layers compared with the bulk material [**Chou and Evans 1999**]. White layer is usually accompanied by a 'dark layer' underneath it, although dark layer may appear without white layer [**Chou and Evans 1999**]. As the name implies, dark layer appears darker than the bulk material after etching.

Several investigations have shown that, irrespective of the process used to generate them, white layers are harder than the parent material. Akcan et al. [**2002**] attributed this to the very fine grain size of the white layer. The very fine grain size (<100 nm) in the white layer has also been reported by others. With the exception of a few investigators, much of the current literature suggests or assumes that white layers formed in grinding and machining of hardened steels are due to a thermally-induced martensite ($\gamma - \alpha$) phase transformation effect. Brinskmeier and Brockhoff [**1999**] discussed evidence of martensite transformation in ground AISI 52100 and SAE 5045 hardened steels. However, white layers are known to form even under conditions where the temperature rise is too low for re-austenitization to occur or in relatively soft materials such as brass. Therefore, it is apparent that white layers may be formed by phenomena other than thermally driven martensitic phase transformation.

Such cases can arise in hard turning as well, since white layers have been reported to form at fairly low speeds and feeds, where temperatures may not be very high. Abrao and Aspinwall [**1996**] and Thiele and Melkote [**2000**] reported white layer formation in AISI 52100 steel while turning with chamfered and new tools with hone (tools with a finite cutting edge radius but negligible wear). An over-tempered layer was observed just below the white layer produced. Similar results were observed when cutting hardened AISI 4340 steel [**Ramesh et al. 1999**]. On the other hand, white layers are also known to form under conditions of large flank wear and high cutting speeds, where temperatures reached may be sufficient for $\alpha - \gamma$ transformation to occur [**Chou and Evans 1999, Ahcan et al. 2002, Brinskmeier and Brockhoff 1999, Barry and Byrne 2002**]. In other words, white layers formed in cutting of hardened steels have been reported under conditions where temperatures and strain fields are very different. This suggests that the mechanisms of formation of white layers under different cutting conditions and their corresponding mechanical properties are not likely to be the same. Ramesh et al. [**2005**] concluded that the predominant mechanism of white layer formation at the highest cutting speed is martensitic phase transformation, which is aided by plastic deformation accompanying chip formation/surface generation. One the other hand, the predominant mechanism of white layer formation at the lower cutting speeds is believed to be grain refinement due to severe plastic deformation, a mechanism similar to that known to take place in other severe deformation processes such as equal channel angular extrusion [**Prangell et al. 2001**]. The white layers formed in AISI 52100 steel (62 HRC) were considerably smaller than the bulk. It was also shown that white layers generated at higher machining speeds were coarser than those generated at lower speeds [**Ramesh et al. 2005**].

1.2.3 Mechanism of Chip Formation during Hard Machining

A significant amount of research in hard turning has focused on understanding chip formation. The mechanics of chip formation in hard turning are very unlike chip formation in softer steels, where continuous chips have typically been observed. This type of chip formation was the basis of early machining models as shown by Merchant [**1944**] as well as Lee and Shaffer [**1951**]**.** Chip types, i.e. continuous, saw-tooth, or discontinuous, of the steel AISI 4340 in machining depends on the combined effects of workpiece material properties, cutting speed, and tool geometry. Discontinuous chips are usually formed in hard machining at large speeds for achieving high production efficiency. The mechanism of discontinuous chip formation is due to the internal crack initiation and extension in front of the tool and meeting with the surface crack. Adiabatic shearing plays an important role in discontinuous chip formation [**Guo and Yen 2004**]. However, many machining operations produce cyclic chips that can be described as the wavy chip, the catastrophic shear chip, the segmental chip, and the discontinuous chip **[Komanduri and Brown 1981]**. In hard turning, periodic saw-toothed chips have been observed by many researchers. Two separate explanations of the mechanism that causes this type of chip formation have developed.

The first theory suggests that chip segmentation is initiated by shear fracture, caused by a compressive stress induced by the cutting tool that exceeds the critical shear stress of the material at the free surface of the workpiece **[Shaw 1993, Vyas and Shaw 1997]**. The crack creeps toward the cutting edge until the compressive strength is sufficient to stop crack propagation and cause plastic deformation of the remaining portion of the chip segment along the fracture line. As the tool continues to move, the chip segment is pushed out along the fracture line, and a new chip segment forms as the compressive stress builds and a new shear fracture initiates ahead of the cutting edge.

A second theory describes the chip segmentation mechanism as catastrophic strain localization **[Davies et al. 1996, Kishawy and Elbestawi 1997]**. Strain localization occurs when thermal softening behavior dominates over the effects of strain rate hardening in the shear zone. This behavior has been observed in many materials with poor thermal properties, such as titanium and nickel alloys. These materials' ability to deform plastically can vary with temperature due to a possible phase transformation and the resulting changes in crystal structure **[Davies et al. 1995]**. The conditions for strain localization are typically met when the strain rate exceeds a critical value. This critical strain rate is a material property, and can be exceeded with increasing cutting velocity. Evidence of this theory is the onset of chip segmentation above a critical cutting velocity **[Kahles and Field 1967]**.

Cutting chips becomes blue in color due to intensive high temperature during machining. With the increase in cutting speed, feed, depth of cut and hardness of the work material the chips turns to gradual deep blue. Due to working parameter values, the cutting of AISI 4340 induces different chip morphologies; continuous, segmented, or discontinuous [**Mabrouki and Rigal 2006**]. Many previous experimental works [**Poulachon et al. 2002, Mabrouki et al. 2004**] show that chip morphology is affected by working parameters (cutting speed, feed) and hardness of the material. Kosa and Ney [**1989**] suggested that in machining ductile metals, the heat and temperature developed due to plastic deformation and rubbing of the chips with tool, may cause continuous built-up of welded debris which affects machining operation. Austenitic stainless steels are generally considered difficult-to-machine because of high work-hardening rate, toughness and ductility. Therefore, tools will be subjected to high frictional heat, and chips will have a tendency to stick and cause severe built-up edge formation. It was observed [**Jawahir and Luttervelt 1993**] that, in machining ductile metals, producing long chips, the chip-tool contact length have a direct influence on the cutting temperature and thermo-chemical wear of cutting tools. The cutting temperature becomes the maximum on the rake face of the tool at a certain distance from the cutting edge where cratering occurs. Such high rake face temperature can also raise the temperature at the flank of the tool. Komanduri and Schroeder [**1993**] reported that machining Inconel with hot-pressed ceramic and cubic boron nitride cutting tool produces different types of longitudinal chips. At lower speed (<30 m/min) the chips are mechanically continuous although highly coiled. With increased speed (up to about 91.5 m/min), shear localization is initiated. The chips formed are comprised of many segments strongly joined together forming a continuous tight coil. With a further increase in speed, the extent of contact between the segments decreases. At about 152.5 m/min, short chips with only a few segments joined together are produced, and from this speed onward, the chip segments are completely isolated. Pashby et al. [**1993**] proposed that the cutting speed at which a change in chip form occurs varied from tool material to tool material. Kitagawa et al. [**1997**] conducted experiments with ceramic tool under flood cooling condition and concluded that with increase in cutting speed, serrations in the chip become obvious and the chip thickness decreases.

Vleugels [**1995**] observed that the contact length between the tool and chip has a direct influence on the cutting temperatures and the amount of heat energy that is dissipated in the tool which enhances thermally activated chemical wear. Toropov and Ko [**2003**] also reported that, in machining ductile metals, the chip contact length plays significant role on the chip and tool temperature which becomes maximum almost at the centre of the chip-tool contact surface where crater wear begins and grooves intensively.

Generally, shear angle decreases with increase in cutting velocity and a high shear angle improves the machinability of steel. Masatoshi Hirao et al. [**1996**] concluded that molybdenum and vanadium mixed nitriding steel produces long cutting chips at low cutting velocity but the cutting tool is sometimes broken by long continuous chips which affects shear angle. Duan and Wang [**2005**] suggested that an increase of work material hardness increases the shear angle, the temperature and the yield strength but reduces the average stress ratio on the primary deformation zone. Sutter [**2005**] reported that continuous chip forms during machining material having good thermal property and low hardness, whereas ribbon like chip or a segmental (or shear localized) chip forms during machining material having poor thermal property and high hardness.

The cutting mechanisms of hard steels and alloys lead to the formation of saw tooth chips, which can be classified as wavy chip, segmental chip, shear localized, and discontinuous chip [**Komanduri and Brown 1981**]. Saw tooth chips cover localized shear, adiabatic shear, as well as catastrophic shear. Such chips are periodic and formed of identical segments, their morphology being the result of instable conditions depending on:

- mechanical, thermal, thermo-mechanical properties of the material
- cutting conditions
- divergence of shearing in the primary zone
- divergence tribological conditions at the interface between the rake face and the inner face of the chip
- possible interactions between primary and secondary shearing zones
- dynamic response of the machine tool structure and its interaction with the cutting process

The machinability of high strength steels includes the conditions under which the formation of adiabatic shear bands can occur, adiabatic shear covers both coupled mechanical and thermal phenomena, the result being a thermal softening of the steel; such self-catalytic and cyclic plastic deformation will occur particularly if the conductivity is poor [**Shaw and Vyas 1998, Shaw 1967**]. Similar chip morphology has also been observed during the machining of ductile materials when they are enbrittled either by work-hardening or by thermal treatment; moreover, in such cases one can observe that cyclic shearing is due to crack initiation at chip surface. The result obtained from quick stop identifies the four stages of the formation of a saw tooth chip [**Poulachon and Moisan 2000**] these successive stages are presented in Fig.1.1 and are described below:

Stage 1: a negative rake angle (γ_f) includes compressive stresses distribution in a zone around the edge radius (r_β). At the workpiece surface before the tool chamfer the joint effects of low values of compression stresses and high shear stresses initiate a crack, followed by a slip plane which runs towards the cutting edge.

Stage 2: the chip volume mentioned $AA'BB'$, in Fig.1.1 and situated between the crack and the edge chamfer is ejected practically without any deformation. The gap AA' closes progressively as the tool moves forward, and the height of the chip h_c, decreases. The speed of the chip upon the rake face of the tool and at the crack transition point A' is so large that it will generate a considerable increase in temperature, near the transformation point (A_3), so that martensite produced by friction can occur in the form of white layers surrounding the chip segment; in addition, a similar white exists on the generated surface, due to the intense and severe friction occurring at the tool land face, and the high value of the thrust force F_f.

Stage 3: the width of the gap AA' gets so narrow that the ejection speed and the plastic deformation of the chip are very high. The increase in temperature is very important, and the two previous white layers join to form the second part of the chip segment. Here, the chip thickness is very small and its cooling is extremely fast.

Stage 4: the chip segment is now formed and the free gap AA' is closed. The compressive stresses distribution, which had decreased during stage 2 and 3, becomes again more important, including a new crack and this periodic phenomenon will repeat itself.

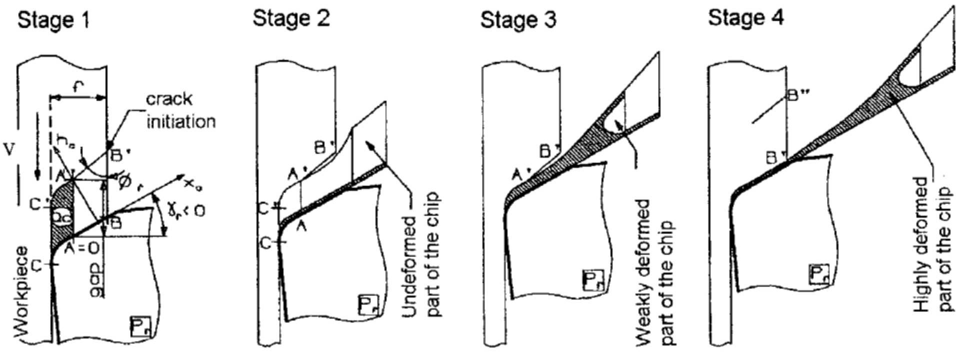


Fig. 1.1: The different stages of the saw-tooth chip formation.

Poulachon and Moisan [**2000**] found that the two main parameters influencing the chip morphology are the hardness of the material and the cutting speed. Localized shear chip occurs from a hardness value of 53 HRC and also for medium hard steels but at higher speeds. It results that the effects of the cutting speed and the hardness are interdependent. The chip formation mechanism based on the occurrence of a crack concerns very hard steels on account of their higher brittleness. Chip formation by cracking may occur with less hard steels but at higher speeds. Mabrouki and Rigal [**2006**] has found out about chip morphology that, the velocity of the cutting phenomenon induces the material removal of AISI 4340 by adiabatic shearing corresponding to a localization of the deformation in the chip. The latter is characterized by a thermal softening appearing in narrow periodic zones characterized by high straining levels. Consequently, the chip has saw-tooth morphology. The segmentation phenomenon is more marked as the heat evacuation, generated during cutting, is in the chip and not in the tool nor in the workpiece.

According to Muller and Blumke [**2001**], high speed machining for a given material can be defined as that speed above which shear-localization develops completely in the primary shear zone. Ekinovic et al. [**2002**] showed that when hardened steel is machined, high speed machining conditions appeared at cutting speed above 150 m/min. Their conclusion was drawn on the basis of evaluation on chip shape collected during machining. Silva et al. [**2013**] investigated the high pressure coolant condition machining of titanium alloy with PCD tools and concluded that segmented chips are generated when machining with high pressure coolant supply, while long continuous chips were generated when machining with conventional coolant flow.

1.2.4 Temperature Control with High Pressure Coolant Jet

Machinability of materials usually judged mainly in respect of chip morphology, chip tool interaction, cutting temperature, cutting forces, dimensional accuracy, surface integrity and wear and life of cutting tool with using cutting fluid and without using cutting fluid. Heat generation and high cutting temperature is inherent characteristics of machining due to shearing of work material, friction between the flowing chips and rake face of the tool as well as friction of auxiliary flank with finished surface. At such elevated temperature the cutting tool if not enough hot hard may loose their form or stability quickly or wear out rapidly resulting in increased cutting forces, dimensional inaccuracy of the product and shorter tool life. The magnitude of this cutting temperature increases, though in different degree, with the increase of cutting velocity, feed and depth of cut, as a result, high production machining is constrained by rise in temperature. This problem increases further with the increase in strength and hardness of the work material. Usually water soluble cconventional cutting fluid is applied to control such elevated cutting temperature but it is ineffective in high speed machining and also is a major source of environmental pollution in the machining industries. Research has also been initiated on control such pollution by neat and clean machining like Cryogenic cooling, MQL cooling and high-pressure coolant (HPC) machining and their technological effects particularly in temperature intensive machining and grinding. A brief review of some of the interesting and important contributions in the closely related areas is presented in this section.

The high specific energy required in machining under high cutting velocity and unfavorable condition of machining results in very high temperature which reduces the dimensional accuracy and tool life by plastic deformation and rapid wear of the cutting points [**Chattopadhyay and Bhattacharya 1968, Chattopadhyay and Chattopadhyay 1982, Singh et al. 1997**]. On the other hand, such high temperature impairs the surface integrity of the machined component by severe plastic flow of work material, oxidation and by inducing large tensile residual stresses, surface and subsurface cracks [**Chattopadhyay and Chattopadhyay 1982**].

The mechanisms of material deformation, friction and material removal lead to the initiation of machined components, where the temperature of the rake and flank is the most important factor to affect the chip formation, tool wear, cutting forces and surface integrity [**Aronson 2004, Jaspers and Dautzenberg 2002**]. At elevated temperature and pressure the cutting edge deforms plastically and wears rapidly, which lead to dimensional inaccuracy, increased cutting forces and premature tool failure [**List et al. 2005**].

Ng et al. [**2002**] proposed that there is a peak cutting temperature at an intermediate cutting speed and when cutting speed is increased from this point, there is a reduction in temperature. Since this claim most of the literature has concluded that there is no corresponding reduction in temperature at higher cutting speeds. Conversely, Vernon and Ozel [**2003**] stated that the limit of cutting speed is a function of the cutting tools used. Ekinovic et al. [**2005**] suggested that temperature is increased with cutting speed up to maximum which is equal to the melting point of the work piece. No temperature reduction occurred at higher cutting speeds. But there is no fixed limit to the cutting speed when machining aluminum alloy because the melting point of this alloys (up to 600ºC) is lower than the temperature at which cemented carbide and ceramic tool materials begin to lose their strength and wear rapidly. Liu et al. [**2002**] observed that the cutting temperature is optimum when the work piece material hardness is HRC 50. With further increase in the work piece hardness, the cutting temperature shows a descending tendency. Liu et al. [**2002**] also suggests that, under different cutting parameters, the role of cutting force changes with work piece hardness. The main cutting force features an increasing tendency with the increase of the work piece hardness. Reed and Clark [**1983**] reported that the hardness, plastic modulus and the fracture toughness of the tool decline with increase in cutting temperature, which accelerates tool wear rate. Moreover, thermal stresses in the tool increase with the temperature resulting in more cracks in the tool and premature failure of the tool. The amount of energy dissipated through the rake face of the tool raises the temperature at the flanks of the tool [**Wu and Matsumoto 1990**].

The high pressure coolant flow traverses the surface faster, significantly lowering the film boiling action of the coolant, penetrating deep into the cutting area and achieving high chip breakability through increased chip up-curl [**Whertheim et al. 1992**]. This consequently reduces the chip-tool contact area, minimizes friction at the chip-tool interface, limits heat transfer to the cutting tool and consequently improving tool performance during machining [**Ezugwu et al. 2011**]. Machining of alloys at high speed conditions can be achieved by a combination of the appropriate tool material, machining technique and the choice of a suitable cooling technology [**Ezugwu et al. 2003**]. High pressure assisted cooling is one of the preferred technologies, currently, under exploitation especially in the aerospace and power plant industries for machining exotic materials. The credibility of high-pressure coolant assisted machining had been thoroughly investigated over the years [**Mazurkiewicz et al. 1989, Ezugwu et al. 1990, Machado and Wallbank 1994, Kovacevic 1994, Ezugwu et al. 2005**]. The system not only provides adequate cooling at the tool-workpiece interface but also provides an effective removal (flushing) of chips form the cutting area. The coolant jet under such high pressure is capable of creating a hydraulic wedge between the tool and workpiece, penetrating the interface deeply with a speed exceeding that necessary even for very high speed machining. This phenomenon also changes the chip flow condition [**Kovacevic et al. 1995**]. The penetration of the high-energy jet at the tool-chip interface reduces the temperature gradient and minimizes the seizure effect, offering an adequate lubrication at the tool-chip interface with a significant reduction in friction. Excellent chip breakability has been reported when machining difficult-to-cut materials with high-pressure coolant supply [**Wrethim et al. 1992, Crafoord et al. 1999, Nabhani 2001**]. This is attributed to a coolant wedge, which forms between the chip and tool forcing the chip to bend upwards giving it a desirable up curl required for segmentation. There is a drastic reduction in the cutting forces required to remove material from the work piece with the application of high-pressure coolant jet.

Nagpal and Sharma [**1973**] proposed that tool-chip interface temperature initially decreases with an increase in jet pressure, up to critical pressure, above which it rise to a relatively constant value for pressures in excess of the critical pressure. Mazurkiewicz et al. [**1989**] reported that a coolant applied at the cutting zone through a high-pressure jet nozzle can reduce the contact length and coefficient of friction at chip-tool interface and thus can reduce cutting forces and increase tool life to some extent. In machining ductile metals even with cutting fluid, the increase in cutting velocity reduces the ductility of the work material and causes production of long continuous chips, which raises the cutting temperature further [**Nedess and Hintze 1989**]. In general, the attempts to apply pressurized cutting fluid can be classified into three groups, such as:

- Coolant/lubricant jet injected into tool-chip interface through an external nozzle [**Mazurkiewicz et al. 1989**]
- Jet delivered into the clearance between flank and machined surface, and

- Jet injected directly through the tool rake face into tool-chip interface [**Wrethim 1992, Mazurkiewicz et al. 1989**].

Kovacevic et al. [**1995**] suggested that the application of high-pressure water jet through the tool rake face, friction is reduced at the tool-chip interface due to formation of a cushion layer, which prevents intimate contact at the tool-chip interface, consequently leading to bending and self-breakage of chips. Whereas in the case of high-pressure water jet through an external nozzle, tool-chip contact area is reduced due to the breakage of the chip by the impinging jet. The enhance effectiveness of the coolant/lubrication by applying the cutting fluid at high pressures in the form of a narrow jet, leads to a reduction in the quantity of the cutting fluid being used, reducing the amount of disposal which is a primary concern of Environmental Protection Authorities.

Cozzens et al. [**1995**] conducted an experimental investigation on single point boring aiming to study the role of cutting fluid, tool and workpiece material, tool geometry and cutting conditions on machinability. The results indicated that the cutting fluid conditions have no significant effect on surface texture, forces and built-up edge. Since boring is a high-speed operation and lubrication is ineffective, no effect was seen on the forces. However, the cutting fluid was found to have a significant effect on surface integrity.

Ezugwu et al. [**1990**] observed that coolant supply at high-pressure tends to lift up the chip after passing through the deformation zone resulting to a reduction in the tool-chip contact length/area. Chip segmentation is considerably enhanced, as the chip curl radius is reduced significantly, due to targeted maximum coolant pressure/force on to the chip which aids the chip shearing process and consequently lowering cutting forces. Coolant is one of the most influential factors affecting tool performance when machining nickel-based alloys [**Cozzens et al. 1995, Khamsehzadeh 1991**]. The use of a high-pressure coolant supply when machining nickel-based (Inconel 901) super alloy with cemented carbide tools gives higher tool lives than when machining with the conventional coolant supply [**Ezugwu et al. 1990**]. The use of a high-pressure coolant supply results in a significant reduction in the tool-chip contact length, and hence in the contact area, which in turn decreases the compressive stress at the tool edge with little change in the cutting forces. This prevents the formation of notching, thus leading to a higher tool life.

Proper selection and application of cutting fluid generally improves tool life. At low cutting speed almost four times longer tool life is obtained by proper cutting fluid [**Satoshi 1997**]. However, surface finish does not improve significantly. Wearing of cutting tools not only causes loss of the cutting edges or tips of the inserts but loss of the entire insert after wear of all the corners. It was reported that coolant injection offers better cutting performance in terms of surface finish, tool force and tool wear when compared to flood cooling [**Alaxender et al. 1998**]. The chip curl radius also depends on the coolant pressure and the flow rate. Therefore at a given power, smaller chip curl radius can be achieved at a lower coolant pressure with a high coolant flow rate [**Crafoord et al. 1999**]. From an environmental perspective, therefore, the significant waste is not the portion of the tool worn away by the tool-work contact, but the remaining portion of the tool that is disposed after its useful life [**Arunachalam and Mannan 2000**]. Cutting tools operate within a safety temperature zone with minimal tool wear when machining at the critical coolant pressure as thermal stresses are kept to a minimum, thereby prolonging tool life [**Ezugwu and Bonney 2003**].

Ezugwu and Bonney [**2004**] reported that machining Inconel-718 with coated carbide inserts under high-pressure coolant supplies improve tool life by up to 7 folds, especially at high speed conditions. Tool life tends to improve with increasing coolant pressure. There is also evidence that once a critical pressure has been reached any further increase, in coolant pressure may only result to a marginal increase in tool life. Lower cutting forces [**Kovacevic 1994, Ezugwu et al. 2005**] are recorded with increasing coolant supply pressure when machining Inconel 718 with SiC whisker reinforced alumina ceramic tool. The reduction in cutting forces observed is also partly due to the chip segmentation when machining with high-pressure coolant supplies. Higher forces [**Ezugwu et al. 2005**] are recorded when machining with conventional coolant flow where continuous type chips are generated.

Chip segmentation is another advantage of employing the high-pressure cooling technique. Because the tool contact time is shorter, the tool is less susceptible to dissolution wear caused by chemical reaction with newly generated chips [**Lindeke 1991**]. A more recent study of the effect of high-pressure coolant flow in face milling of Ti-base Ti-6Al-4V alloy with cemented carbide tools reported a 2.5 times increase in tool life than when machining with conventional coolant flow [**Klocke 2002**]. Studies have shown that it is possible to increase cutting speed by over 67 and 150% when machining titanium alloys with carbides under high coolant pressures of 15 and 30 MPa, respectively, compared to conventional coolant supply.

1.2.5 Research on Tool Wear in Hard Turning

The useful life of a tool is limited by tool wear. The principle concern of metal cutting research has been to investigate the basic mechanism of wear by which the life of a tool is governed. Wear can be described as total loss of weight or mass of the sliding pairs accompanying friction. The wear between two rubbing surfaces occur due to

- ➢ Macrotransfer type mechanical wear process like abrasion and adhesion
- ➢ Microtransfer type thermochemical process like diffusion
- ➢ Electrochemical process like localized galvanic action, oxidation, etc.

Tool rejection criteria for finishing operation were employed in this investigation. The values established in accordance with ISO Standard 3685 for tool life testing. A cutting tool was rejected and further machining stopped based on one or a combination of rejection criteria [**Ezugwu et al. 2005**]:

i.	Average Flank Wear	≥	0.3 mm
ii.	Maximum Flank Wear	≥	0.4 mm
iii.	Nose Wear	≥	0.3 mm
iv.	Notching at the depth of cut line	≥	0.6 mm
v.	Average surface roughness value	≥	1.6 µm
vi.	Excessive chipping (flanking) or catastrophic fracture of cutting edge.		

While much attention has been paid to the influence of hard turning on surface integrity, surprisingly little has been done to understand the effects of resultant surface integrity on performance (wear resistance, strength, fatigue resistance, etc.). Significant concerns exist about white layer and tensile residual stresses on the workpiece surface, but most research has disputed these concerns about hard turned surface quality. Griffiths and Furze [**1987**] showed that white layers reduced wear when running block-on-ring tests on EN24T (similar to AISI 4340). Tonshoff and Brinksmeier [**1980**] attempted to use micro-hardness and residual stresses to identify mechanical and thermal influences on the workpiece and relate this to functional behavior. Matsumoto et al. [**1991**] fly cut AISI

4340 at 58 HRC and found that hard machined fatigue samples exhibited slightly increased endurance limits compared to ground samples. Rotating bending tests showed a 7% decrease in fatigue limit with increased tool wear [**Tonshoff et al. 1995**]. The results also indicated that hard turned surfaces always exhibited comparable fatigue strength to ground surfaces. Abrao and Aspinwall [**1996**] performed axial fatigue tests on hard turned bars, and found that bars turned with PCBN tools performed better than bars machined with alumina tools and also better than ground surfaces. Matsumoto et al. [**1999**] showed similar results, indicating that hard turned and super finished components had comparable or improved fatigue life. Smith [**2001**] found improved wear resistance and axial fatigue life on hard turned surfaces, even with white layers.

Most of the major parameters including the choice of tool and coating materials, tool geometry, machining method, cutting speed, feed rate, depth of cut, lubrication, must be controlled in order to achieve adequate tool lives and surface integrity of the machined surface [**Ezugwu and Tang 1995, Wang 1997**]. A crater is usually formed at some distance from the cutting edge and it is most frequently observed when cutting steels and other high-melting-point metals at relatively high cutting speeds [**Choudhury and Rao 1999**]. This crater gradually becomes deeper with time and may lead to the breakage of the cutting edge, rendering the tool useless.

Luo et al. [**1999**] reported that when turning AISI 4340 steel using mixed alumina and PCBN tools the flank wear is reduced as work material hardness increased up to a critical value. A further increase in the work piece hardness accelerates the tool wear rate. The reduction in tool wear up to critical is attributed to the elevation of the cutting temperature, which reduces the shear strength of the work material; however, this effect is not observed when the hardness exceeded critical value. The material transfer leads to the formation of a crater on the tool rake face and consequently reduces the tool mechanical resistance and its efficiency. Even if the issues of machine tool design, dimensional accuracy, and surface integrity can be addressed satisfactorily, tool wear remains a major obstacle to further implementation of hard turning. Most research in the area of tool wear has focused on the influence of tool material properties, workpiece material properties, and cutting conditions on wear behavior, although some studies have also reported the effects of wear on surface integrity.

Resistance to tool wear is related to CBN content, grain size, binder material, tool geometry, cutting edge geometry (sharp, honed, or chamfered), workpiece properties, and cutting conditions. The effects of tool wear include: reduced tool life, increased surface roughness, increased cutting forces; more tensile residual surface stresses, and increased white layer thickness. While tool wear and tool life ultimately dictate whether or not hard turning can produce acceptable surfaces over the life of a tool, and whether or not it can be justified economically compared to grinding, research in the area of tool wear seems to have taken a back seat to studies of chip formation and surface integrity. This seems unfortunate because the research has shown that acceptable surfaces can be produced at proper conditions, so for many applications uncertainty about wear behavior is all that has limited hard turning.

Tool material properties and workpiece properties obviously affect the wear behavior of tools. Several efforts have focused on tool composition, with the goal of determining optimal mixtures for the composite tools used in hard turning. Bossom [**1990**] showed that low CBN content tools (<70% CBN) produced better tool life and surfaces than high CBN content tools (>90%). Similar results have been cited by many others [**Matsumoto et al. 1999**]. Takatsu et al. [**1983**] performed tests on JIS SUJ2 bearing steel hardened to 62 HRC with tools that were identical other than CBN content. They found that flank wear and crater wear were both minimized at a CBN percentage of 55%. This confirms that lower CBN content tools perform better than high CBN content tools, but no consistent explanation for the improved performance has been presented.

Workpiece material properties also affect the wear behavior of PCBN tools in hard machining. Luo et al. [**1999**] machined AISI 4340 steel at hardness ranging from 35-55 HRC, and found that hardness affected cutting forces and tool life. Both cutting forces and tool life were optimal (low forces, long life) at a workpiece hardness of 50 HRC. Silva et al. [**2013**] investigated machining of hard material *i.e.* Ti-6Al-4V with ultra hard Polycrystalline Diamond (PCD) tools using high pressure coolant and concluded substantial improvement in tool life ranging from 9 to 21 folds. They also found there is no significant difference in tool performance when machining at high speed conditions. Matsumoto and Narutaki [**1996**] found adhesion of iron on the tool face when turning hardened steel with a high CBN content tool, and proposed that this adhered layer contributed to decreased tool life. However, they also found that adhesion of MnS on the tool face when machining a carburized bearing steel created a lubricating layer that reduced tool/chip friction and increased tool life. Barry and Byrne [**2001**] found a 400% difference in the wear rate of nominally similar 4340 steels with only slight differences in the workpiece inclusion content and size. According to Trent [**1983**], the cutting tool generally undergoes both flank wear and crater wear during machining. Flank wear generally causes an increase in the cutting forces, dimensional inaccuracy and vibration. Crater wear takes place on the rake face of the tool where the chip slides over the tool surface. Wang et al. [**1996**] reported that the normal turning chips often have considerable strength and cause crater wear, crack development or other kinds of surface damage on the rake face of the tool. Da silva [**2006**] reported that rapid increase in nose wear rate occurred when machining Ti-6Al-4V alloy with PCD tools using conventional coolant flow at the cutting conditions investigated. The ability to remove heat from the cutting tool increases with increase in coolant pressure. Machado [**1990**] observed significant reduction in tool temperature when machining super alloys, achieved through high pressure coolant delivery. Silva et al. [**2013**] also reported that strength of cutting tools is improved. This tends to minimize tool wear, thus increasing tool life.

It seems that no cohesive body of knowledge has developed to explain the interactions between the cutting tool and workpiece that lead to tool wear. Surely research will continue in this area until wear phenomena are better understood. In the meantime, it is also important to understand the effect of tool wear on the hard turning process, and more specifically, on the quality of machined surfaces. Since much attention has been paid to surface integrity, the general influence of tool wear on white layer generation and residual stresses is better known that the mechanisms for tool wear itself. In general, CBN tools form scars on both the flank and rake surfaces of the cutting tool. Historically, flank wear has been studied more than crater wear because it is easier to measure and because it is believed to relate more directly to surface finish and surface integrity [**Abrao et al. 1995**]. Increasing flank wear tends to increase the friction between the tool and workpiece, and the additional heating that results from friction was shown to cause white layer formation by Konig et al. [**1993**]. They also reported that the thermal effects from increased friction lead to more tensile residual stresses at the workpiece surface, but more compressive subsurface stress profiles. Flank (and nose) wear are the dominant failure modes when machining the titanium, Ti-6Al-4V, alloy with PCD inserts using conventional and high pressure coolant supplies [**Silva et al. 2013**]. They also concluded adhesion and attrition are dominant wear mechanisms at the cutting conditions investigated. Chou and Barash [**1995**] suggested that flank wear is the main contributor to white layer formation. Chou and Evans [**1996**] showed that surface roughness and cutting forces increased significantly with flank wear when turning M50 steel. They found similar results for M50 formed by powder metallurgy [**Chou and Evans 1997**] and Sista et al. [**1997**] showed similar results when hard turning M2 tool steel.

Kitagawa et al. [**1997**] investigated tool wear and cutting tool temperature by means of turning experiment in the presence of 10% water base coolant. Temperature rose monotonically, up to about 1200º C, with increasing cutting speed. They confirmed that notch wear VN were the major types of wear observed. However taking into account the decreasing of notch wear at higher cutting speed, they estimated that the wear characteristics observed cannot be exclaimed by temperature alone and the wear is rather developed by an abrasive process than a thermally activated adhesion mechanism.

Diffusion phenomena were first reported by Molinari and Nouari [**2000**] who showed that at conventional speed, tool wear is mainly due to abrasion and adhesion, but is dominated by diffusion process at higher speeds. The strong bond existing at the chip tool interface [**Nabhani 2001a**] and the high diffusion rate [**Bhaumik et al. 1996**] in addition to the instability of the segmented chip formation process are responsible for accelerated tool wear during machining [**Nabhani 2001b**].

Severe flank wear and notching at the tool nose and/or the depth of cut line are the dominant failure modes when machining nickel-based alloys with carbide tools [**Wang et al. 1996, Ezugwu and Wang 1996, Kaminski and Alvelid 2000**]. The recommended cutting speeds range is from 10 to 30 m/min when machining nickel-based alloys with cemented carbide tools [**Fang 2002**]. Cemented carbide tools cannot be used to machine nickel-based alloys at high speed since they cannot withstand the conditions of extreme high temperature and stress in the cutting zone. Rapid increase in notching occurs on carbide tools at higher cutting speed. This usually leads to the premature fracture of the entire insert edge [**Ezugwu and Bonney 2004**]. Flank wear generally causes an increase in the cutting force and the interfacial temperature, leading normally to dimensional inaccuracy in the work pieces machined and to vibration which makes the cutting operation less efficient [**Bouzid et al. 2004**]. Large nose radius and cutting edge angle values may improve the surface finish of the machined part provided tool vibration can be avoided [**Kopac and Bahor 1999**].

Because tool wear affects cutting forces, cutting temperatures, resultant surface quality, and tool life, it is important to quantify this behavior and relate it to changing process conditions. A summary of the literature indicates that tool wear tends to increase workpiece temperatures, increase cutting forces (especially the thrust force), cause more tensile residual stresses, generate larger white layers, and diminish surface finish. However, most work has been qualitative in nature. Research that investigated wear of different grades of tool materials on various workpiece materials has not produced quantitative descriptions of wear modes. Research focused on the effects of wear on temperatures, forces, and surface quality has not sufficiently described the condition of the cutting tool, because the effect of the crater scar on the cutting process has been neglected. Surprisingly, the effects of process conditions (speeds, feeds, and depth of cuts) on wear behavior are relatively scarce in the literature. Thus, this research aims to describe in a quantitative way the influence of cutting conditions on the chip formation mechanism, wear behavior of carbide tool and relate the wear behavior to changes in cutting temperatures and resultant surface quality.

1.2.6 Summary of the Review

The literature review on hard turning and machinability of hardened steels highlights the vast potential of the control of machining temperature and its detrimental effects. It is obvious that the machining temperature holds a vital influence on chip formation, tool life, tool wear and surface quality. All these responses are very important in deciding the overall performance of the tool and the cooling system applied. At an elevated temperature the cutting tools may undergo plastic deformation and attain rapid tool wear because of adhesive, abrasive, chemical and diffusion wear at the flanks and the crater. The dimensional accuracy and surface integrity of the work piece also deteriorate due to high temperature. The conventional cutting fluids are not that effective in high speed machining particularly in continuous cutting of materials like hardened steels. Furthermore, the conventional cutting fluids are not environment friendly. The disposal of the cutting fluids often leads to local water pollution and soil contamination. Recycling and reuse of conventional cutting fluids are further problematic.

From all these investigations, it is evident that applying cutting fluid in the form of a jet at higher pressure into the cutting zone is more beneficial than conventional cooling techniques. A high-pressure fluid jet brought as a coolant/lubricant through a hole in the rake face of tool reduces secondary shear, lowers interface temperatures, and changes chip shape. In practice, at low pressure the cutting fluid is not capable of penetrating deep enough into the tool-chip interface to dissipate heat as quickly as possible from the appropriate regions in the cutting zone. Further, all these investigations are limited to stationary single edge cutting tool operations. However there is a great crave for improving machining performance by perking up cooling methods in the case of turning, drilling and milling especially while machining difficult to machine materials.

HPC jet cooling is a promising technology in high speed machining, which economically addresses the current processes, environmental and health concerns. In this unique process cutting oil is impinged through a nozzle precisely at the narrow cutting zone. The success of implementing this technology across the metal removal industries is therefore depends on increased research activities providing credible data for in depth understanding of high-pressure coolant supplies at the chip-tool interface and integrity of machined components.

The growing demands for high MRR, precision and effective machining of exotic materials is restrained mainly by the high cutting temperature. It is revealed from the abovementioned literature survey that the cutting temperature, which is the cause of several problems restraining productivity, quality and hence machining economy, can be substantially controlled by high-pressure coolant jet. Thorough investigation is essential to explore the potential benefits of high-pressure coolant jet machining in such cases. But enough work has not been done systematically yet in this direction.

1.3 Objectives of the Present Work

The objectives of the present work are:

a) Experimental investigation on the role of high-pressure coolant jet in respects of
   i) average chip-tool interface temperature
   ii) chip reduction coefficient
   iii) white layer formation

iv) tool wear and

v) surface roughness

in machining hardened steel at different level of hardness (40 HRC, 48 HRC, 56 HRC) by coated carbide inserts (SNMM and SNMG) at different speeds and feed rates combinations.

b) Develop a model of tool wear based on abrasion and adhesion wear model.

1.4 Scope of the Thesis

One of the possible and emerging technologies to overcome the aforementioned problems associated with hard machining using conventional cooling system is the application of high-pressure coolant (HPC) in high speed machining of hardened steels. For any machining operation, the tool life achieved, tool wear rate, material removal rate (MRR), cutting temperature, quality of the surface generated and surface integrity of the machined component as well as the shape of the chips can all be used to measure machinability. Considering all these, the present research work has been carried out to explore the role of high-pressure coolant (HPC) on major machinability characteristics in turning hardened medium carbon steels by coated carbide inserts under different machining conditions.

Chapter 1 offers the current status of hard turning using expensive ceramic tools and aims the possibilities of using the relatively cheap coated carbide tools assisted by high pressure coolant jet. This chapter discusses the problems of hard turning using PCD, CBN and PCBN tools. Some of the most detrimental problems like white layer and dark layer formations have been discussed to get the root causes of these layer formation and its' associated significance. The controlling of cutting temperature has been given the utmost priority here. The methods adopted by the researchers for controlling the tool-chip interface temperature are conferred in Chapter 1. It also presents the general necessities associated with machining industries, function of cutting tools, tool wear, tool life, techno-environmental and socio-economical problems related with the high cutting temperature and the practice of conventional cooling methods and the expected role of high-pressure coolant. Investigations and findings of previous works and objectives of the present work are also presented in this chapter.

Chapter 2 deals with the material preparation by heat treatment mechanism of medium carbon steels. Heat treatment process begins with the hurdles dealt with regarding the selection, sizing, shaping of the work material, limiting the number of work pieces and ends with the detailed description of correct heat treatment process to obtain three different hardness values *i.e.* HRC40, HRC48, HRC56. Then it presents the description of high-pressure coolant system for the present work to enable proper cooling of the cutting zone. Calibration of tool-work thermocouple comprising of job material and coated insert is also presented in the chapter. Chapter 2 also offers a glimpse of the procedure and conditions of the machining experiments carried out and the experimental results on the effects of HPC in comparison with dry machining in respect of chip morphology [chip shape, color, and chip reduction coefficient], average chip-tool interface temperature, tool wear, surface roughness in turning hardened medium carbon steels under different cutting conditions.

Chapter 3 presents a brief outline of previous works on tool wear modeling followed by development of a flank wear model and its validation with experimental results. The modeling contains an equation that fits into all conditions of workpiece hardness, tool insert configurations and machining conditions for which the experiment was performed. The assumptions are clearly stated for which the model is applicable. The percentage of error was also calculated and presented in the form of table.

Chapter 4 contains the detailed discussion on the experimental results and possible interpretations on the results obtained.

Finally, a summary of major contributions and scope of future work with recommendations are given in **chapter 5** and references are provided at the end.

Chapter-2

Experimental Investigations

2.1 Introduction

In this present research work, intensive experimental investigations have been carried out in turning hardened steel (40 HRC, 48 HRC, 56 HRC) by coated carbide inserts (SNMG 120408 and SNMM 120408). Investigations have incorporated close observations of the different machining responses which act as a function of turning operations. Generation of high cutting temperature during machining is one of the most critical and primary level response during turning which not only reduces tool life but also impairs the product quality. The temperature behaves proportionally with the increased values of cutting process parameters and increased strength and hardenability of the work piece materials. Cutting force is another primary level machining response which directly relates the amount of cutting power requirements. Chips morphology has also been studied in order to examine and relate cutting temperature and cutting force effects on chip's color, breakability and shear angle. Surface roughness and tool wear are secondary level responses which mainly depend on cutting load in terms of cutting temperature and force. Volumetric loss of cutting tool along with tool wear and surface roughness had been investigated as well. Cutting fluids are widely used to improve the machining responses. But due to its ineffectiveness in desired cooling and lubrication and corresponding health hazards, corrosion and contamination of natural environment, high pressure coolant jet machining has been implemented here in order to have better experimental results.

2.2 Material Preparation

The material used in the thesis was medium carbon steel (04-11 HRC) with approximately 0.475% carbon content. It was a hollow cylindrical bar of length 200 mm with external and internal diameters of 120 mm and 45 mm respectively because there was a problem with the distribution of hardness within the material. The core of the material didn't become as hard as the surface. This was due to the uneven quenching of the material. The outer surface dissipates heat more rapidly than the core which results in a gradual decrease of the hardness towards the core. To eliminate this problem, hollow cylindrical shaped material was used for the heat treatment. It facilitated the cooling from both outer and inner surface of the material and the hardness distribution after the heat treatment became uniform. Fig.2.1 shows the schematic view of the workpiece used in this investigation. A test sample made from the same material (external and internal diameters of 120 mm and 45 mm and length 30 mm) was also prepared for the hardness test.

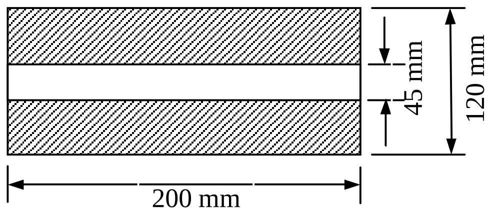


Fig. 2.1 Work material specimen for hardening

Electric furnace of high heating element (RG-3000˚C) was used for heat treatment. Before loading the work piece and the test sample, the furnace had to be made oxygen free to avoid oxidation because a scale is formed on the surface of the work material during hardening. In this circumstance, two ceramic pipes of internal diameters of 3 mm and 4.5 mm were connected with the furnace inlet and outlet respectively. The other end of the ceramic pipe with 3 mm internal diameter was connected to an argon gas cylinder with the help of a hose pipe. The door of the electric furnace was sealed and isolated from the atmosphere by an asbestos sheet. Argon gas was then passed (7.0 L/min and 130 bar) through the furnace chamber to drive out air to make an inert environment in the furnace chamber. After 2 minutes, turn on the furnace with 5 amperes current rating with 5.5 liters/min of argon gas supply at a pressure of 130 bars. It took three hours to raise the temperature to 900°C and soaked the work material at that temperature for one and half hour in the heating chamber. A quench tank having capacity 600 liters was used for quenching the work material. The quench tank was large enough to hold the part being treated and have adequate circulation and temperature control. The temperature of the oil (Bluta oil grade 27) should not exceed 40°C. The oil reduces the absorption of atmospheric gases that, in turn reduces the amount of bubbles. As a result, oil wets the metal surface and cools it more rapidly than water. In addition to rapid and uniform cooling, the oil removes a large percentage of any scale that may be present.

The work piece and test sample was pulled quickly but carefully out from the furnace and was immersed vertically into the oil quenching tank. The work piece is stirred at oil tank vigorously for about 20 minutes for uniform cooling and was continued until the specimen is cool enough. The test sample was also quenched in the same oil tank following same manner. Quenched medium carbon steel always required to temper because of steels are often more harder than needed and too brittle for most practical uses. It was done by heating the workpiece and test sample to a specific temperature (300^0C), holding it at that temperature for two hour and then cooling it instill air. The purpose of tempering was also to produce definite physical properties within the specimen. The sample was cleaned and ground a flat surface of 0.5 mm deep along the face of the sample. Hardness of the sample was measured on the C scale of Rock-well hardness tester. The hardness distribution within the sample is shown Fig.2.2.

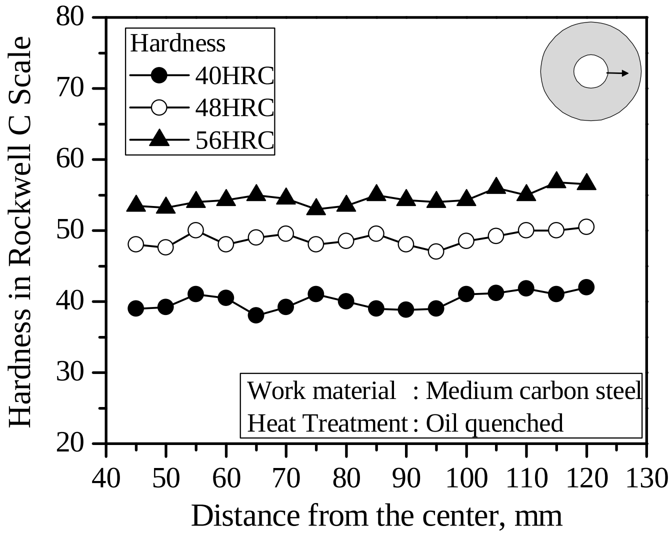


Fig. 2.2 Variation of hardness (HRC) along the radius of sample

2.3 Experimental Procedure and Conditions

The concept of high-pressure coolant presents itself as a possible solution for high speed machining in achieving slow tool wear while maintaining cutting forces at reasonable levels, provided that the high-pressure cooling parameters can be strategically tuned. It has the benefits of a powerful stream that can reach the cutting area, it provides strong chip removal, and in some cases enough pressure to deburr. High-pressure coolant injection technique not only provided reduction in cutting forces and temperature but also reduced the consumption of cutting fluid. The aim of the present work is primarily to explore and evaluate the role of high-pressure coolant on machinability characteristics of commonly used tool-work combination mainly in terms of cutting temperature and chip-forms, which govern productivity, product quality and overall economy.

The machining tests were carried out by straight turning of hardened steel of different hardness (40 HRC, 48 HRC and 56 HRC) in a reasonably rigid and powered centre lathe (7.5 kW, China) at different cutting speeds (V_c) and feed rates (S_o) under dry and high-pressure coolant environments. Keeping in view less significant role of depth of cut (t) on cutting temperature, saving of work material and avoidance of dominating effect of nose radius on cutting temperature, the depth of cut was kept fixed to only 1.0 mm and 2.0 mm, which would adequately serve the present purpose.

The tool geometry is reasonably expected to play significant role on such cooling effectiveness. Keeping these views, two different tool configurations (SNMG and SNMM) have been undertaken for the present investigation. The inserts were clamped in a PSBNR (Widia) type tool holder. The positioning of the nozzle tip with respect to the cutting insert has been settled after a number of trials. The high pressure coolant jet is directed along the auxiliary cutting edge at an angle 20^o to reach at the principal flank and partially under the flowing chips through the in-built groove parallel to the cutting edges. The photographic view of the experimental set-up is shown in Fig.2.3.

Fig.2.3 Photographic view of the experimental set-up for turning hardened steel with high pressure coolant (HPC) jet

The ranges of cutting speed and feed rate chosen in the present investigation are representative of the current industrial practice for the tool-work material combination that has been investigated. The conditions under which the machining tests have been carried out are briefly given in Table 2.1.The machining responses have been monitored and studied using sophisticated and reliable equipments and techniques as far as possible.

Table 2.1 Experimental conditions

Machine tool	: Lathe (China), 7.5 kW	
Work materials	: Hardened medium carbon steel	
Hardness	: 40 HRC, 48 HRC and 56 HRC	
Size	: Length= 200, External dia. =120 mm and Internal dia. = 45 mm	
Cutting tool		
	SNMG 120408, Widia	SNMM 120804, Widia
Coating	: TiCN, WC, Co	
Geometry	: -6°,-6°,6°,6°,15°,75°,0.8 (mm)	
Tool holder	: PSBNR 2525 M12 (ISO specification), Widia	
Process parameters		
Cutting velocity, V_c	: 58, 81, 115 and 161 m/min	
Feed rate, S_o	: 0.10, 0.12, 0.14 and 0.16 mm/rev	
Depth of cut, t	: 1.0 mm and 2.0 mm	
High pressure coolant	: 80 bar, Coolant: 6.0 l/min through external nozzle	
Coolant type	: VG-68 (ISO grade)	
Environment	: Dry and High pressure coolant (HPC) condition	

The form, color and thickness of the chips directly and indirectly indicate the nature of chip-tool interaction influenced by the machining environment. The chip samples were collected during short run machining for all the V_c-S_o combinations under both dry and HPC conditions. The form and colour of all those chips were noted down. The thicknesses of the chips were repeatedly measured by a slide calliper to determine the value of chip reduction coefficient, ξ (ratio of chip thickness after and before cut) which is an important index of machinability. The average cutting temperature was measured under all the machining conditions undertaken by simple but reliable tool-work thermocouple technique with proper calibration.

The life of the tools, which ultimately fail by systematic gradual wear, is generally assessed at least for R&D work, by the average value of the principal flank wear (V_B), which aggravates cutting forces and temperature and may induce vibration with the progress of machining. The pattern and extent of wear (V_S) of the auxiliary flank affects surface finish and dimensional accuracy of the machined parts. Growth of tool wear is sizeably influenced by the temperature and nature of interactions of the tool-work interfaces which again depend upon the machining conditions for given tool-work pairs.

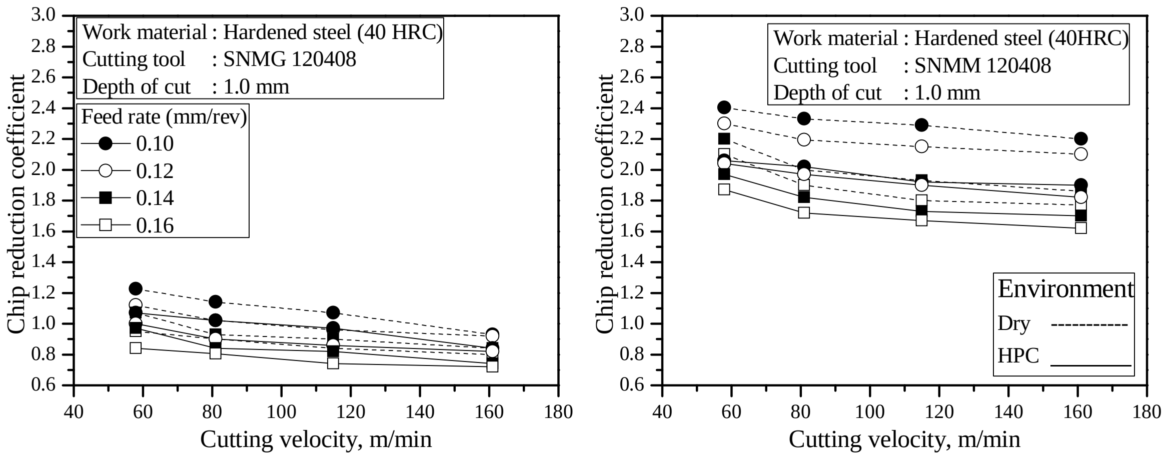
During machining under each condition, the cutting insert was withdrawn at regular intervals and V_B, V_S were measured under a optical microscope (Carl Zeiss, Germany) fitted with a precision micrometer. After machining the hardened medium carbon steel by both SNMG and SNMM inserts, at different V_c-S_o combinations under both dry and HPC conditions the surface finish was measured by a Talysurf (Surtronic 3+).

2.4 Experimental Results

2.4.1 Machining Chips

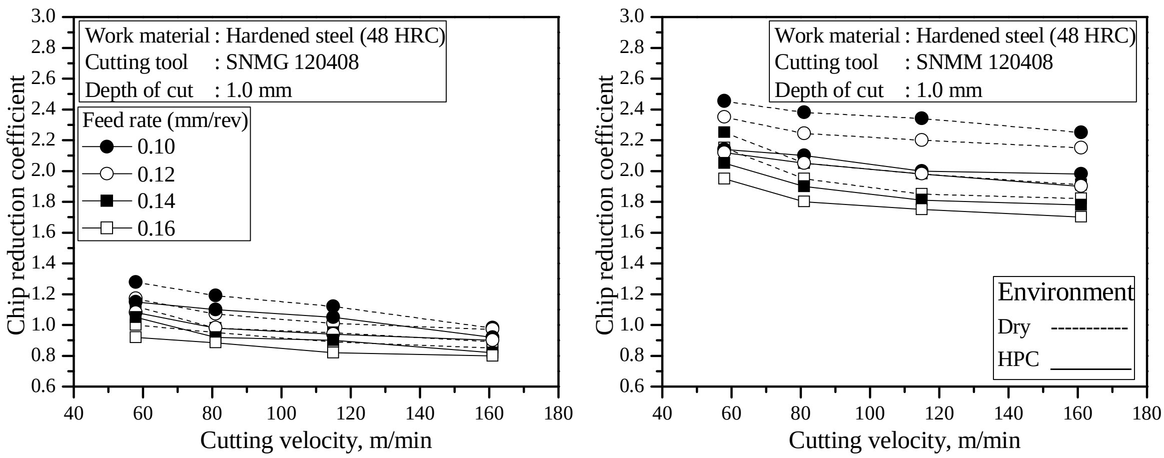
An important machinability index is chip reduction coefficient, ξ (ratio of chip thickness after and before cut). For given tool geometry and cutting conditions, the value of chip reduction coefficient depends upon the nature of chip-tool interaction, chip contact length, curl radius and form of the chips all of which expected to be influenced by high pressure coolant in addition to the level of cutting speeds and feed rates. The thickness of the chips was repeatedly measured by a slide caliper to determine the value of chip reduction coefficient. The variation in value of chip reduction coefficient with change in tool configuration, cutting speeds and feed rates as well as machining environment evaluated for hardened medium carbon steel of different hardness have been plotted and shown in Fig.2.4, Fig.2.5 and Fig.2.6.

The machining chips were collected during all the treatments for studying their shape, colour and nature of interaction with the cutting insert at its rake surface. Chips have been visually examined and categorised with respect to their shape and colour. Chip shape and colour for different steels are incorporated in Table 2.2, Table 2.3 and Table 2.4.



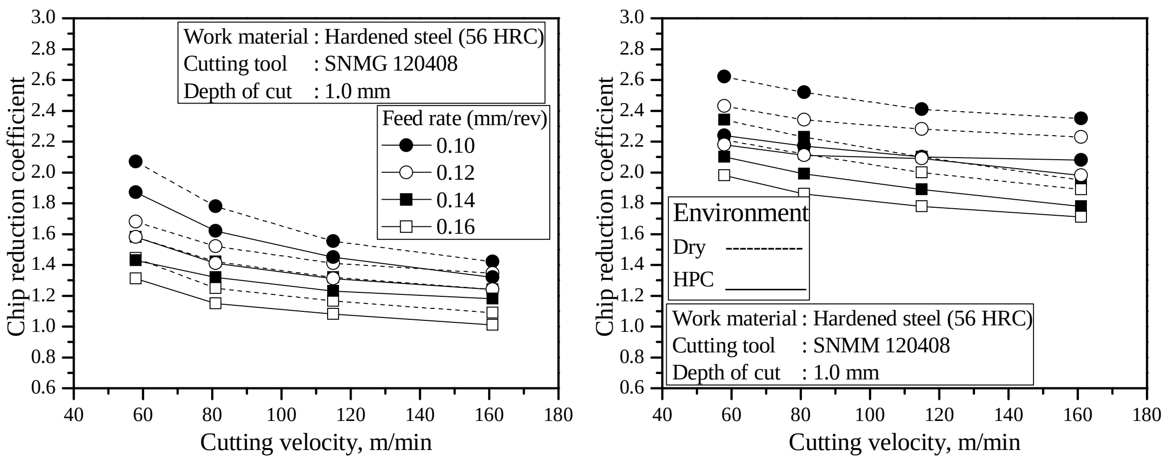
(a) **SNMG** (b) **SNMM**

Fig.2.4 Variation of ξ with V_c at different S_o in turning hardened steel (40 HRC) by (a) SNMG and (b) SNMM insert under dry and HPC conditions



(a) **SNMG** (b) **SNMM**

Fig.2.5 Variation of ξ with V_c at different S_o in turning hardened steel (48 HRC) by (a) SNMG and (b) SNMM insert under dry and HPC conditions



(a) **SNMG** (b) **SNMM**

Fig.2.6 Variation of ξ with V_c at different S_o in turning hardened steel (56 HRC) by (a) SNMG and (b) SNMM insert under dry and HPC conditions

Table 2.2 Shape and color of chips produced during machining 40 HRC steel

S_o (mm/rev)	V_c (m/min)	INSERT							
		SNMG 120804				SNMM 120804			
		Environment							
		Dry		HPC		Dry		HPC	
		Chip shape	Chip color	Chip shape	Chip color	Chip shape	Chip color	Chip shape	Chip color
0.10	58	snarled	blue	helical	metallic	snarled	metallic	helical	metallic
	81	snarled	blue	snarled	blue	snarled	metallic	half turn	metallic
	115	snarled	blue	half turn	golden	snarled	blue	half turn	metallic
	161	snarled	blue	snarled	golden	snarled	blue	helical	metallic
0.12	58	snarled	blue	snarled	blue	snarled	metallic	helical	metallic
	81	snarled	blue	snarled	blue	snarled	blue	half turn	metallic
	115	snarled	blue	snarled	golden	snarled	blue	helical	metallic
	161	snarled	blue	snarled	golden	snarled	blue	half turn	golden
0.14	58	snarled	blue	snarled	blue	snarled	blue	helical	metallic
	81	snarled	blue	snarled	golden	snarled	blue	helical	metallic
	115	snarled	blue	helical	golden	snarled	blue	snarled	golden
	161	snarled	blue	helical	golden	snarled	metallic	snarled	golden
0.16	58	snarled	blue	helical	golden	snarled	blue	helical	metallic
	81	snarled	blue	snarled	golden	snarled	blue	half turn	metallic
	115	snarled	blue	helical	golden	snarled	blue	helical	blue
	161	snarled	blue	snarled	golden	snarled	blue	half turn	metallic

Table 2.3 Shape and color of chips produced during machining 48 HRC steel

S_o (mm/rev)	V_c (m/min)	INSERT							
		SNMG 120804				SNMM 120804			
		Environment							
		Dry		HPC		Dry		HPC	
		Chip shape	Chip color	Chip shape	Chip color	Chip shape	Chip color	Chip shape	Chip color
0.10	58	snarled	blue	snarled	golden	snarled	blue	snarled	metallic
	81	snarled	metallic	snarled	golden	snarled	metallic	snarled	metallic
	115	snarled	blue	snarled	blue	snarled	golden	snarled	metallic
	161	snarled	blue	snarled	golden	snarled	metallic	half turn	metallic
0.12	58	snarled	blue	snarled	golden	snarled	blue	helical	metallic
	81	snarled	metallic	snarled	golden	snarled	metallic	snarled	metallic
	115	snarled	blue	snarled	blue	snarled	metallic	helical	metallic
	161	snarled	metallic	snarled	golden	snarled	metallic	snarled	golden
0.14	58	snarled	metallic	helical	metallic	snarled	blue	helical	metallic
	81	snarled	blue	snarled	golden	snarled	blue	helical	metallic
	115	snarled	blue	snarled	blue	snarled	blue	snarled	golden
	161	snarled	golden	snarled	golden	snarled	metallic	snarled	golden
0.16	58	snarled	blue	helical	metallic	snarled	blue	helical	metallic
	81	snarled	blue	snarled	golden	snarled	blue	snarled	metallic
	115	snarled	metallic	snarled	blue	snarled	blue	snarled	blue
	161	half turn	blue	snarled	golden	snarled	blue	snarled	metallic

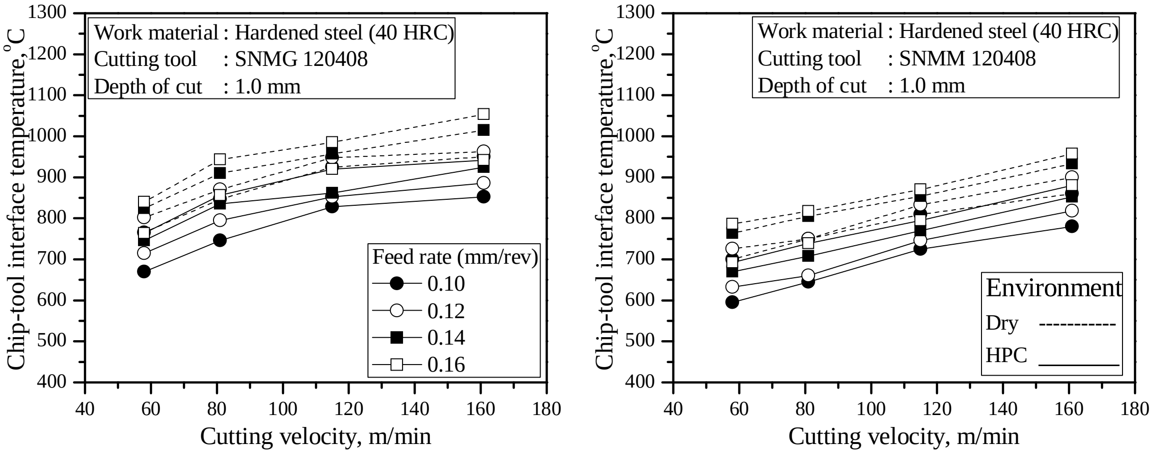
Table 2.4 Shape and color of chips produced during machining 56 HRC steel

S_o (mm/rev)	V_c (m/min)	INSERT							
		SNMG 120804				SNMM 120804			
		Environment							
		Dry		HPC		Dry		HPC	
		Chip shape	Chip color	Chip shape	Chip color	Chip shape	Chip color	Chip shape	Chip color
0.10	58	snarled	blue	helical	metallic	snarled	blue	snarled	golden
	81	snarled	blue	snarled	blue	snarled	blue	snarled	blue
	115	snarled	blue	half turn	golden	snarled	blue	snarled	blue
	161	snarled	blue	snarled	golden	snarled	blue	snarled	blue
0.12	58	snarled	blue	snarled	blue	snarled	blue	snarled	blue
	81	snarled	blue	snarled	blue	ribbon	blue	snarled	blue
	115	snarled	blue	snarled	golden	ribbon	blue	snarled	golden
	161	snarled	blue	snarled	golden	snarled	blue	snarled	blue
0.14	58	snarled	blue	snarled	blue	snarled	blue	snarled	blue
	81	snarled	blue	snarled	golden	snarled	blue	snarled	blue
	115	snarled	blue	helical	golden	ribbon	blue	snarled	golden
	161	snarled	blue	helical	golden	snarled	blue	snarled	golden
0.16	58	snarled	blue	helical	golden	snarled	blue	snarled	golden
	81	snarled	blue	snarled	golden	snarled	blue	snarled	blue
	115	snarled	blue	helical	golden	ribbon	blue	snarled	blue
	161	snarled	blue	snarled	golden	snarled	blue	snarled	golden

2.4.2 Cutting Temperature

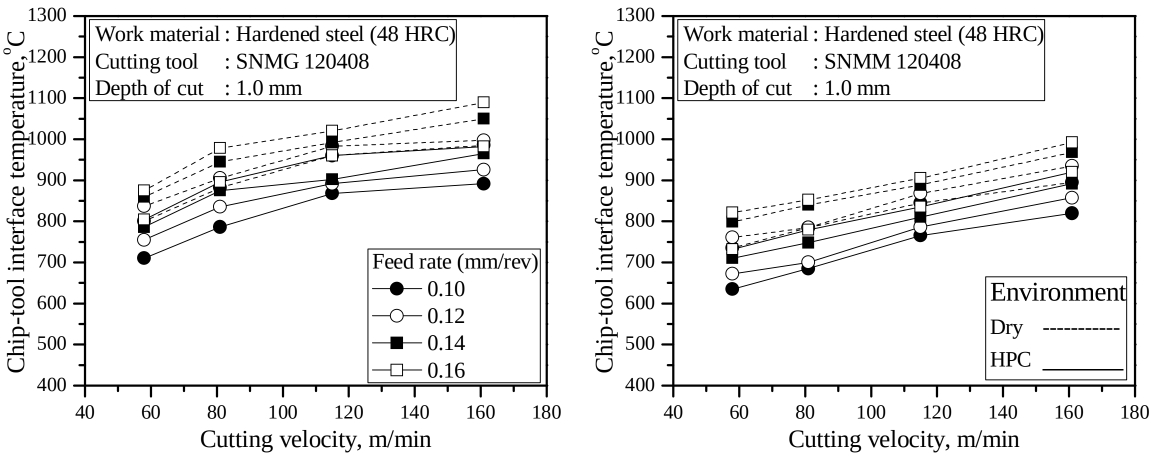
High production machining associated with high velocity and feed rate inherently generates high heat as well as high cutting zone temperature. The cutting temperature if not controlled properly, cutting tools undergo severe flank wear and notch wear, lose sharpness of the cutting edge by either wearing or become blunt by welded built-up edge and weaken the product quality. In normal cutting condition all such heat sources produce maximum temperature at the chip-tool interface, which substantially influence the chip formation mode; cutting forces, tool life and product quality. High production machining needs to increase the process parameters further for meeting up the growing demand and cost competitiveness. Cutting temperature is increased with the increase in process parameter as well as with the increase in hardness and strength of the work material. Therefore, attempts are made to reduce this detrimental cutting temperature.

In the present work, the average cutting temperature was measured under all the machining conditions undertaken by simple but reliable tool-work thermocouple technique with proper calibration. The evaluated role of HPC on average chip-tool interface temperature in turning hardened steel at different V_c-S_o combinations in compare to dry condition have been shown in Fig.2.7, Fig.2.8 and Fig.2.9.



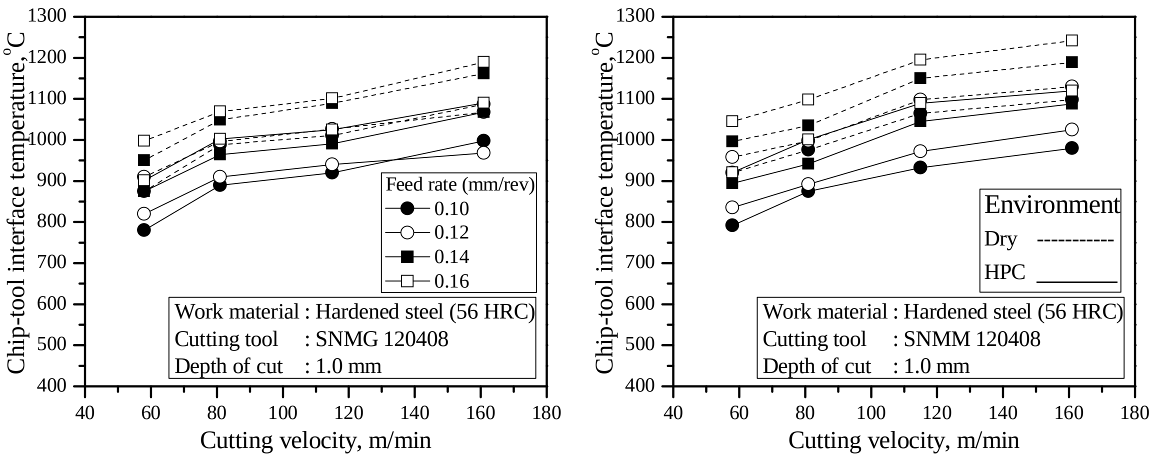
(a) **SNMG** (b) **SNMM**

Fig.2.7 Variation of cutting temperature with V_c at different S_o in turning hardened steel (40 HRC) by (a) SNMG and (b) SNMM insert under dry and HPC conditions



(a) **SNMG** (b) **SNMM**

Fig.2.8 Variation of cutting temperature with V_c at different S_o in turning hardened steel (48 HRC) by (a) SNMG and (b) SNMM insert under dry and HPC conditions



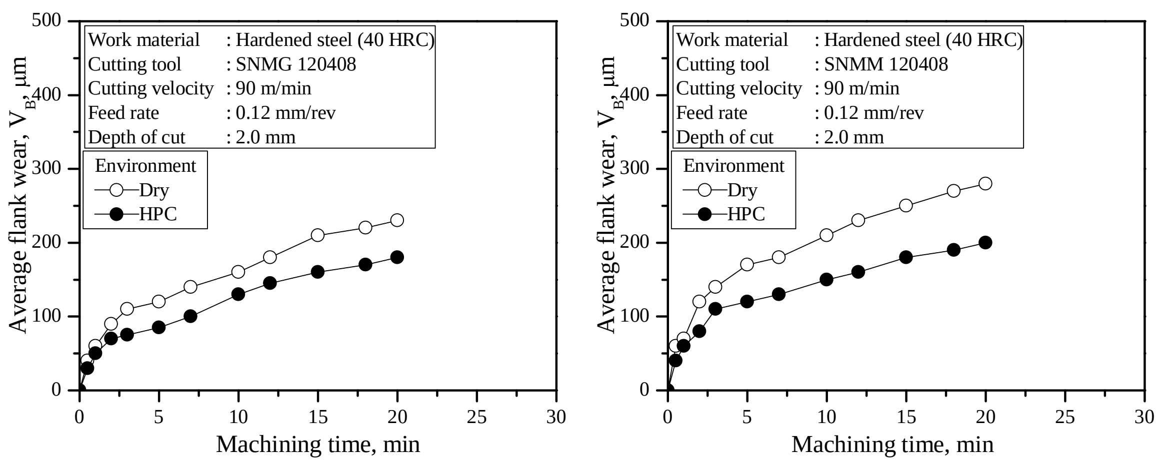
(a) **SNMG** (b) **SNMM**

Fig.2.9 Variation of cutting temperature with V_c at different S_o in turning hardened steel (56 HRC) by (a) SNMG and (b) SNMM insert under dry and HPC conditions

2.4.3 Tool Wear

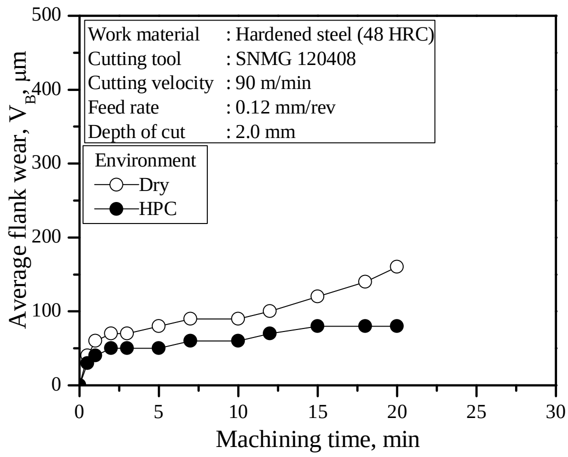
The cutting tools in conventional machining, particularly in continuous chip formation processes like turning, generally fails by gradual wear by abrasion, adhesion, diffusion, chemical erosion, galvanic action etc. depending upon the tool-work materials and machining condition. Tool wear initially starts with a relatively faster rate due to what is called break-in wear caused by attrition and micro-chipping at the sharp cutting edges.

Cutting tools may also often fail prematurely, randomly and catastrophically by mechanical breakage and plastic deformation under adverse machining conditions caused by intensive pressure and temperature and/or dynamic loading at the tool tips particularly if the tool material lacks strength, hot-hardness and fracture toughness. However, in the present investigations with the tools and work material and the machining conditions undertaken, the tool failure mode has been mostly gradual wear. The growth of average flank wear, V_B with progress of machining recorded while turning hardened steel of different hardness by both SNMG and SNMM inserts under both dry and HPC conditions have been shown in Fig.2.10, Fig.2.11 and Fig.2.12. The auxiliary flank wear which affects surface finish have also been recorded at regular intervals of machining under all the conditions undertaken. The growth of average auxiliary flank wear, V_S with time of machining of hardened carbon steel under both dry and HPC conditions have been shown in Fig.2.13, Fig.2.14 and Fig.2.15.

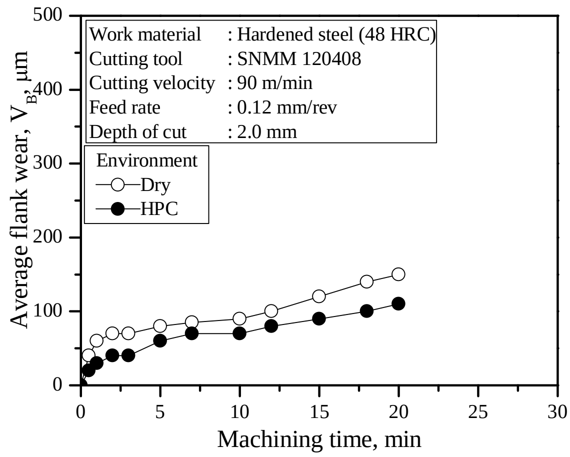


(a) **SNMG** (b) **SNMM**

Fig.2.10 Growth of V_B in (a) SNMG and (b) SNMM inserts during in turning hardened steel (40 HRC) under dry and HPC conditions

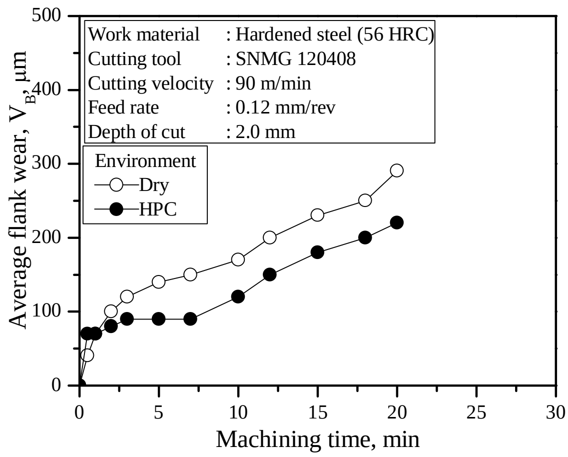


(a) **SNMG**

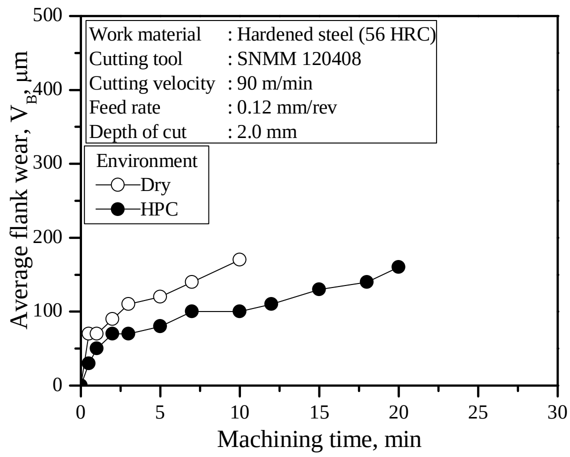


(b) **SNMM**

Fig.2.11 Growth of V_B in (a) SNMG and (b) SNMM inserts during in turning hardened steel (48 HRC) under dry and HPC conditions



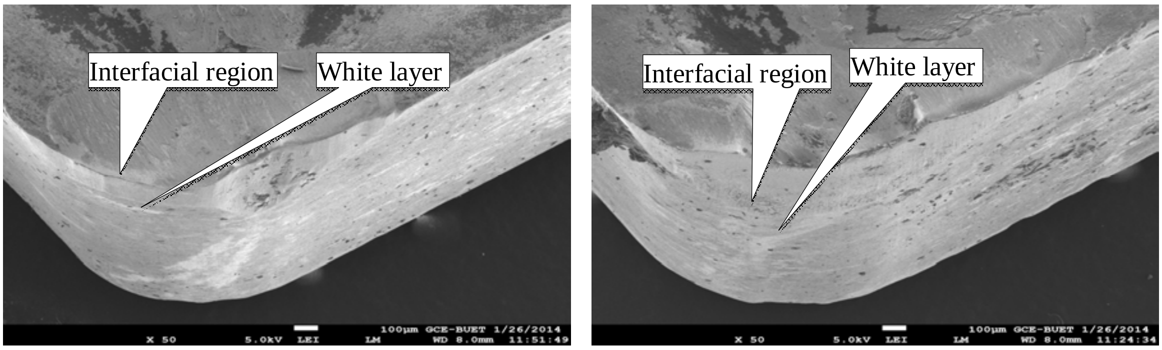
(a) **SNMG**



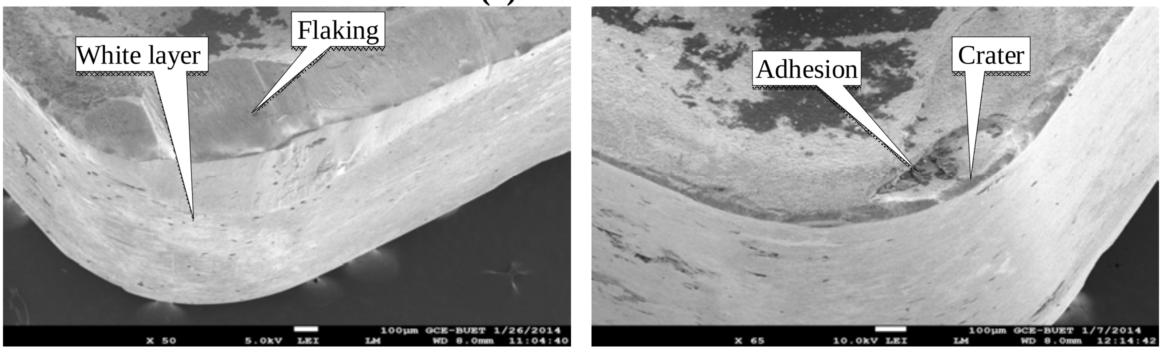
(b) **SNMM**

Fig.2.12 Growth of V_B in (a) SNMG and (b) SNMM inserts during in turning hardened steel (56 HRC) under dry and HPC conditions

The pattern and extent of wear that developed at the different surfaces of the tool tips after being used for machining hardened medium carbon steel over reasonably long period have been observed under Scanning Electron Microscope (Philips XL 30, Belgium) to see the actual effects of different environments on wear of the carbide inserts of present two configurations. Fig.2.13, Fig.2.14 and Fig.2.15 show the scanning electron microscopy (SEM) views of the worn out inserts (SNMG and SNMM) after being used for machining hardened medium carbon steel of different hardness (40 HRC, 48 HRC and 56 HRC) at V_c=90 m/min, S_o =0.12 mm/rev and t =2.0 mm for 20 min. under dry and high pressure coolant condition.



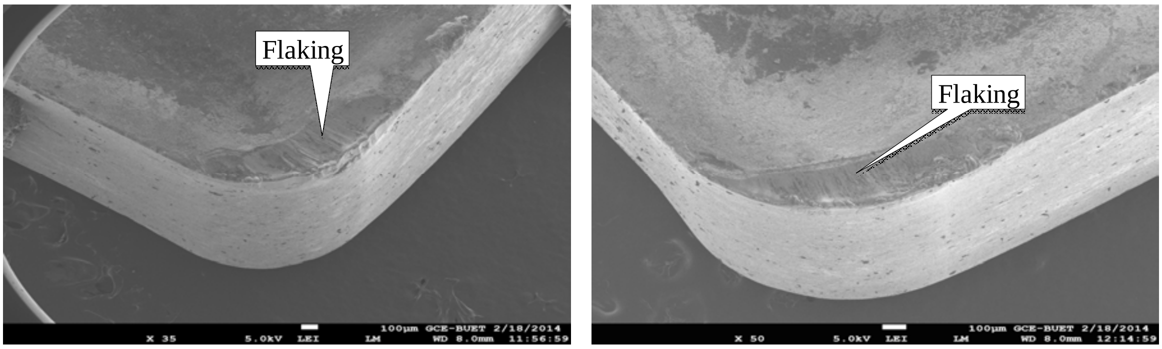
(a) SNMG 120408



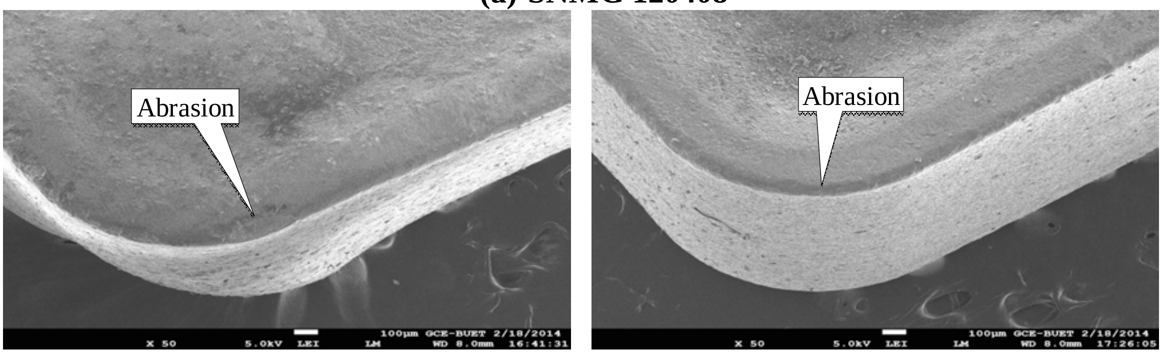
(b) SNMM 120408

Dry machining **HPC machining**

Fig.2.13 SEM views of the worn out insert [Time 20 min] (a) SNMG and (b) SNMM after machining hardened steel (40 HRC) under dry and HPC conditions



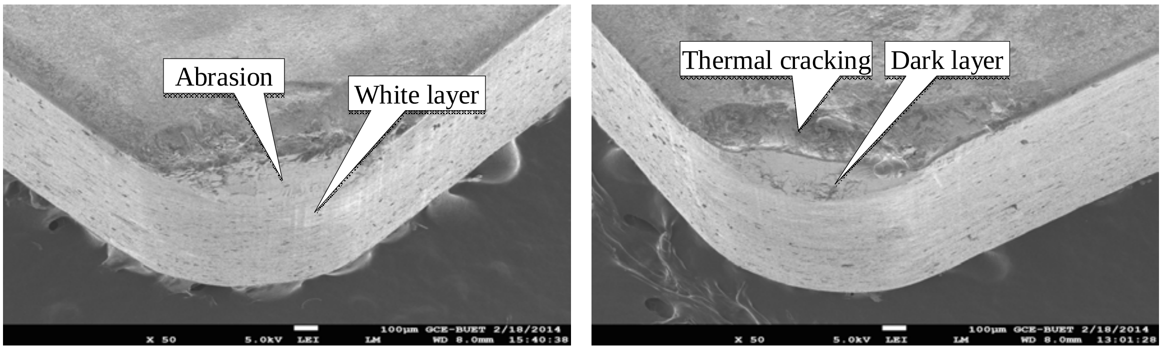
(a) SNMG 120408



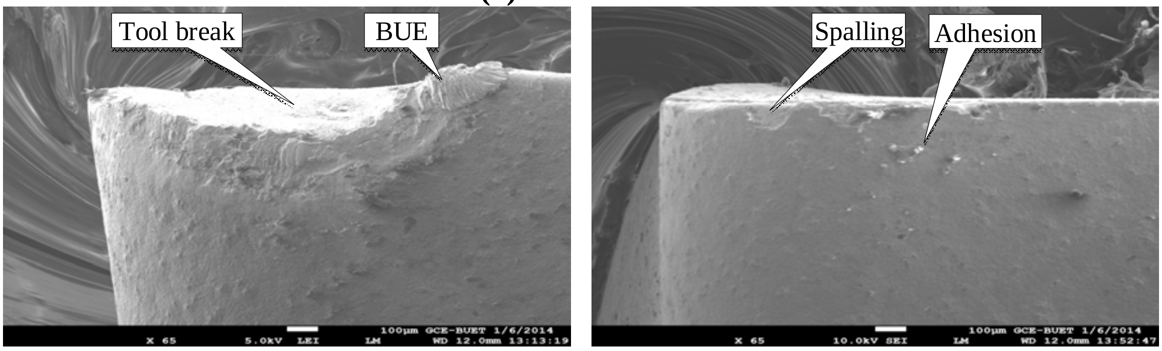
(b) SNMM 120408

Dry machining **HPC machining**

Fig.2.14 SEM views of the worn out insert [Time 20 min] (a) SNMG and (b) SNMM after machining hardened steel (48 HRC) under dry and HPC conditions



(a) SNMG 120408



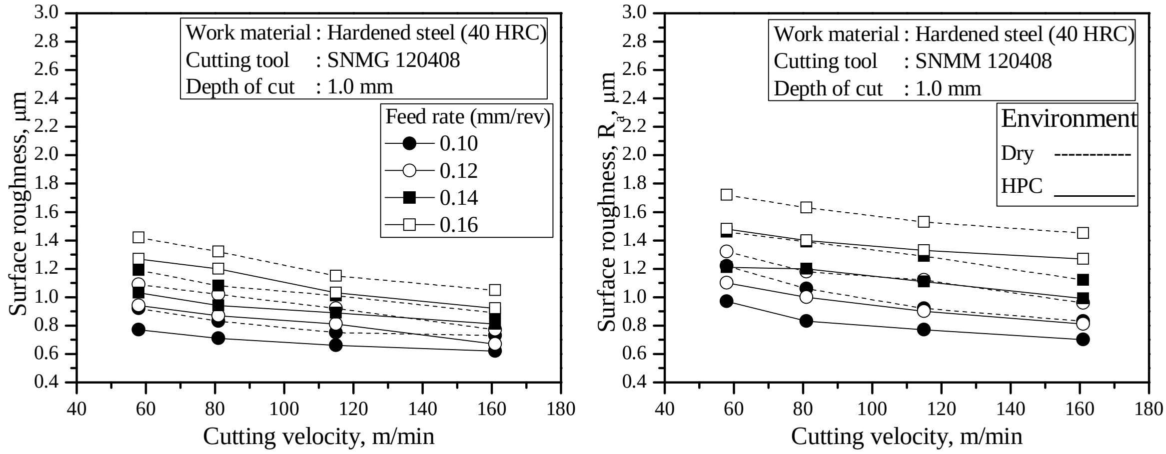
(b) SNMM 120408

Dry machining **HPC machining**

Fig.2.15 SEM views of the worn out insert [Time 20 min] (a) SNMG and (b) SNMM after machining hardened steel (56 HRC) under dry and HPC conditions

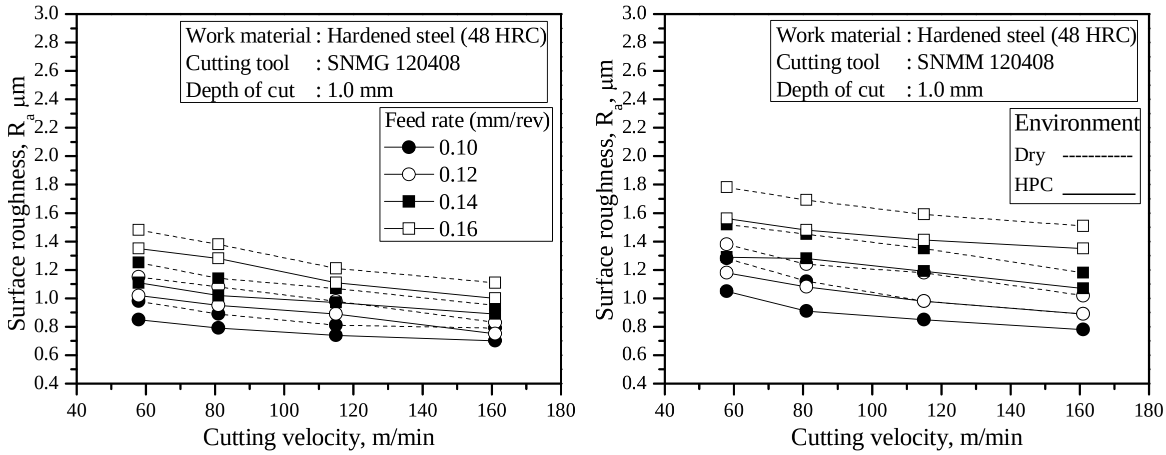
2.4.4 Surface Roughness

In the present work, only surface roughness has been investigated to evaluate the relative role of HPC on those two major aspects. Surface roughness is an important index of machinability which is substantially influenced by the machining environment for given tool-work pair and speed-feed conditions. Surface roughness has been measured at two stages; first, after a few seconds of machining with the sharp tool while recording the cutting temperature and second, with the progress of machining while monitoring growth of tool wear with machining time. The surface roughness attained after 50 seconds of machining of the hardened steel by the sharp SNMG and SNMM inserts at various V_c-S_o combinations under dry and HPC conditions are shown in Fig.2.16, Fig.2.17 and Fig.2.18 respectively. The variation in surface roughness observed with progress of machining of the hardened steel by SNMG SNMM inserts at a particular set of V_c, S_o and t under dry and HPC conditions have been shown in Fig.2.19, Fig.2.20 and Fig.2.21.



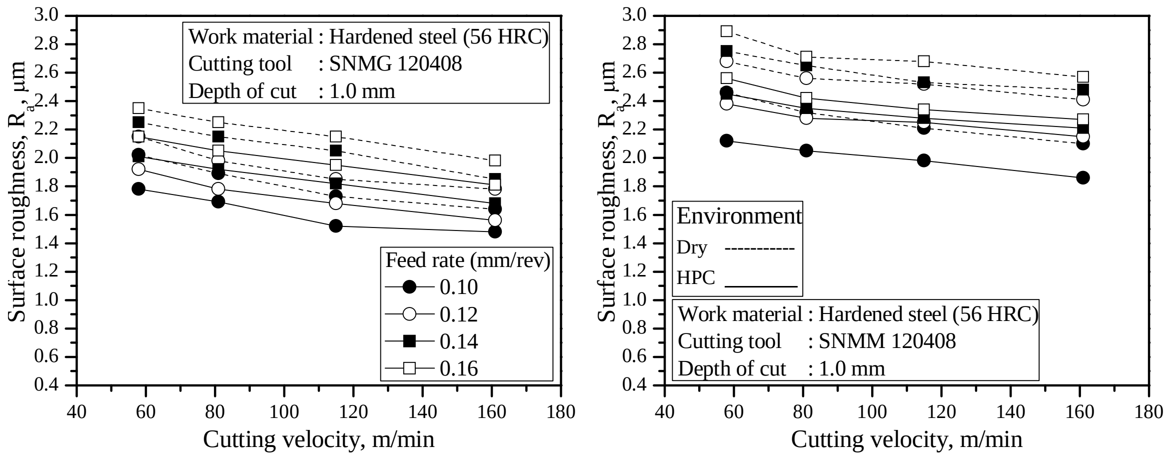
(a) **SNMG** (b) **SNMM**

Fig.2.16 Variation of R_a with V_c at different S_o in turning hardened steel (40 HRC) by (a) SNMG and (b) SNMM insert under dry and HPC conditions



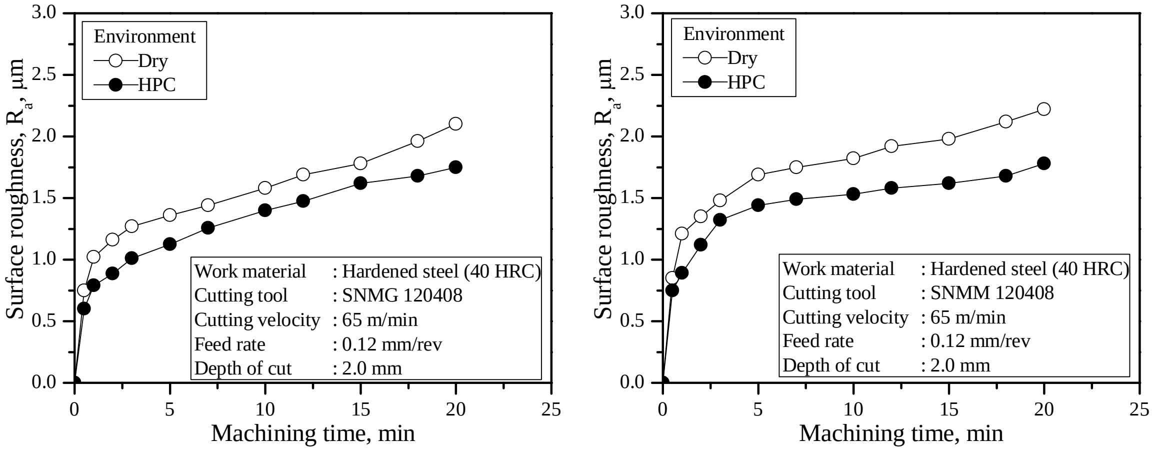
(a) **SNMG** (b) **SNMM**

Fig.2.17 Variation of R_a with V_c at different S_o in turning hardened steel (48 HRC) by (a) SNMG and (b) SNMM insert under dry and HPC conditions



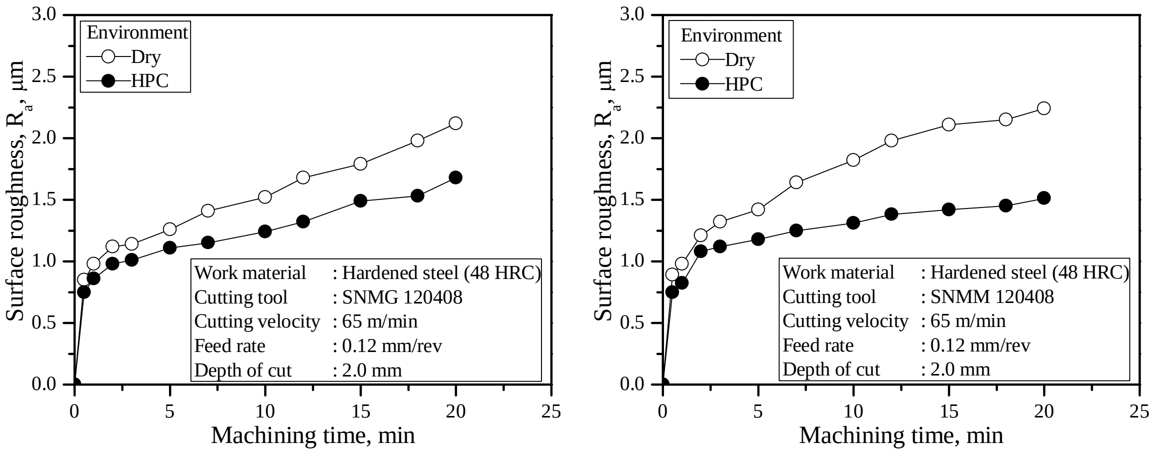
(a) **SNMG** (b) **SNMM**

Fig.2.18 Variation of R_a with V_c at different S_o in turning hardened steel (56 HRC) by (a) SNMG and (b) SNMM insert under dry and HPC conditions



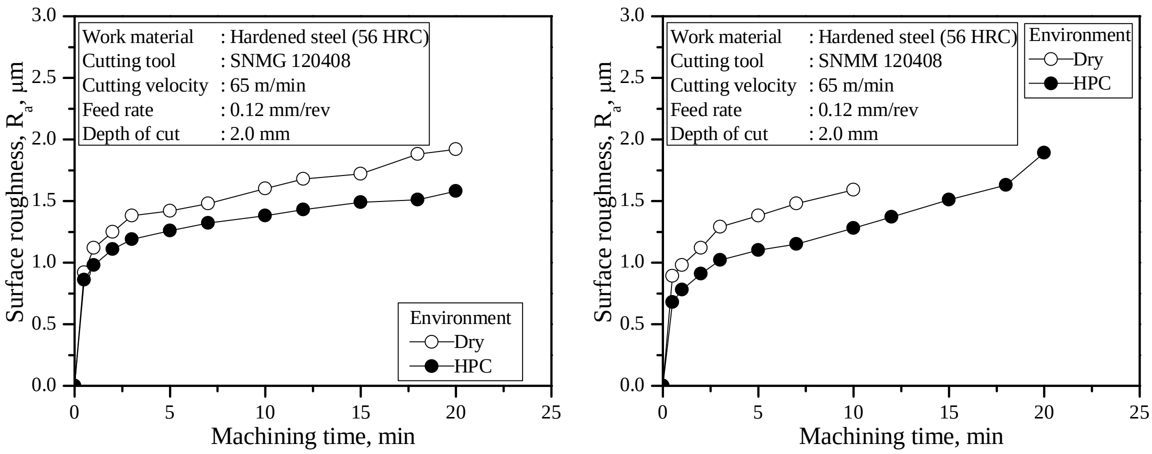
(a) **SNMG** (b) **SNMM**

Fig.2.19 Surface roughness developed with progress of machining of hardened steel (40 HRC) by (a) SNMG and (b) SNMM inserts under dry and HPC conditions



(a) **SNMG** (b) **SNMM**

Fig.2.20 Surface roughness developed with progress of machining of hardened steel (48 HRC) by (a) SNMG and (b) SNMM inserts under dry and HPC conditions



(a) **SNMG** (b) **SNMM**

Fig.2.21 Surface roughness developed with progress of machining of hardened steel (56 HRC) by (a) SNMG and (b) SNMM inserts under dry and HPC conditions

Chapter-3

Modeling of Tool Wear

3.1 Introduction

A cutting tool may fail mainly by three basic reasons [**Bhattacharyya 1984**]:

i. By a process of plastic deformation when the temperature and the stresses are high, plastic deformation may cause loss of form stability.

ii. By a process of mechanical breakage when the cutting force is very large or by developing fatigue cracks under chatter conditions.

iii. By a process of gradual wear which is a result of interaction between the work and the tool material. When form stability has been achieved, wear is the process by which a cutting tool fails.

In this present research work, concentration has been provided to analyze the behavior of gradual flank tool wear which is a result of interaction between the work and tool flank face. After the tool has been used for some times, wear land will appear at the flank of the tool below the cutting edge extending approximately parallel to the cutting edge. Various types of wear can occur while cutting process takes place. Among these, mechanical, thermo-chemical, electro-mechanical wear types are dominant. In this research work, while turning AISI 1040 steel by SNMM and SNMG carbide inserts at the stated experimental condition has conducted, gradual tool wear is found in the form of mechanical wear. On the other hand, mechanical wear can take place based on different mechanisms namely abrasion, adhesion and diffusion.

Abrasion mechanism works due to ploughing into softer matrix by hard constituents such as carbides and also includes the fragments of built-up edge. This action is more severe on the tool flank due to the nature of contact. However, if the carbide inclusions are large and distributed in the form of a grid, abrasive wear takes place.

Adhesion mechanism works when there is a metallic bond which is formed over the tool faces and work piece surfaces. Subsequent rupture of these bonds causes transfer of the tool base material. Localized temperature between the contact areas plays a key role in adhesion.

Diffusion is such a mechanism which is highly time and temperature dependant. When the generated temperature at the chip tool interface becomes high enough, solid state diffusion takes place where atoms in a metallic crystal shift from one lattice point to another causing a transfer of the element in the direction of the concentration gradient. There also exists a quasi-continuous contact between the chip and the work piece and thus facilitating thermo-chemical reactions and structural transformations. Electron micrograph or micro-fractography reveals whether diffusion wear takes place while machining by observing white layer which is very hard and brittle. Diffusion wear model has been developed on the basis of Fick's second law of diffusion. Ingle et. al. [**1994**] investigated crater wear which was found to consist of chemical and mechanical wear components. He machined 1045 steel with a cemented carbide tool and based on the work of Bhattacharyya and Ham [**1969**] and Bhattacharyya et. al. [**1969**] and an expression was developed to estimate the amount of tungsten transported by diffusion during the cutting time;

$$W = 1.1284\ C_o F\, T \left(\frac{D}{\tau}\right)^{\frac{1}{2}} (\text{contact area}) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.1)$$

Where,

W = Amount of tungsten dissolved

C_o = Equilibrium concentration of tungsten at interface

F = Ferrite volume fraction

T = Cutting time

D = Diffusivity of tungsten in ferrite

τ = Tool chip contact time

Hence, as the temperature rises, tool wear mechanism shifts from abrasion to diffusion through adhesion. Tool wear involving abrasion and adhesion mechanism has been termed as mechanical wear. A statistical model has been developed by Davies [**1957**]. He suggested a Monte Carlo approach for modeling mechanical wear based on the following assumptions.

- Quanta of energy are added to the rubbing particles all of which leave the same site.

- The quanta of energy are added to the particles at domains randomly spaced over the surface at moments randomly spaced in time.

- The quantized energy of a particle diffuses continuously over the surface and into the material at a known rate.

- The surface energy of a particle causes it to detach as a wear particle.

Bhattacharya and Ham [**1969**] extended this approach developing expressions for the width of flank wear due to mechanical wear from abrasive and adhesive sources. The width of the flank wear, V_B (T), at time T is given by:

$$V_B(T) = K^{**} V_c T^{(1-\alpha)} \qquad \text{.......................(3.2)}$$

Where,

$$K^{**} = \frac{3K^*}{2C^*(1-\alpha)} \qquad \text{.......................(3.3)}$$

Where,

$$K^* = \frac{k\ m}{\rho\left(\frac{\tan\alpha}{1-\tan\alpha\ \tan\gamma}\right)} \qquad \text{.......................(3.4)}$$

And

$$C^* = \frac{C^2}{\sigma^2} \qquad \text{.......................(3.5)}$$

Where,

V_c = Cutting speed

T = Cutting time

α = Clearance angle

C = Constant

σ = Deviation from the mean

ρ = Density of the tool material

m = Mass of wear particle

γ = True rake angle

k = Constant governing decay rate

Archard [**1953**] has shown that for different types of worn particles and depending on the nature of deformation which produces the wear particles, the relationship between the wear rate and applied load changes. He has developed an expression for volumetric rate of wear given as:

$$\frac{dW}{dT} = \frac{Z}{H\left[P_z^{3/2} V_c\right]} \quad \text{......................(3.6)}$$

Where,

H = Hardness of the tool material

Z = Wear co-efficient

P_z = Normal force on the surface

V_c = Cutting speed

In this model, wear co-efficient is assumed to act in the similar manner as diffusion co-efficient and can be expressed as

$$Z = Z_0 \exp\left(\frac{-U}{R\,\theta_f}\right) \quad \text{......................(3.7)}$$

Later on, Bhattacharyya and Ghosh [**1964, 1967**] suggested that the flank temperature like interface temperature is proportional to $\sqrt{V_c}$.

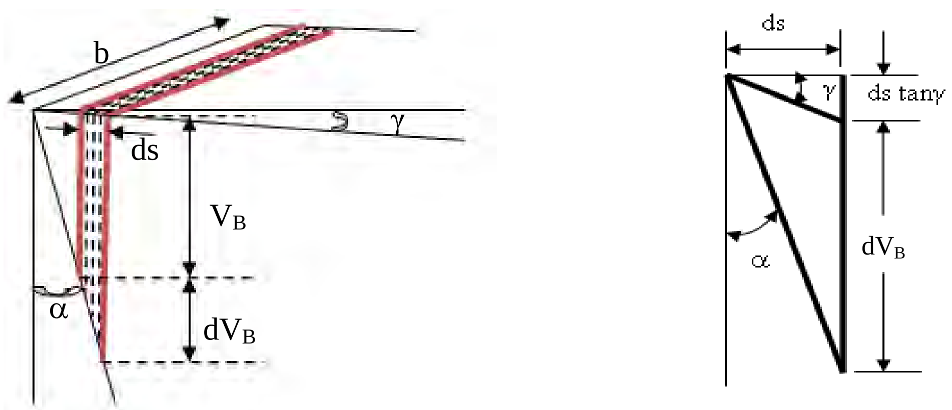


Fig. 3.1 Wear growth characteristics

On the other hand, from the tool geometry (Fig. 3.1) the volume of the worn tool material during a time interval (ΔT) is given by

$$dV = bds\left(\frac{V_B + dV_B}{2}\right) \qquad \text{………………….(3.8)}$$

Where,

$$ds = \frac{dV_B \tan\alpha}{1 - \tan\gamma\ \tan\alpha} \qquad \text{………………….(3.9)}$$

Where,

b = Actual width of cut

V_B = Flank wear growth

dV_B = Increment of flank wear height growth during time interval (Δt)

γ = Rake angle

α = Clearance angle

Since, volumetric rate of wear is directly proportional to the tool wear rate, combining Archard's findings with the tool geometry model, flank wear can be modeled as

$$V_B = \frac{5}{4}\left(\frac{KV_c A^{\frac{3}{4}}(1 - \tan\alpha \tan\gamma)}{b \tan\alpha}\right) \qquad \text{………………...(3.10)}$$

Where, A is a constant based on the tool and work piece combination. This model worked well when applied to experiments conducted by Bhattacharyya et al. and experiments conducted by the internationally recognized tool wear collection body OECD/CIRP. However, a large amount of data for specific tool and workpiece combinations must be collected before this approach can be used. Bhattacharyya points out the reliability of the model depend on the accuracy of the data, making this approach susceptible to compounded errors. It is also inconvenient to collect a large amount of data every time new machining conditions are encountered.

Most engineering metals contain impurities that are imparted to improve material strength. If the hard particles are securely constrained in the metal matrix composite, these particles will cause two-body abrasive wear, representing hard particles in the metal sliding over a soft surface [**Kwon 2000].** On the other hand, if the particles are released to the interface of the tool and the workpiece or the chip in cutting, the hard particles roll between the contacting surfaces, causing three-body abrasive wear [**Huang and Liang 2004**]. Rabinowicz [**1979]** developed empirical equations for calculating the volumetric loss of the three-body abrasive wear based on a lapping process and is given by:

$$V = \frac{xN\tan\upsilon}{3H_t} \qquad \text{Where, } H_t/H_a \le 0.8$$

$$V = \frac{xN\tan\upsilon}{5.3H_t}\left(\frac{H_t}{H_a}\right)^{-2.5} \qquad \text{Where, } 0.8 \le H_t/H_a \le 1.25$$

$$V = \frac{xN\tan\upsilon}{2.43H_t}\left(\frac{H_t}{H_a}\right)^{-6} \qquad \text{Where, } 1.25 \le H_t/H_a$$

Where, υ is the average roughness angle of abrasive particle, H_t and H_a are the hardness of job and abrasive particles respectively. The above equations were rearranged and used in turning process according to the work of Huang et al. [**2007**] by assuming uniform stress distribution between the tool flank face and the work piece as:

$$V_{abrasion} = K_{abrasion}\left(\frac{1}{H_t^n}\right)V_c bL_{VB}\sigma\Delta T \qquad \text{……...…………(3.11)}$$

Huang et al. [**2007**] calculated geometric volumetric loss according to Fig. 3.2 is

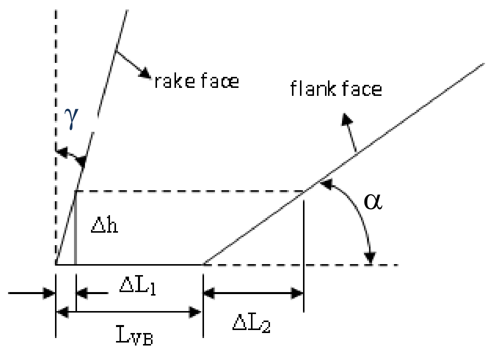


Fig. 3.2 Changes of tool geometry due to flank wear

Where, b is assumed as width of cut and Δh is defined as reduction in depth of cut due to wear. Neglecting Δh^2,

$$\Delta V_{wear} = 0.5b\Delta.\ _1\Delta h + b(L_{VB} - \Delta L_1)\Delta\Delta - 0.5b\Delta.\ _2\Delta h \qquad \text{……...…………(3.12)}$$

$$\Delta V_{wear} = \frac{bL_{VB}\Delta L_{VB}}{\cot\alpha - \tan\gamma} \qquad \text{……...…………(3.13)}$$

Combining volumetric loss of tool wear and modified equation of two body abrasive wear, flank wear due to abrasion can be calculated by

$$K_{abrasion}\left(\frac{1}{H_t^n}\right)V_c bL_{VB}\sigma\Delta t = \frac{bL_{VB}\Delta L_{VB}}{\cot\alpha - \tan\gamma} \quad \text{……...…………(3.14)}$$

3.2 Flank Wear Model

In this research work, turning has been carried out under high pressure coolant condition. To have a better understanding of the behavior of the flank wear progression with the variation of cutting time, chip-tool interface temperature, chip reduction co-efficient, cutting force, a series of experimental investigations have been carried out at different speed, feed and depth of cut combination.

Clearly, tool wear is the ultimate outcome of cutting temperature, cutting force and chip formation process irrespective of its environment. The specialty of HPC machining lies in the fact that HPC enables significant reduction in both cutting temperature and cutting force. As a result, tool wear rate is lower compared to dry and tool life is also enhanced. From the experimental investigation, several things are observed.

At first, tool flank wear increases gradually with the increase of machining time. At any particular time, flank wear aggravates with the increase of speed, feed and depth of cut. Again, flank wear rate can be reduced if exact pressure and flow rate can be impinged at chip-tool interface by HPC technique. Hence, it can be stated that,

$$V_B \infty \frac{t\, V_c\, S_o T}{PQ} \quad \text{……...…………(3.15)}$$

Where, T denotes machining time. V_c, S_o, and t stand for cutting speed, feed rate and depth of cut respectively. P and Q are the pressure and flow rate of the HPC jet. A research on turning AISI 4340 steel under varying pressure and flow rate of HPC jet revealed that cutting temperature and chip reduction co-efficient can be well predicted from cutting speed, feed, depth of cut, coolant pressure and flow rate indicating that cutting temperature and force, both are a function of these cutting variables [**Sultana and Dhar 2010**]. Hence, it can be re-written that

$$V_B \propto \varphi\,(T\, P_z\, \theta) \quad \text{……...…………(3.16)}$$

Where, φ denotes proper function of machining time (T), average cutting temperature (θ) and main cutting force (P_z).

The trend of the flank wear progression mainly follows exponential function. Among different exponential functions such as: one, two and three parametric exponential, exponential decay, exponential associate and exponential growth functions, flank wear progression with the machining time can be predicted by Exponential Associate function. But, tool flank wear can be predicted by more generalized functions through further research on it. In this research, flank wear has been predicted by Exponential Associate function and can be modeled as

$$V_B = y_o + A_1\left(1 - e^{\frac{-T}{b_1}}\right) + A_2\left(1 - e^{\frac{-T}{b_2}}\right) \qquad \text{........................(3.16)}$$

Where V_B denotes the average flank wear and T stands for machining time, y_o is a constant which depends on the experimental condition. The coefficients A_1 and A_2 and the exponents b_1 and b_2 largely depend on the workpiece hardness value *i.e.* HRC40, HRC48, HRC56, insert configuration *i.e.* SNMM, SNMG and cutting environment *i.e.* dry, HPC. Hence, to form the model accurately, it is essential to consider all 12 combinations of the influencing parameters. Since the categories for insert, hardness and environment are independent of each other, it is necessary to incorporate some dummy variables to consider the effects of all the conditions. A plot of principal flank wears versus machining time for all the machining conditions is shown in Fig. 3.3. It is seen from Fig. 3.3 that flank wear is lowest for HPC machining environment, with SNMG insert and for workpiece hardness of HRC48. So, in modeling of tool flank wear, this curve is set as the base curve and the model is developed by adding the extra amount of tool wear that is responsible for the change of conditions *i.e.* HPC to dry, SNMG to SNMM, HRC48 to HRC40, HRC48 to HRC56. The values of coefficients A_1, A_2, b_1, b_2 and y_o in Equation 3.16 for HPC-SNMG-HRC48 are found by exponential associate approximation technique of experimental data using the OriginPro 8. The curve fitting is shown in Fig. 3.4 where the experimental and model curves are presented simultaneously along with the coefficient values.

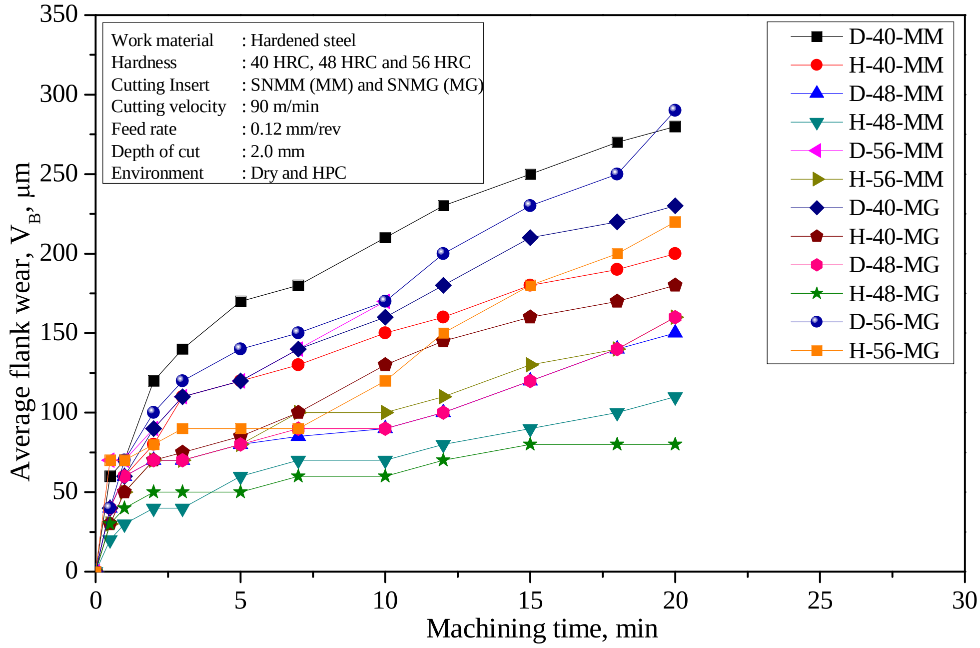


Fig 3.3 Average flank wear for all the machining conditions.

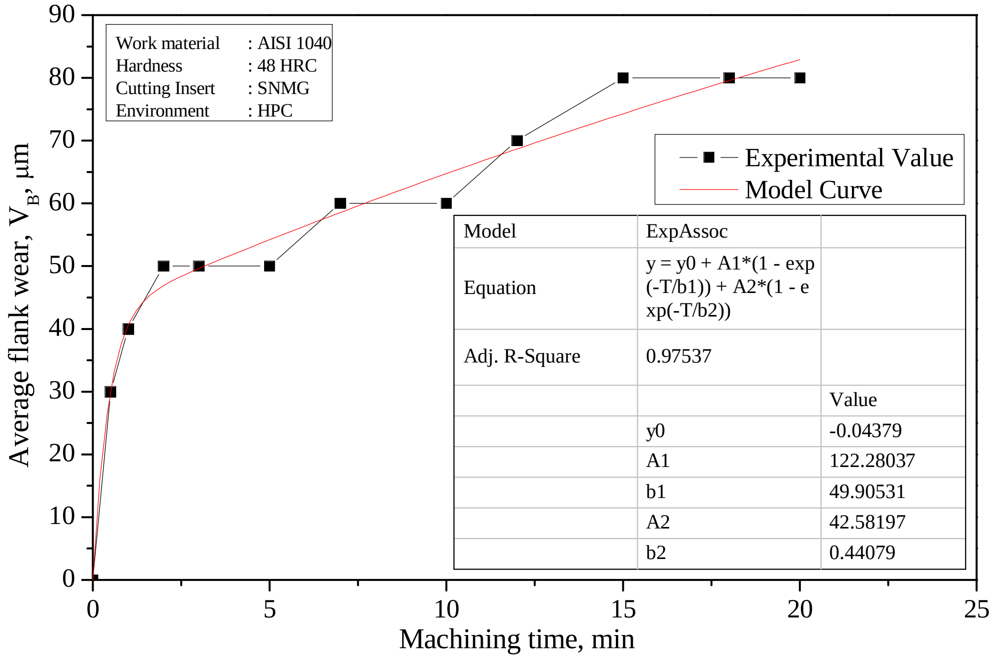


Fig. 3.4 Modeling of tool wear by exponential associate function for High Pressure Coolant machining using SNMG tool insert for workpiece hardness of HRC48.

As the machining conditions are independent, is it necessary to incorporate some dummy variables to combine independent conditions into one equation. For this model a total of four dummy variables E (for environment), I (for tool insert configuration), H_1 (for hardness change from HRC 48 to 40), and H_2 (for hardness change from HRC 48 to 56) are used. The dummy variables can have either of two values 1 or 0, each value of which represent the presence or absence of that particular condition. But H_1 and H_2 cannot have simultaneously value of 1. For example, if E = 1, then it is DRY machining, and if E = 0, then it is HPC machining. Table 3.1 represents the dummy variables and their values corresponding to the machining conditions.

Table 3.1 Dummy variable notations and their significance

Conditions	Dummy Variable	Values	Significance
Machining Environment	E	1	Dry
		0	HPC
Tool Insert Configuration	I	1	SNMM
		0	SNMG
Material Hardness	H_1	1	HRC40
		0	HRC48
		0	HRC56
	H_2	0	HRC40
		0	HRC48
		1	HRC56

Fig. 3.4 shows that the progression of principal flank wear with time follows exponential associate function with very high value of coefficient of determination, R^2 = 97.537%. The generated equation for HPC-SNMG-HRC48 condition is shown in Eq. 3.18.

$$V_B = -0.04379 + 122.2803\left(1 - e^{\frac{-T}{49.9053}}\right) + 42.5819\left(1 - e^{\frac{-T}{0.4407}}\right) \quad \text{.........(3.18)}$$

The effect of environment change is incorporated into Equation 3.18 by using the dummy variable E which converts the present equation like following,

$$V_B = -0.04379 + 122.2803\left(1 - e^{\frac{-T}{49.9053}}\right) + 42.5819\left(1 - e^{\frac{-T}{0.4407}}\right) + iE \quad \text{.........(3.19)}$$

Where, i is a straight line expression. It is equivalent to the effect of environment changes and is determined by linear regression method. The format of i is $\alpha + \beta T$, where T is independent variable and the value of the coefficients are determined by linear regression analysis of changes in principal flank wear (ΔV_B) versus machining time (T). The regression analysis gives the Equation 3.20.

$$i = 15.1868 + 2.4744T \qquad \text{………(3.20)}$$

By replacing i with its expression into Equation 3.19, Equation 3.21 is formed which reflects the model of tool wear consisting of the effect of only machining environment change from HPC to dry.

$$V_B = -0.04379 + 122.2803\left(1 - e^{\frac{-T}{49.9053}}\right) + 42.5819\left(1 - e^{\frac{-T}{0.4407}}\right) + (15.1868 + 2.4744T)E \qquad \text{………(3.21)}$$

The effect of tool insert configuration change is incorporated into Equation 3.21 by using the dummy variable I which converts the present equation like following,

$$V_B = -0.04379 + 122.2803\left(1 - e^{\frac{-T}{49.9053}}\right) + 42.5819\left(1 - e^{\frac{-T}{0.4407}}\right) + (15.1868 + 2.4744T)E + jI \qquad \text{………(3.22)}$$

Where, j is a straight line expression. It is equivalent to the effect of tool insert configuration changes and is determined by linear regression method. The format of j is $\alpha + \beta T$, where T is independent variable and the value of the coefficients are determined by linear regression analysis of changes in principal flank wear (ΔV_B) versus machining time (T).

$$j = 11.7058 + 1.3652T \qquad \text{………(3.23)}$$

Equation 3.24 is formed by replacing the expression of j into Equation 3.22 which reflects the model of tool wear consisting of the effect of environment change from HPC to dry and tool insert configuration change from SNMG to SNMM.

$$V_B = -0.04379 + 122.2803\left(1 - e^{\frac{-T}{49.9053}}\right) + 42.5819\left(1 - e^{\frac{-T}{0.4407}}\right) + (15.1868 + 2.4744T)E + (11.7058 + 1.3652)I \qquad \text{………(3.24)}$$

The effect of hardness change is incorporated into Equation 3.25 by using two dummy variables H_1 and H_2 which converts the present equation like following,

$$V_B = -0.04379 + 122.2803\left(1 - e^{\frac{-T}{49.9053}}\right) + 42.5819\left(1 - e^{\frac{-T}{0.4407}}\right) + (15.1868 + 2.4744T)E + (11.7058 + 1.3652)I + kH_1 + l\,H_2 \quad \text{.........(3.25)}$$

Where, k and l are two straight line expressions. It is equivalent to the effect of tool insert configuration changes and is determined by linear regression method. The format of both k and l is $\alpha + \beta T$, where T is independent variable and the value of the coefficients are determined by linear regression analysis of changes in principal flank wear (ΔV_B) versus machining time (T).

$$k = 20.1685 + 4.8179T \quad \text{.........(3.26)}$$

$$l = 14.8971 + 4.5292T \quad \text{.........(3.27)}$$

Equation 3.27 is formed by replacing k and l by their corresponding expressions into Equation 3.24 which reflects the model of tool wear consisting of the effect of environment change from HPC to dry, tool insert configuration change from SNMG to SNMM and hardness change from HRC48 to HRC40 or HRC56. The Equation 3.27 is the final model of principal flank wear.

$$V_B = -0.04379 + 122.2803\left(1 - e^{\frac{-T}{49.9053}}\right) + 42.5819\left(1 - e^{\frac{-T}{0.4407}}\right) + (15.1868 + 2.4744T)E + (11.7058 + 1.3652)I + (20.1685 + 4.8179T)H_1 + (14.8971 + 4.5292T)H_2 \quad \text{.........(3.28)}$$

This model is applicable for determining the amount of principal flank wear of tool inserts with machining time for the following conditions only-

- AISI 1040 steel with hardness – HRC40, HRC48, HRC56
- Coated carbide tool inserts with configuration – SNMM, SNMG
- Turning environment – Dry, High Pressure Coolant (HPC)
- Process variables – V_c = 90 m/min, S_0 = 0.12 mm/rev, t = 2.0 mm
- Machining time up to 20 min.

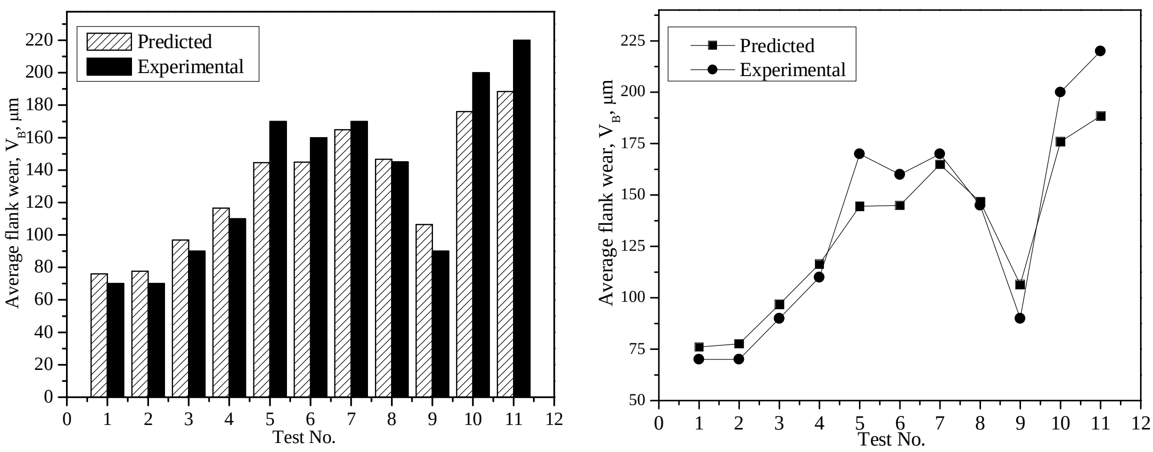
3.3 Validation of Flank Wear Model

In order to validate the model, the measured flank wear in turning AISI steels by coated SNMM, SNMG inserts at constant V_c-S_o-t at dry and high pressure coolant machining has been compared with the predicted flank wear. The test was carried out for machining time starting from 0.5 min to 20 min. The selection of machining environment, material hardness and tool insert configuration is totally random. Binary values of dummy variables exhibit the presence and absence of that particular condition. The percentage of error is also computed and showed in Table 3.2.

Table 3.2 Selection of dummy variables and validation of flank wear model

Test No.	Machining Time, T (min)	Dummy Variable				Principal Flank Wear, V_B (model)	Principal Flank Wear, V_B (exp.)	% Error
		E	I	H_1	H_2			
1	0.5	1	1	0	1	76.04	70	-8.62
2	1	1	0	0	1	77.65	70	-10.92
3	2	1	0	1	0	96.83	90	-7.58
4	3	1	1	0	1	116.52	110	-5.92
5	5	1	1	1	0	144.54	170	14.97
6	7	1	0	1	0	144.94	160	9.41
7	10	1	0	0	1	164.86	170	3.02
8	12	0	0	1	0	146.66	145	-1.14
9	15	0	1	0	0	106.47	90	-18.29
10	18	0	0	0	1	175.99	200	12.01
11	20	0	0	0	1	188.39	220	14.36

A bar chart corresponding to Table 3.2 is drawn to see the difference in experimental and predicted values in Fig 3.5. From the table it is shown that the maximum percentage of error less than 20% indicating a good resemblance with experimental result.



(a) Bar chart (b) Graph

Fig. 3.5 Comparison of experimental and predicted values of tool flank wear

Chapter-4

Discussion on Experimental Results

4.1 Machining Chips

Machining chips inherently tells us the interaction characteristics at chip-tool interface. To assess the performance of the machining, it is always a good move to inspect the machining chips. In my research work, I inspected the color and shape of the chips and measured the chip reduction coefficient (ξ) which is the ratio of the uncut chip thickness to that of cut chip. Chip properties largely depend on different hardness values of the work materials; tool geometry-especially the rake angle and the cutting parameters *i.e.* cutting speed, feed rate and depth of cut. They are also somewhat dependent on the cutting environments and the nature of the chip-tool interaction.

Table 2.2, Table 2.3 and Table 2.4 present the shape and color of machined chips under both dry and HPC conditions using SNMG and SNMM inserts for work piece hardness values of HRC40, HRC48 and HRC56 respectively. From the table we can see that the color of the chips is ranging from metallic color to blue under dry condition for both the inserts in all three workpieces. The blue color indicates the generation of high heat at the chip-tool interface. At lower speed and feed, the energy consumption is relatively lower, but at high speed and feed, high energy is consumed, friction between tool and work material increases and high temperature is reached which causes the color of the machining chips become blue. On the other hand, the color of the chip is metallic, golden and blue under high pressure coolant condition for both SNMG and SNMM inserts for any value of hardness of workpieces. The high pressure coolant jet lifted the chip upward, created a wedge effect, and reached at the interface that ultimately reduced the temperature at the cutting zone which in turn creates metallic and golden color chips along with blue color chips.

Now, if we compare the result between the SNMG and the SNMM insert, we find that the SNMG insert was the one which showed better result under high pressure coolant condition. The effect of high pressure coolant jet was more significant for the groove type SNMG insert. This better result can be accredited to effectively larger positive rake of the tool and enhanced cooling by the coolant jets impending along the groove parallel to the cutting edges. It is also noticeable that, with increasing hardness of the workpiece blue color chip formation becomes prominent trend for dry cutting environment but for HPC condition metallic and golden color is followed by blue colors. It gives clear message that when the hardness is very high the high pressure coolant supply sometimes cannot reduce the temperature sufficiently enough to turn the chip color from blue to other color.

The chip reduction coefficient (ξ) is another important index of chip formation and specific energy consumption for a given tool-work combination. In case of turning, the machined chip thickness is greater than the uncut chip thickness because during turning process, the chips are under compression from three sides. As a result, the chip thickness ratio shows a value smaller than 1. If the friction at chip-tool interface can be reduced, the compressive force on chips will be reduced also which will yield a higher value of chip thickness ratio. All parameters in machining are directly or indirectly linked with the chip reduction coefficient. If there is excessive heat generation at the cutting zone, there will be high friction between the tool and the work material. This frictional force will cause high energy consumption hence higher cutting force. These will lead to a low chip thickness ratio which is not desirable.

Fig. 2.4, Fig. 2.5 and Fig. 2.6 show the variations of ξ with V_c at different S_0 in turning HRC40, HRC48 and HRC56 steels respectively for both dry and HPC conditions using SNMM and SNMM inserts. For SNMG insert the value of the chip reduction coefficient (ξ) is smaller than 1.0 at every condition of lower hardness except highest hardness where the value is around unity. But for SNMM insert the value is far greater than SNMG, in fact double to some extent. It is because of the groove present (absent on SNMM) on the rake surface of the SNMG insert that restrict the expansion of the chips under compression which reduces the cut chip thickness. As the cutting speed and feed rate increase, the value of the chip reduction coefficient (ξ) decreases. This is due to the higher energy consumption associated with higher material removal rate. For all speed-feed combinations, the application of high pressure coolant shows lower values of chip reduction coefficient as compared to dry cutting for all three workpiece hardness values. The high pressure cooling jet, with both its lubricating and cooling effect, minimized the shrinkage of shear zone and plasticization and reduced the formation of built-up-edge. It also reduces the cutting temperature preventing softening of the workpiece during turning and reducing the expansion due to compression. As a result, the chip reduction coefficient possesses lower value in HPC than in dry machining for any hardness values. The percentage reduction in chip reduction coefficient (ξ) is accomplished by applying the high pressure coolant jet for both SMNG and SNMM inserts under all speed-feed conditions in three different workpieces is more satisfactory in low speed feed combinations.

4.2 Cutting Temperature

Heat generation at the chip-tool interface is of prime concern in the machining process. The machining temperature at the cutting zone must be reduced to an optimum level. During machining, shearing of work material, friction between the flowing chips and rake face of the tool and friction of auxiliary flank with finished surface are the principal sources of heat generation. The magnitude of the cutting temperature increases with the increase of material removal rate *i.e.* with the increase of cutting velocity, feed and depth of cut in hard turning of different hardened steels, as a result, high production machining is constrained by the ascend in temperature. This problem increases further with the increase in strength and hardness of the work materials.

High cutting temperature adversely affects, directly or indirectly, chip formation, cutting forces, tool life, dimensional accuracy and surface integrity of the product. In order to cope with this problem, numerous attempts have been made to reduce this detrimental cutting temperature. It has been followed that in some cases, dry machining is preferable for hard and difficult-to-machine materials at low speeds. But at high speeds, cutting fluids can play a significant role. Application of conventional cutting fluids may cool the tool and the workpiece in bulk to some extents, but it cannot cool and lubricate expectedly and effectively the chip-tool interface where the temperature is maximum. This is mostly because the flowing chips make mainly bulk contact with the tool rake surface and may be followed by elastic contact just before leaving the contact with the tool. This bulk contact does not allow the cutting fluid to penetrate into the chip-tool interface. Elastic contact allows slight penetration of the cutting fluid only over a small region by capillary action. The cutting fluid action becomes more and more ineffective at the interface with the increase in cutting velocity when the chip-tool contact becomes almost fully plastic.

In this research work, a tool-work thermocouple was calibrated to determine the average chip-tool interface temperature and the values were plotted against different cutting speed under both dry and high pressure coolant condition for both coated SNMG and coated SNMM inserts. It was expected that the application of high pressure coolant jet would be much more effective at high speed-feed condition in reducing the average chip-tool interface temperature which plays an imperative role on productivity, dimensional accuracy, surface integrity and overall economy in turning hardened medium carbon steels.

The evaluated role of HPC on average chip-tool interface temperature in turning hardened steels at different V_c-S_0 combinations in compare to dry condition have been shown in Fig. 2.7, Fig. 2.8 and Fig. 2.9. The variation was studied for both SNMG and SNMM inserts under dry and high pressure coolant conditions for workpieces of hardness HRC40, HRC48 and HRC56. At high speed-feed conditions, the MRR is high which requires high energy consumption. This high energy input helps the cutting zone temperature increase. This is why the controlling of temperature is more important in high speed machining.

From Fig. 2.7, Fig. 2.8 and Fig. 2.9 it is evident that with the increase in cutting velocity, the cutting temperature increases for both dry and HPC conditions irrespective of using SNMM and SNMG inserts but the cooling effect gets more significant at higher speeds where the temperature difference between dry machining and HPC machining is higher. It is also obvious that with the increase of workpiece hardness, the cutting temperature also increases and it reaches above 1200^0C then the application of HPC reduces it below 1000^0C. The possible reason may be that high pressure coolant jet reached the chip-tool interface even at high speed-feed condition. The high velocity jet uplifted the chip creating a wedge effect and reached at the shear zone. There it performed both the cooling and lubricating effects and eventually reduced the temperature. This reduction in temperature is very much appreciable in retaining tool life and product quality. So, we can conclude that results of our research work show that application of high pressure coolant contributes to a decrease in average chip-tool interface temperature by a momentous margin depending on hardness values and cutting parameters which is further demonstrated by the color of the machining chips.

4.3 Tool Wear

At conventional speed, tool wear is mainly due to abrasion and adhesion, but is dominated by diffusion process at higher speeds. High pressure coolant directly reduces the diffusion process by decreasing the cutting zone temperature. As a result, a delayed progression of tool wear is followed under the high pressure coolant condition. The wear of cutting tools is generally quantitatively evaluated by the magnitudes of V_B, V_S, V_M, V_{SM}, V_N etc. Among them, average principal flank wear, V_B is considered to be the most significant parameter at least in research work. The earlier investigation carried out by the researchers reveals that the application of conventional cutting fluid does not always help in reducing tool wear in machining steels by coated or uncoated carbide inserts rather in some cases exacerbate wear.

Rise in cutting force and temperature is directly related with the growth of principal flank wear (V_B). So, the principal flank wear is the foremost concern among all the tool wears. The life of carbide tools, which usually fails by wearing, is assessed by the actual machining time after which the average value of its principal flank wear reaches a limiting value, like 300 µm. So, decreasing the rate of growth of principal flank wear without sacrificing the MRR is, therefore, our prime concern.

In order to measure the V_B an optical microscope was used. The inserts were withdrawn at regular intervals to study the pattern and extent of wear on principal and auxiliary flank faces under both dry and high pressure coolant conditions. The gradual growth of principal flank wear (V_B) was observed during turning of hardened medium carbon steels by coated carbide inserts (SNMG and SNMM) at a cutting velocity of 90 m/min, feed rate 0.12 mm/rev and depth of cut 2.0 mm under both dry and high pressure coolant conditions. It can be clearly observed that the principal flank wear (V_B) decreases significantly under high pressure coolant condition.

In high pressure cooling system, the coolant jet was pressurized about 70 bars. This high pressure carried the coolant jet into the plastic contact between tool tip and workpiece where it cooled the interface and lubricated properly. It also helped to reduce the heat generation caused by the friction between auxiliary flank face and finished surface by appropriate lubrication. Such improvement by high pressure coolant may also be attributed to retention of proper sharpness and hardness of the cutting edge by the steady and intensive cooling, protection from oxidation and corrosion and absence of built up edge formation which accelerates both crater wear and flank wear by flaking and chipping.

In the process of systematic growth of cutting tool wear, the cutting tools usually first undergo rapid wear called break-in wear at the beginning of machining due to attrition and micro-chipping and then uniformly and relatively slow mechanical wear followed by faster wear at the end. The mechanism and the rate of growth of cutting tool wear depend much on the mechanical and chemical properties of the tool and the work materials and their behavior under the cutting conditions. While machining these hardened medium carbon steels, no notching was found to develop in any of the inserts even under dry machining condition possibly for the good chemical stability and uniform hardness of these steels.

During turning of relatively soft and ductile materials by uncoated or coated carbide tools at reasonably high speed-feed condition, crater wear is governed mainly by adhesion and diffusion for rubbing at higher stresses and temperature and flank wear mainly by abrasion for less pressure and temperature. But adhesion and diffusion type temperature sensitive wear may also occur, in addition to abrasion wear, at the tool flanks if the flank temperature becomes high. Turning of strong metals like hardened medium carbon steel at reasonably high velocity and feed (90 m/min and 0.12 mm/rev respectively) under dry condition is expected to cause sufficiently high temperature at the tool flanks. Adhesion and diffusion, therefore, are also likely to have contributed to the flank wear in the present case, and seemingly high pressure coolant jet has prevented such temperature sensitive adhesion and diffusion as well as reduced abrasion wears.

Fig. 2.10, Fig. 2.11 and Fig. 2.12 show the growth of average principal flank wear (V_B) with time for dry and HPC environments with SNMG and SNMM inserts for three workpieces with hardness HRC40, HRC48 and HRC56 respectively. It is obvious from these figures that for a certain period of time the magnitude of V_B is lower in case of HPC assisted machining. In fact, the difference is greater for SNMM inserts due to the absence of grooves on the flank surface of the inserts. From Fig. 2.12 it is shown that in machining high hardness material (HRC56) the wear rate is very high in compared to other materials and machining conditions which proves that the increased hardness induces higher tool wear and lower tool life. From the same figure it can be seen during machining with SNMM inserts in dry condition for 10 minutes the insert suddenly breaks where the same material is machined under HPC cutting condition and good result is found in terms of tool life and flank wear. Fig. 2.13, Fig. 2.14 and Fig. 2.15 show the scanning electron microscopy (SEM) views of the worn out inserts (SNMG and SNMM) after being used for machining hardened medium carbon steel of different hardness (40 HRC, 48 HRC and 56 HRC) at V_c= 90 m/min, S_o = 0.12 mm/rev and t = 2.0 mm for 20 min. under dry and high pressure coolant condition. From the figures, it is clear that tool wear occurs at both auxiliary flank surface as well as principle flank surface. For low hardness *i.e.* HRC40 the wear pattern is mainly crater wear due to abrasion and diffusion for rubbing between surfaces. In case of SNMG insert the principal flank surface is very smooth but in SNMM insert the surface is rough due to skinning out of the coating but no formation of built-up-edge. Application of HPC causes chemical wear of the tool but produces better surface finish with the cost of tool as the lubrication is formed by the worn out tool particles. This is also supported by the SEM view at Fig. 2.13(b).

While machining medium hardness material *i.e.* HRC48, the inserts are found with mainly abrasion wear for both in dry and HPC assisted machining. In case of SNMG insert use, there is flaking on the tool rake surface which is an indication of sudden impact or brittleness of tool material. This brittleness was due to uneven cooling on the contact surface. In dry cutting there is depression on the inserts which is caused due to high cutting temperature generation which in turn softens the material and impression is formed. Lack of coolant supply is also responsible for it.

Fig. 2.15(b) reveals built-up-edge (BUE) formation followed by breaking of insert while machining HRC56 steel in dry condition using SNMM inserts at low cutting speed because shear is strongest at the contact surface with the cutting tool, the first layer of metal impacting and seizing on it work-hardens more than the rest of the volume of metal. As a consequence of this work hardening, this first layer of metal is stronger than the adjacent metal moving away from the workpiece. Effectively, first layer becomes part of the tool. The process repeated itself and, after some time, a built up edge is formed. This BUE formation endow with some benefits i.e. slight increase in tool life, less power consumption as some of the cutting is done with BUE not the insert itself. The BUE at the same time produces excessive work-hardening, poor surface finish and uncontrolled dimensions due to dynamic change of tool geometry. The wear is of abrasion and adhesion type and formation of metallic bonds followed by transfer of these elementary particles which results in smooth wear profile on the rake surface. On the other hand, in HPC machining there is no sign of BUE as the high pressure fluid jet pointed to chip tool contact point remove any deposited material from the rake surface of the insert. Although no BUE is formed but significant amount of tool wear is clearly visible which is caused by abrasion and adhesion wear along with chemical wear. The SEM views of the worn out inserts after machining of hardened medium carbon steels at effective cutting velocity of 90 m/min, feed rate 0.12 mm/rev and depth of cut 2.0 mm for different periods of time which qualitatively point toward the conclusion that the application of high pressure coolant jet has provided substantial reduction in overall wear of the inserts.

4.4 White Layer Formation

Inspection of the SEM images of the twelve inserts for different cutting conditions shows that the white layer is formed in some of the samples with refined grain structure compared to bulk microstructure. In some cases, the formation of white layer is accompanied by dark layer formation. Although in machining HRC56 material by SNMG insert in HPC condition only dark layer is formed. The tool wear mechanism is related with white layer formation in different aspects. Fig. 2.13 shows that a clear white layer is visible on the principal flank surface for both dry and HPC machining when machined with SNMG insert. But when machined with SNMM only is dry machining the white layer is formed. In case of HRC48 material no formation of white layer is noticed. But again in HRC56 material there is white as well as dark layer in SNMG insert. An interfacial region is observed with white layer for HRC40 material. The grain size of the white layer is determined by the cooling time during heat treatment and also by the cooling during machining. The phase transformation is the predominant mechanism of white layer formation in high speed cutting, which is aided by plastic deformation aided by chip formation. On the other hand, the predominant mechanism of white layer formation is at the lower cutting speed is grain refinement due to severe plastic deformation.

4.5 Surface Roughness

If hard turning is to replace any grinding operation, it must be capable of producing surfaces of acceptable quality. Surface roughness (R_a) is an important index of machinability which is substantially influenced by the machining environment for given tool-work pair and speed-feed conditions. Surface roughness has been measured at two stages; first, after a few seconds of machining with the sharp tool while recording the cutting temperature and second, with the progress of machining while monitoring growth of tool wear with machining time. The surface roughness attained after 50 seconds of machining of the hardened steel by the sharp SNMG and SNMM inserts at various V_c-S_o combinations under dry and HPC conditions are shown in Fig. 2.16, Fig. 2.17 and Fig. 2.18 respectively. The first noticeable point from the figures is gradual decrease of surface roughness with increase in cutting velocity for both types of tool inserts. The reasons behind this phenomenon is the work-hardening at higher velocity as higher velocity transmit higher kinetic energy to deform which causes the temperature to go up and then subsequent rapid cooling facilitates work-hardening and produces smoother surfaces. The second noticeable point is that application of HPC reduces surface roughness significantly as the HPC jet lift up the chips so as to prevent the chips from rubbing the finished surface. The HPC application reduces the coefficient of friction at the interface of the tool and chip over the rake face, provides lubrication and faster cooling rate all of which are responsible for this reduction of R_a. Fig. 2.19, Fig. 2.20 and Fig. 2.21 show the development of R_a with progression of machining time for cutting velocity 65 m/min, feed rate 0.12 mm/rev and depth of cut 1.5 mm for hardness values of HRC40, HRC48 and HRC56 respectively. The aforesaid reasons are also responsible to reduce the surface roughness.

4.6 Tool Wear Model

The model was developed using the regression technique following least error method for determining the amount of principal flank wear at any machining time not exceeding 20 minutes. The percentage of error for any specified machining condition is less than 20% which indicate a good resemblance with the experimental result and can be considered as a coherent model to predict the principal flank wear for any particular machining time. It is to be mentioned that the machining time should be less than equal to 20 minutes. The selection of any condition, shown in Table 3.1, ensures that the magnitude of that particular variable is “1”. Its effect on tool wear can be nullified by selecting “0”. From Table 3.2 it is seen that the experimental and predicted results are very close to each other. The maximum percentage error is 18.29% which is found for HPC-SNMM-HRC48 for machining time 15 minutes. It is noticeable that more than 50% data has error less than 10% and more than 90% data has error less than 15%. It is also evident from Fig. 3.5.

Chapter-5

Conclusions and Recommendation

5.1 Conclusions

This research work justifies the capability of the hard turning process for differently hardened workpieces under high pressure coolant condition with coated carbide inserts. The goal of this study was to evaluate the effects of high pressure coolant system on the wear behavior of the coated carbide cutting tools and on the resultant surface quality along with the white layer formation, chip formation and cutting temperature. The following conclusions can be drawn from the aforesaid results and discussion.

- The present high pressure coolant system enabled the reduction in average chip-tool interface temperature up to significant level for both SNMG and SNMM inserts depending on the cutting conditions. The reduction is more with increasing hardness of workpieces.

- The shape and color of the machined chips became favorable due to the application of HPC as it provided effective cooling at the cutting zone. High pressure jet also improved the nature of interaction at the chip-tool interface which results a decrease in chip-tool interface temperature.

- Increased hardness of the workpieces does not necessarily accelerate tool wear but promote surface roughness for both inserts. The temperature increases with hardness but machining with SNMG insert produces lower temperature in compare to SNMM insert for different hardness.

- Application of high pressure coolant jet produced reduced tool wear, good dimensional accuracy and surface finishes that are acceptable for most applications. In general, this study shows that hard turning is capable of producing precision parts and can replace grinding for many applications.

- By selecting the coated tools, it is possible to cut faster due to the improved wear resistance of the tools, which in turn allows decreased feeds (and thus better surface finish), produces higher material removal rates, and reduces the cost per part. The results also uncover the fact that SNMG inserts performs better than SNMM inserts under both environmental conditions for all three workpieces.

- White layer formation is detrimental for hard machined parts and HPC assisted machining reduces white layer formation.

- The developed tool wear model is applicable for workpieces with hardness of HRC40, HRC48 and HRC56. The model should be used for machining with SNMM, SNMG inserts and machining environments is dry or high pressure coolant jet application. The validation of the model shows good resemblance with experimental results which concludes that the model can be used to predict principal flank wear at any specific machining time. The tool wear model considers both abrasion and adhesion wear mechanism as the model is developed on the basis of experimental result of tool wear with time. And this research exhibits that the abrasion and adhesion is the prominent tool wear mechanism.

Acceptable dimensional accuracy and surface finishes are possible by hard turning. The quality of hard turned surfaces is generally good. Even when white layers exist; they are below 2 µm and would be removed by super finishing, which often follows hard turning or grinding. Surface finish is slightly poorer than grinding values in case of higher hardness *i.e.* HRC56 due to plastic flow of the material around the nose of cutting tools. This plowing action is inevitable due to the negligible chip thickness that occurs at the two boundaries of the contact area between the tool and workpiece. Flank wear progression is non-linear, but corresponds to a linear increase in the volumetric wear loss. Cutting speed has a much more detrimental effect on tool life than feed. Increased feeds are actually advantageous if the goal is to maximize the number of parts per tool instead of cumulative cutting time. The improved performance under the high pressure coolant condition allows cutting at higher speeds, which in turn yields lower chip-tool interface temperature, improved surface finish, higher material removal rates, reduced machining time per part, and reduced cost.

5.2 Recommendation

This research work fills a void in differently hardened steels turning research by establishing techniques to quantify wear behavior and developing a cooling system that accounts for minimizing the detrimental effects of increased cutting zone temperature. Some of the recommendations for future research work in this field are-

- In the experiment, one cooling jet was used, but if three cooling jets are used pinching towards the rake face, principal and auxiliary flank face, the result may get better which is yet to be investigated.

- The pressure and flow rate used were 80 bars and 6 liters/minute respectively. These two parameters can be changed and its effects can be further analyzed to find the optimum result.

- The research is carried out on three workpieces of hardness value of HRC40, HRC48 and HRC56. In future work some other workpieces of intermediate hardness can also be machined to see the result on very little increment of hardness to get more accurate results.

- In measuring chip-tool interface temperature, only the average values were considered. The peak values are yet to be tested to uncover the temperature distribution in the chip-tool contact length.

- Another area that needs significant attention is tool design. All testing presented in this research work used identical tool geometry, although it is not expected that this geometry is optimal for any or all cases. Previous works have shown that tool geometry affects nearly everything about the process: tool wear and failure, cutting force behavior, surface roughness, residual stresses and white layer generation. Both experimental and modeling work should be used to identify the best tool geometry and edge preparation for different materials, cutting conditions and applications.

- The tool wear model developed is limited to the use of specific hardness value, environment, and insert configuration. But further research can be performed to develop an equation which fits for a range of hardness values.

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