CUTTING TEMPERATURE FORCE AND ROUGHNESS IN HIGH PRESSURE COOLANT ASSISTED HARD TURNING

A Project Thesis

by

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The thesis titled "**Cutting Temperature, Force and Roughness in High Pressure Coolant Assisted Hard Turning**" submitted by **Md. Akhtar-Hossain**, Roll No: **100608003F**, Session-**October 2006**, has been accepted as satisfactory in partial fulfillment of the reqnirement for the degree of **Master in Industrial and Production Engineering** on 12 October, 2008.

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I do hereby declare that this work has been done by me and neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma except for publication.

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Abstract

Machining hardened steels has become an important manufacturing process, particularly in the automotive and bearing industries. Abrasive processes such as grinding have typically been required to machine hardened steels, but advances in machine tools and cutting materials have allowed hard turning on modern lathes to become a realistic replacement for many grinding applications. There are many advantages of hard turning, such as increased flexibility, decreased cycle times, reductions in machine tool costs, and elimination of environmentally hazardous cutting fluids. Despite these advantages, implementation of hard turning remains relatively low, primarily due to concerns about the quality of hard turned surfaces and a lack of understanding about the wear behavior of cutting tools.

The effects of high pressure coolant on cutting performances in respect of chip formation, cntting temperature, cutting forces and surface roughness have been studied using carbide insert. The same experiments were carried out on the above under dry condition in order to compare the results with those obtained under minimal cutting fluid condition.

The result indicated that the machining with high pressure coolant performed much better than dry machining mainly due to substantial reduction in cutting temperature enabling favorable chip-tool interaction. This also facilitated the reduction in cutting forces and surface finish.

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Chapter-1

Introduction

1.1 Introduction

Producers of machined components and manufactured goods are continually challenged to reduce cost, improve quality and minimize setup times in order to remain competitive. Frequently the answer is found with new technology solutions. Such is the case with grinding where the traditional operations involve expensive machinery and generally have long manufacturing cycles, costly support equipment, and lengthy setup times. The newer solution is a hard turning process, which is best performed with appropriately configured turning centers or lathes.

Hard turning is defined as the process of single point cutting of part pieces that have hardness values over 45 HRC. Along with developing researches and studies, types of materials being cut by hard turning method are growing in numbers and applications. Quenched medium carbon steel is among the materials being investigated to employ hard turning method due to its wide application in various industries. Medium carbon steels since it is hardened by quenching at a temperature 900°C, hold it one hour at that temperature then its tempering at 160°C in brine solution mixed with ice causes the remove of residual stress developed on it, and therefore can achieve high strength and hardness level around 51 to 54 HRC. Uncoated carbide SNMG inserts are used in the machining of hardened steel in both dry and high pressure coolant conditions. However, uncoated carbide SNMG inserts are expensive but the practices in the industry are still wide spread. Finish machining is intended to achieve high level of surface finish and is characterized with low feed and depth of cut. In order to improve the productivity, tools with proper geometry have been provided by tool manufacturers.

The machining of hardened steel is almost always cited in literature using dry cutting, because the increase of the temperature makes chip deformation and shearing of the hardened material, easier. Nevertheless, high temperatures cause an inconvenience such as workpiece amendment, which affects dimensional and geometric accuracy and runs the risk of surface integrity. On the other hand, the complete absence of coolant, chip transportation causes an increase of tool-chip and tool-workpiece friction, as a result increase cutting force as well as abrasive wear and attrition. Currently, this problem is tried to be controlled by reducing heat generation and removing heat from the cutting zone through optimum selection of machining parameters, proper cutting fluid selection and application. Some recent techniques have enabled partial control of the machining temperature by using heat resistant tools like coated carbides, CBN etc.

Potential advantage in economical and ecological aspects has made hard turning a profitable alternative to the incumbent grinding as the finishing operation. High material removal rate and relatively low tool cost are some of the economical benefits. Nevertheless, the drive to minimize the use of coolant whenever feasible has advantaged hard turning which has been successfully performed. Now a days, due to technological innovations, machining without cutting fluid, i.e. dry cutting, is already possible, in some sitnations. During dry cutting operations, the friction and adhesion between chip and tool tend to be higher, which causes higher temperatures, higher wear rates and, consequently, shorter tool lives. The main cutting force required to slide more than that of HPC. Feed force as well as surface roughness increased. Therefore, the permissible feed and depth of cut have to be restricted. So the completely dry cutting is not suitable for hard turning processes since cutting fluid is necessary to prevent the chips from sticking to the tool and causing its breakage. Though injection of conventional coolant in a form of mist improves machinablity index to some extent, it cannot remove the problems associated with the conventional cutting fluid.

High pressure jet-assisted at pressures of approximately 70-95 atmospheres itself as a possible solution for high speed hard turning in achieving low cutting temperature, roughness while maintaining cutting force as responsible levels, if the high pressure cooling parameters can be strategically tuned. Coolant applied at the cutting zone through a high pressure jet nozzle could reduce the contract length and coefficient of friction at chip-tool interface and thus could reduce cutting force and improve tool life to some extent. High pressure coolant injection technique not only provide reduction of cutting force and temperature but also reduce the consumption of cutting fluid by 50% .It has been reported that the coolant and lubrication is improved in high speed machining of difficult to machine materials by the use of high pressurized coolant jet .

HPC jet-assisted machining has been widely used on so-called "hard to machine materials" such as high-temperature alloys like hardened steels and titanium. These materials cannot be cut effectively without cooling, even though dry cutting is becoming increasingly widespread. The use of cryogenic coolant easily reduces cutting temperature and chip load, provides improved tool life and surface finish as a result increase all the machinability indices. But the use of cryogenic coolant is limited due to the high cost and difficult handling of cryogen.

During hard turning, generated heat is mainly dissipated in the chip and in the workpiece, a rather small part of heat flows to the tool. However, the highest temperature is obtained at the tool–chip interface that leads to diffusion wear and cutting edge degradation. The other important functions of the cutting fluids are to flush away the chips from the cutting zone and to provide corrosive resistance to the machined component. The heat generated usually alters the microstructure of the alloy and induces residual stresses. Residual stresses are also produced by plastic deformation without heat. Heat and deformation generate cracks and micro structural changes, as well as large micro hardness variations. Residual stresses have consequences on the mechanical behavior.

Chapter-2

Literature Review

2.1 Introduction

In parts of the world, many research and investigations have been done on different materials, machinability mainly in respect of cutting forces, cutting temperature, surface integrity, chip tool interaction, dimensional accuracy, chip morphology, wear and tool life with or without using cutting fluid. Research has also been initiated on control of such pollution by HPC machining and their technological effects particularly in temperature intensive machining. A brief review of some of the interesting and important contributions in the closely related areas is presented in this section.

2.2 Literature Review

The manufacture of a product had been attempted to be done as rapidly and inexpensively as possible. Now that more environmental regulations are being put in place, manufacturers are forced to re-evaluate their manufacturing processes and reduce or eliminate their waste streams. The waste streams present in machining include cutting fluid flow, chip flow, and cutting tool usage. The machining temperature could be reduced to some extent by improving the machinability characteristics of the work material and surface integrity minimized by optimizing the tool geometry and by proper selection of the process parameters. Hard turning of machine parts is a production process that holds considerable promise for the future since it is an effective means of increasing productivity. In recent years hard turning become an attractive and effective solution of finish machining process because it has many advantages, such as higher flexibility, shorter cycle times, lower cost. and a higher material removal rate [**Koning et al. 1993**]. High pressure jet of conventional coolant has been reported to provide some reduction in cutting temperature [**Robert 2004**]. High-pressure coolant can often cut cycle times in half or better and improve surface finish and double or quadruple tool life while delivering a reduction in cycle time [**Frederick Mason 2001**].The idea of delivering coolant under high pressure to the cutting region in order to increase tool life during machining began in early 1950s [**Pigott and Colwel 1952**]. The primary objective of this machining technique is to measuring cutting force; reduce the temperature generated at the tool-chip interfaces and surface roughness when cutting at high speed.

Udea et al. [**1999**] investigate the influence of the cutting temperature and the workpiece material of the cutting edge. From two-color pyrothermal radiation of the tool conducted through a hole of an internally turned tube, it can be clearly stated that the temperature increases with the cutting speed and with the hardness of the work piece. [**Elbestawi et al. 1996**] Experimentally found that the cutting performance of PCBN tools during the high speed finish milling of H13 tool steel of hardness up to HRC 55 their experimental result show that the wear on high CBN tools decrease as the workpiece hardness increase. [**Fleming and Bossom, 1998**] estimated that the self induced heat generation at the cutting zone is up in the range of 650-750°C, and is enough to reduce the hardness of the material in contact with the cutting tool. The heat induced soft cutting means that the PCBN is not in contact with the workpiece in its hard state, thus giving the PCBN a longer tool life compared with that of other cutting materials. **[Liu et al. 2002]**, shows that, the changing role of cutting temperature is not in accord with the traditional metal cutting theory. When the workpiece material hardness is HRC 50, the cutting temperature is optimum. With further increase in the workpiece hardness, the cutting temperature shows a descending tendency.

Luttervelt et al. **[2004]** investigated that the predictive model, only the average friction value was used, and ploughing forces were assumed to be negligible. Because of the relatively small depth of cut in hard turning, vibrations in the signals related to slight deviations of the workpiece rotation axis are relatively strong. Moreover, for a small depth of cut the influence of a "skewed" clamping situation is more dominant. [**Xinfeng et al. 2006]** For the small cutting force components (the main cutting force component and the feed force component) and the very low cutting parameter, the forces are comparable to the resolution of the measurement device.

Liu et al. **[2002]** investigated that, under different cutting parameters, the rule of cutting force change with workpiece hardness change accords with traditional metal cutting theory. The main cutting force features an increasing tendency with the increase of the workpiece hardness, but the changing extent is different at the two sides of the workpiece hardness. The deformation created by the chip formation reduces when the workpiece hardness is increased. The chip formation mechanism. chip and the chip shape change also. When workpiece hardness is over 50 HRC that the hackle chip can bring more heat away is the main reason for the decrease of the cutting temperature.

Unsuitable cutting conditions also create residual tensile stress. [**Tonshoffins et al. 2000**] Observed that the deformation coefficient hardened GCr15 increases and when the machined parameter can change than the coefficient is decreased. When the workpiece hardness is 50 HRC, the changing coefficient is less than 1. The cutting temperature is small if the chip deformation is small, which is one of the reasons the cutting why the cutting temperature falls when the workpiece hardness is high.

In hard turning, the temperatures generated by the cutting speeds of today's advanced tooling can actually prevent low pressure flood coolant from entering the cutting zone. The majority of the cooling and lubricating aspects of a flood coolant stream are lost as the coolant is vaporized prior to entering the cutting zone [**Frederick Mason 2001**]. It is the great problem for machining, HPC play well role to minimize this type of problem. Frederick Mason found better solution from it and he states that HPC systems generate high velocity coolant. This high speed coolant easily penetrates the vapor barrier to effectively lubricate and cool the tool. In fact, when machinists apply high pressure coolant to a long standing process, which has always produced blue chips, they are often amazed that the same or even higher speeds and feeds produce shiny, silver chips that are cool to the touch.

Cutting fluids have the dual tasks of cooling the cutting surface and flashing chip. In some operations such as turning, for example, cutting fluid is important to remove the chips from workpiece. [**Klocke 1997 and Derflinger 1999**]. Cutting fluid also help to control cutting face temperature and this can prolong tool life, improve cut quality, and positively influence part finish. It has the benefit of a power full stream that can reach onto the cutting area, provides strong chip removal and in some cases enough pressure is too prohibited. Possibility of controlling high cutting temperature in high production machining by some alternative method has been reported. High-pressure coolant injection technique provided reduction in cutting forces and temperature **[Robert 2004]**. Mazurkiewicz et al. **[1998]** reported that a coolant applied at the cutting zone through a high-pressure jet nozzle could reduce the contact length and coefficient of friction at chip-tool interface and thus could reduce cutting forces and increase tool life to some extent. This is achieved by directing coolant under high pressure at the chip-tool interface.

Tonshoff et al. **[2000]** observed that the improved hard tool materials like PCBN, uncoated carbide, ceramics, and more rigid machine tools provide high flexibility and ability to manufacture of complex workpiece geometry in a single step which also represents the main advantage of hard turning. Furthermore, the hard turning enables the avoidance of coolants and it is a green machining technology.

A large number of theoretical and experimental studies on surface roughness of hard turned products have been reported . These studies show that cutting conditions such as cutting speed, feed rate, depth of cut, tool geometry, and the material properties of both the tool and workpiece significantly influence surface finish of the machined parts. In some studies, roughness has been measured directly with a stylus to obtain the surface profile. Thus, a stylus can be used for in-process measurement **[Rakit et al. 1973]**. However, use of a stylus results in destruction of the sensor head due to high surface speeds of the workpiece.

Tracing has also been accomplished by using a vibratory stylus [**Sata et al. 1985**]. Real-time measurement of roughness implies assessing the conditions of the workpiece just behind the cutting edge of the tool. Surface inspection has been conducted typically as a post process operation, which is both time consuming and uneconomical since a number of non-conforming parts can be produced prior to inspection. However, since the workpiece rotates at relatively high speeds in turning operations, in-process measurements should be taken with non-contact transducers. The use of an optical instrument has also been reported for in-process measurement [**Shirirashi and Sato 1990**]. Optical reflection has been restricted to measurements of relatively smooth surfaces generated by lapping, grinding and other fine machining. This technique is based on the principle that reflected light from the relatively smooth surface exhibits an exponential distribution with regard to the detecting angle. A definite relation has been found between the average inclination of roughness profile and the surface roughness, providing that a limited range of the finishing operation remains consistent. [**Sathyanarayanan and Radhakrishnan 1988**].

Zhao and Webster [**1989**] used a contact type inductance sensor to develop a roughness module to be used in measuring roughness in real time during turning operation. Although inductance sensors have been studied on a machined workpiece installed in a lathe, the measurements were not performed during the machining process because the environmental conditions in the machining centre create errors in directly measuring surface roughness. Thus, inductance sensors have been found to be ineffective in situations with high cutting speeds and heavy cutting loads in conventional machining operations. Rather than using direct measurement. several researchers have derived surface roughness indirectly using the relative vibration signals between tool and workpiece generated during the turning process.

Mital et al. **[1988]** observed that The built-up edge and tool wear have been found to affect roughness, as would the type of tool used. These process factors (including machine tool flexibility and workpiece properties) have been shown to cause variations in cutting forces. which eventually generate relative vibrations between the tool and the workpiece. [**Stephenson et al. 1994**], In hard turning, cutting forces and heat generation are higher in hard turning since cutting speeds are relatively low, a greater fraction of the heat generated during chip formation will be conducted into the part. Coolants are often not used in hard turning in order to reduce costs and to prevent tool breakage from thermal shock. Finishing cutting processes [**Reach and Moisan, 2002**], such as grinding or hard turning, have a great influence on the surface integrity, because of the thermomechanical material removal mechanisms. The hard turning process is interesting with regard to its capacities to produce a low surface roughness (Ra< 0.2 μm) during a long cutting time and also to induce compressive residual stresses when machining at low feed rate and low cutting speed. Feed rate is the major parameter that influences the surface roughness, whereas cutting speed is the major parameter that influences the residual stress level.

Field and Kahles, [**1971**] has been defined surface integrity as the relationship between the physical properties and the functional behaviour of a surface. The surface integrity is built up by the geometrical values of the surface such as surface roughness (for example, Ra and Rt), and the physical properties such as residual stresses, hardness and structure of the surface layers. Residual stress strongly affects the fatigue life of a component. **[Brinksmeier et al. 1982]** give a good overview of the subject of residual stresses. In their article, a comprehensive description is given of different machining operations and how they create different residual stress. The difference in stresses created by different operations also affects the performance of a machined component. **[Mittal and Liu, 1998]** present a more focused study on the effects of hard turning on residual stress. Their work is divided into two parts. In the first part, they show how different machining parameters in hard turning affect residual stress. In the second part, they describe a method to achieve optimal pre-stress in a component to maximize fatigue life in a rolling contact. Their work is groundbreaking in the sense that it suggests machining parameters should be optimised towards enhancing fatigue life of the machined component. **[Matsumoto et al. 1999]**, who conclude that hard turning produces compressive residual stresses that contribute to a long fatigue life. They also determine that edge geometry is the dominant factor deciding the residual stress profile. Similarly, **[Abra ~o and Aspin wall, 1996]** report that hard turned components improve fatigue life compared to ground components. Furthermore **[Fujimoto and Ohhata, 1992]** reports fatigue life improvements of 3-7 times. A possibility to enhance product life would add to the list of previously discussed advantages of hard turning. With the information available concerning the surface integrity, there is indication that hard turning of bainite steel is a possible process. An interesting next step would be to perform a fatigue test with hard turned components. **[Mittal and Liu, 1998]** have already shown that an extremely good surface finish can be obtained with hard turning.

The robustness of the process also must be documented. Showed how the surface of a 52, 100 components at first is compressive, but soon turns to tensile when tool wear appears.

In a study related to hard turning of bearing races, **[Liu and Mittal, 2001]** found that the integrity of the hard turned surface is better than that generated by abrasive super finishing processes. The microprofile of the turned surface has a lower root mean square surface roughness for equivalent average surface roughness. The parameter Rq is more sensitive to peaks and valleys than Ra. However, Ra is seldom used, as it is relevant when looking at a surface profile as a statistical function **[Mummery, 1992]**. The study does not mention the effect of tool wear on the machined parts. Another investigation completed by **[Matsumoto and Liu, 1984]** adds to the findings that hard turning has the capability of producing surfaces mostly superior to, or at least as good as, ground surfaces. However, other authors noted that while finish comparable to grinding can be realized, it is not always possible to obtain the high degree of geometric accuracy required due to thermal effects and stiffness of the machine tool system.

Thiele and Melkote, [1999] published the results of an investigation concerning the effect of cutting edge geometry and workpiece hardness on surface generation in finish hard turning. They found that increasing the edge hone radius tends to increase the average surface roughness. They attributed this to the increase in the plowing component compared to the shearing component of deformation. The effect of edge hone on the surface roughness decreased with increase in workpiece hardness. However, Thiele and Melkote did no refer to the effect of edge hone when tool wear starts to occur. [**Kishawy and Elbestawi, 1999**] published in 1999 their conclusions regarding the effects of process parameters on material side flow during hard turning. They noted that even a small feed should improve the surface finish, it could actually lead to more material side flow on the machined surface and hence, to a deterioration of the surface quality. In addition increasing the tool nose radius led to ploughing of a larger part of the chip, hence, a severe material side flow exists on the machined surface. Their experiments were carried out on bars of carbon nitride case hardened steel AISI 4615 (60HRC) using BZN 8100 PCBN cutting inserts.

Chen, [**2000**] observed that the cutting forces and surface finish when machining medium hard steel (45–55HRC) using CBN tools. Chen noted that a better roughness can be achieved increasing the cutting speed and using the tool at a certain degree of wear while other authors consider that Ra is relatively insensitive to cutting velocity and depth of cut. [**Chou and Song, 2001**] studied the effects of tool nose radius size on surface finish, tool wear, cutting forces, and white layer depth, for different cutting conditions. AISI 52100 steel at 61HRC was turned using ceramic tools (70% $Al2O3$ and 30% TiC). They came to the conclusion that large tool nose radii only give surface finish. but offer no additional advantage, comparable tool wear, similar cutting forces and increased specific cutting energy.

Ko and Kim, [**2001**] instigated the surface integrity and machinability in intermittent hard turning considering a ball bush made of AISI 52100 as workpiece. The conclusions were that the low content CBN tool is superior to a high content CBN tool in terms of tool wear and surface integrity for intermittent hard turning. However, they concentrated their attention on the so-called white layer and the characteristics of the residual stresses. Not many authors specifically concentrated their research on the effect of tool wear to surface roughness evolution in hard turning. Their findings and area of investigation are still reduced to a restricted number of machining conditions. [**Penalva et al. 2002**] approached such a subject striving to relate surface finish on cutting edge geometry that deteriorates with wear. In their study, they have shown that replication of the tool tip profile on the machined surface is acceptable.

Turning of hardened steels has been an attractive alternative to costly, yet environmentally harmful, grinding processes. Potential process benefits of hard turning over grinding have been reported including short cycle time, process flexibility, part longevity, and less environmental impact [**Koning, 1993**]. Scientific and engineering issues of hard- turning, been frequently investigated, range from cutting mechanics [**Devies et al. 1996**], tool wear surface integrity, to part accuracy [**Bougher et al. 1998**]. It has also been indicated that hard turning is sensitive to process parameters, narrow applicable machining parameters. Cutting tool geometry is one of critical process parameters in hard turning, especially edge preparation (chamfer or hone) because of low feed and light cut employed in hard turning. It has been shown that large hone radii result in deeper subsurface structural changes due to high plowing forces [**Thiele and Melkote, 1999**]. Surprisingly, tool nose radius, one of tool geometry parameters, has not been systematically investigated, probably due to its intuitive effects on part surface finish.

2.3 Summary of Literature Review

Several researchers describes the various characteristics in terms of component of force, temperature, surface roughness, tool life, tool wear, and effects of individual parameters on tool life, material removal and economics of operation. The temperature as well as force and surface roughness is significantly reduced by administering coolant under high pressures directly to the cutting interface. This could therefore, minimize thermally related wear mechanisms.

The ultimate aim of hard turning is to remove material from work piece in a single cut rather than a lengthy grinding operation in order to reduce processing time, production cost, surface roughness, and setup time, and to remain competitive. In recent years, interrupted hard turning, which is the process of turning hardened parts with areas of interrupted surfaces, has also been encouraged. The process of hard turning offers many potential benefits compared to the conventional grinding operation. Additionally, reduced force, temperature, tool wear, tool life, quality of surface turned, and amount of material removed are also predicted.

Chapter-3

Objectives

High pressure jet assisted hard turning has been widely used, Because of high cutting temperature generated during machining not only reduces tool life but also impairs the product quality. The temperature becomes more intensive when cutting velocity and feed are increased for higher MRR and the work materials are relatively difficult to machine for their high strength, harden ability and lesser thermal conductivity. These materials cannot be cut effectively without cooling, even though dry cutting is becoming increasingly widespread. Cutting fluids are widely used to reduce the curling temperature as well as reduce force and snrface integrity. In this regard, it has already been observed through previous research that proper application of HPC may play vital role in providing not only environment friendliness but also some techno-economical benefits. The objectives of this project is to investigate the effects of temperature, forces (main cutting force and feed force), and surface finish assisted hard turning of heat treated hardened steel under dry and high pressure coolant conditions, and to sufficient reduction in temperature, forces and surface roughness in respect to:

- average chip-tool interface temperature
- cutting forces
- surface roughness

Chapter-4

Experimental Investigations

4.1 Introduction

Medium carbon steels was heat treated to produce desired hardness as well as great variety of microstructures and properties. The whole process was done in an inert environment by using continuous flow of argon gas. Generally, heat treatment uses phase transformation during heating and cooling to change a microstructure in a solid state. In heat treatment of specimen, the processing was most often entirely thermal and modifies only structure. Thermo-mechanical treatments, which modify component shape and structure, and thermo-chemical treatments which modify surface chemistry and structure, are also important processing approaches which fall into the domain of heat treatment.

4.2 Material Hardening

Material: The material used in the project thesis was medium carbon steel with approximately 0.39% carbon content. It was a long hollow cylinder which had been sliced in small pieces with the help of band saw to fit into the electric furnace. The length of the pieces was 25.4 cm with external and internal diameters of 9.5 cm and 6 cm respectively. The weight of each piece without spikes and hook was about twelve kilograms.

Specimen Preparation: To make provision for pulling the red hot metal pieces from furnace, hook had to be facilitated. A 12 cm long solid shaft of medium carbon steel with external diameter same as the internal diameter of hollow pieces had been inserted into the hollow piece. The joint was secured by welding. Using drilling and boring tools a through hole of diameter 2.54 cm was made in the solid insert. This was done so that hot water vapor can easily come out when it would be quenched in brine. Another through hole was created in the solid shaft in radial direction. A triangular hook of mild steel was attached to the work piece so that the work-piece can be pulled out from the furnace with the help of a tong. A test sample made from the same material was also prepared. It was a rectangular block with dimension 25mm×15mm×10mm. This was made for the hardness test.

Heating: Electric furnace of high heating element 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. Due to scale forming, carbon quickly deposited from the work piece. 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 passed through the furnace chamber to drive out air as well as oxygen. It was done by high flow rate of argon gas of about 7 liters per minute at a pressure of 130 bars. After two minutes, the flow rate is slowed down and held it at 5.5 liters per minute. At this point turn on the furnace with 5 amperes current rating. It took three hours to raise the temperature to 900°C and held the work material at that temperature for one hour.

Quench tank: A quench tank having capacity 140 liters was set up on the floor of heat treatment lab. 10 kilograms ice and 10 kilograms of sodium chloride is mixed with 120 liters of water to prepare a 10% brine solution. This mixture reduces the absorption of atmospheric gases that, in turn reduces the amount of bubbles. As a result, brine wets the metal surface and cools it more rapidly than water. In addition to rapid and uniform cooling, the brine removes a large percentage of any scale that may be present.

Quenching: The work piece was pulled quickly but carefully out from the furnace using a tong and was immersed it vertically into the brine solution. The solution is stirred vigorously for about 10 minutes and was continued the quench until the specimen is cool enough to handle using bare hands. Heat transfer is not so fast through the steam layer. On the other hand the very act of transforming the water into steam means the water has to take in enormous amounts of energy to transform the water from liquid state to gaseous state (steam). Moving the part and re-circulating the water aids in getting the best quench. The test sample was also quenched in the same solution following same manner.

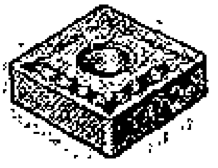
Tempering: Quenched carbon steels always required to temper because of steels are often more harder than needed and too brittle for most practical uses. Also, several internal stresses like residual stresses are set up during the rapid cooling from the hardening temperature. As a result, to relieve the internal stresses and reduce brittleness, tempered was done. The procedure of tempered by the re-heating of specimen below its re-crystallization temperature (160°C). Holding the specimen at that temperature for a one hour then cooled it usually in still air. The resultant strength, hardness, and ductility depend on the temperature to which the specimen is heated during the tempering process. The purpose of tempering was also to produce definite physical properties within the specimen.

Results: The sample was cleaned and ground a flat surface of 0.015 inches deep along the face of the sample. Hardness of the sample was measured on the C scale of Rock-well hardness tester. The hardness of the sample before heat treatment was 90-105 HRB and after heat treatment it became around 54-56 HRC.

4.3 Experimental Conditions

The experiment trials were carried out by turning a hardened steel of hollow cylindrical shape in a powerful and rigid lathe 10 hp at different cutting velocities (Vc) and feed rates (S_0) under dry and high pressure coolant condition. The high pressure coolant was supplied at an average flow rate of 6.0 liter/ min and pressure of 80 bars and directed via a nozzle on the tool holder to the region where the chip breaks contact with the tool. Uncoated carbide SNMG insert was used for the machining trials. The following cutting conditions and environments were employed in this investigation:

Table-1 Experimental conditions

Machine tool	: Lathe Machine(China), 7.5 kW
Work materials	: Hardened steel
Hardness (HRC)	: 56
Size	: External dia.=87, internal dia.=61 mm and length=230 mm
Cutting insert	: Carbide, SNMG 120408 (P30 grade ISO specification), WIDIA 
Tool holder	: PSBNR 2525 M12 (ISO specification), WIDIA
Working tool geometry	: -6°,-6°,6°,15°,75°,0.8 mm
Process parameters	
Cutting velocity, V_c	: 70, 100, 130, 156 m/min
Feed, S_o	: 0.12, 0.16, 0.20, 0.24 mm/rev
Depth of cut, t	: 1.5 mm
High-pressure Coolant	: Pressure: 80 bar, Coolant: 6 l/min through external nozzle having 0.5 mm tip diameter.
Environment	: Dry and High-pressure coolant

The average chip-tool interface cutting temperature was measured under dry and high pressure conditions undertaken by simple but reliable tool-work thermocouple technique with proper calibration. The average cutting forces was measured under dry and high pressure coolant conditions with the help of lathe tool, dynamometer charge amplifier and computer. The roughness of the machined surface after each cut was measured by a Talysurf.

4.4 Experimental Investigations

4.4.1 Tool-Work Thermocouple Calibration

For the improvement of cutting performance, the knowledge of temperature at the chip-tool interface with good accuracy is essential. Several experimental and analytical techniques have been developed for the measurement of temperatures generated in cutting zone. Thermocouples have always become a popular tool to be used in temperature measurements during metal cutting. This method is very useful to indicate the effects of the cutting speed, feed rate and cutting parameters on the temperature. Thermocouples are conductive, rugged and inexpensive and can operate over a wide temperature range.

The set-up was prepared to be mounted on a precession lathe. The tool holder used was screw type where the un-coated carbide SNMG inserts was mounted. The workpiece was hardened steel. Tool and workpiece were insulated from the machine tool. A multi-meter was used to record emf as milivolt. For thermocouple, one end of multi-meter was connected to the workpiece and other end was tool. During machining, the emf as milivolt was recorded from multi-meter under dry and high pressure coolant conditions. So, to know the chip tool interface temperature we need to calibrate the emf with temperature. For calibration, tool-work brazed together and the insulated thermocouple was inserted in sensitive hole in a graphite plate. A thermometer and multi-meter was placed in another two consecutive holes of graphite plate. Heating was done by the means of electric heater. Due to the heating, thermoelectric emf is generated between the tool and the workpiece. This emf was recorded by multi-meter at the same time temperature was record by the thermometer. Corresponding emf-temperature was recorded in the interval of heat apply. The cutting zone forms the hot junction while a cold part of the tool and the workpiece forms the cold junction. This technique is easy to apply but only measures the mean temperature over the entire contact area and high local temperatures which may occur for a short period of time cannot be observed. The photographic view of calibration by tool-workpiece thermocouple technique and variation of temperature with different emf (mV) has been shown in Fig. 4.1 and Fig. 4.2 respectively.

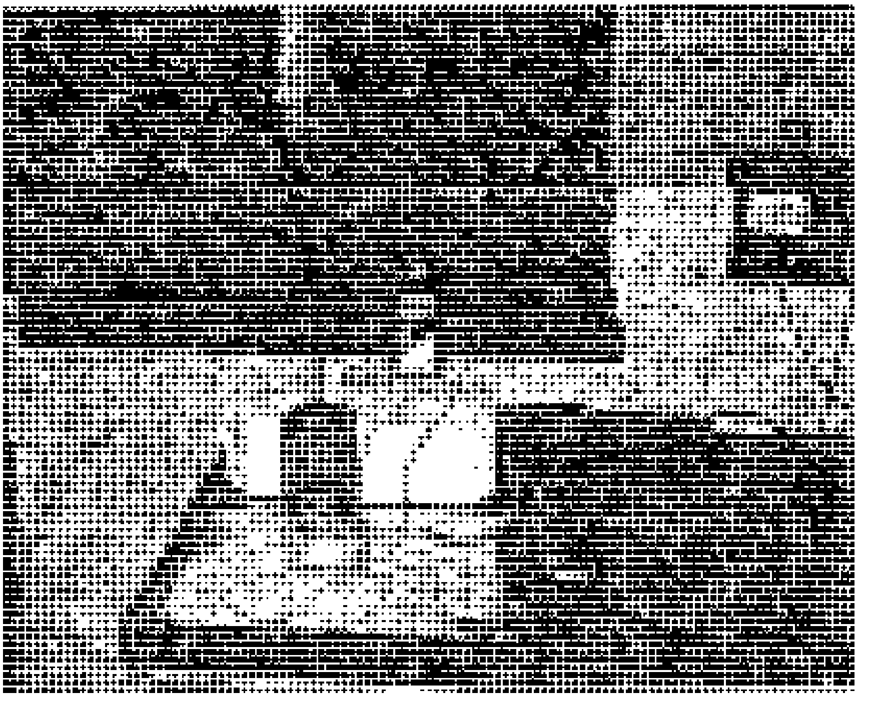


Fig. 4.1 Photographic view of calibration set-up by tool-work thermocouple technique.

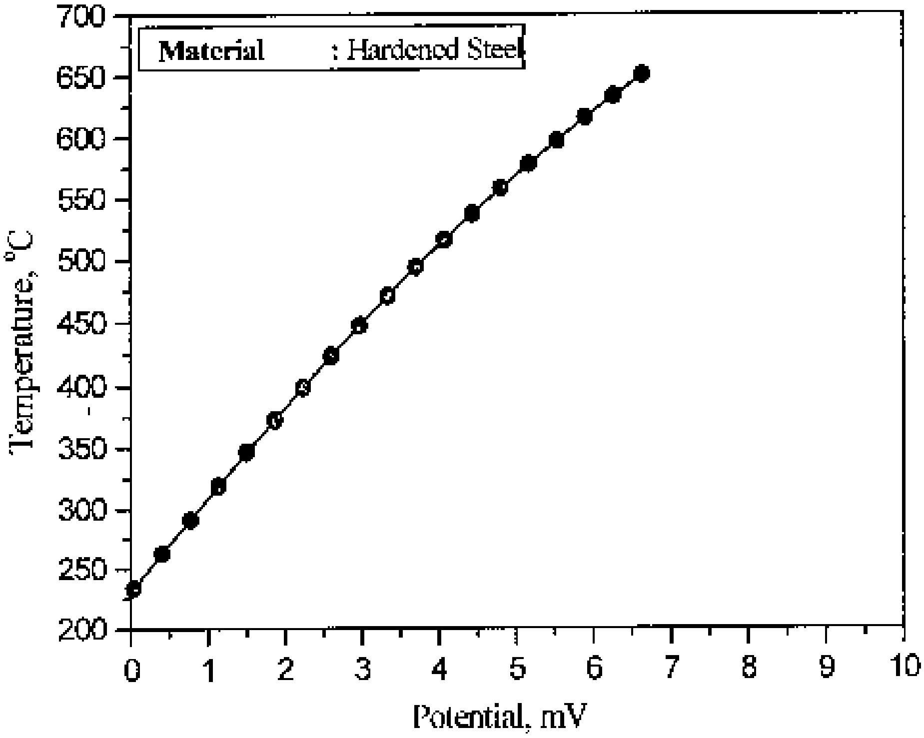


Fig. 4.2 Temperature calibration curve for hardened steel and carbide.

4.4.2 Cutting Temperature

During metal cutting, the metal is deformed plastically in shear zone and is removed from this region in the form of chips. The workpiece material ahead of the cutting edge is deformed plastically and removed in from the workpiece materials in the form of chips. The energy required to deform the workpiece material and the chips is mainly converted into heat. There are three zones in which the heat is generated:

- Primary deformation zone, where plastic deformation takes place.
- Secondary deformation zone, where the deformation takes place in the tool-chip interface and as the result of friction force.
- Tertiary deformation zone, where the heat is generated due to friction between tool clearance face and newly generated workpiece surface.

All such heat sources produce maximum temperature at the chip-tool interface, which substantially influence the chip formation mode, cutting forces and tool life. Therefore, attempts are made to reduce this detrimental cutting temperature. Conventional cutting fluid application may, to some extent, cool the tool and the job in bulk but cannot cool and lubricate expectedly effectively at the chip-tool interface where the temperature is high. This is mainly because the flowing chips make mainly plastic contact with the tool rake surface and may be followed by elastic contact just before leaving the contact with the tool. Plastic contact does not allow the cutting fluid to penetrate in the 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 V_c when the chip-tool contact becomes almost fully plastic.

In the present work, the average chip-tool interface temperature could be effectively measured under dry and high pressure coolant condition very reliably throughout the experimental domain. However, the distribution of temperature within the tool, work and chip cannot be determined effectively using experimental techniques. The evaluated role of HPC on average chip-tool interface temperature in turning the hardened steel by the un-coated carbide SNMG insert at different V_c and S_o under dry and HPC conditions has been shown in Fig.4.3.

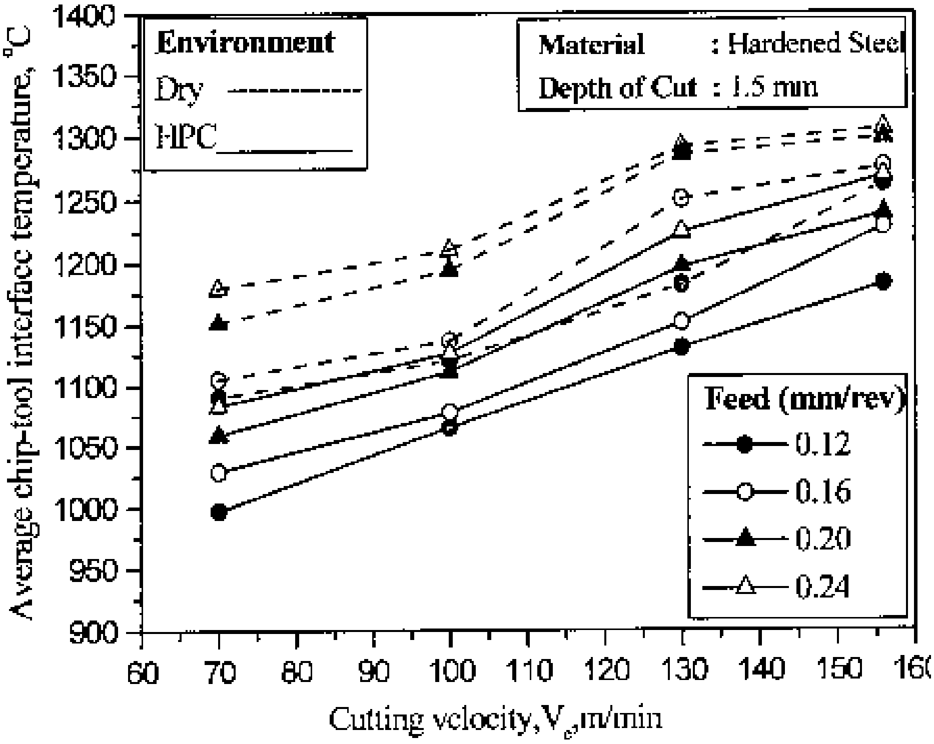


Fig. 4.3 Variation in average chip-tool interface temperature with cutting velocity, V_c and feed rate, S_0 in turning hardened steel under **dry** and **High-pressure coolant** condition

4.4.3 Cutting Forces

Main cutting force, P_Z generated during the machining trials were recorded with the aid of a dynamometer after each complete pass. The signals of the forces generated during machining were fed into a charge amplifier connected to a dynamometer. This amplifier converts the analogue signal to digital signal that can be read on a digital oscilloscope. Lower cutting forces were recorded with increasing coolant supply pressure when machining hardened steel with un-coated carbide inserts SNMG. Higher cutting forces were recorded in dry cutting with higher feed. This is because coolant supply at high-pressure is able to access the cutting interface, ensuring effective cooling, lubrication and reducing the cutting interface temperature. Feed force was obtained from calculating each main cutting force by the applying formula. Feed force was higher when machining under dry condition with higher feed rates. The variation of main cutting force, P_Z feed force, P_X with different cutting velocity, V_c and feed rates, S_o under dry and high-pressure coolant condition in turning hardened steel by uncoated SNMG insert has been shown in Fig. 4.4 and Fig. 4.5 respectively.

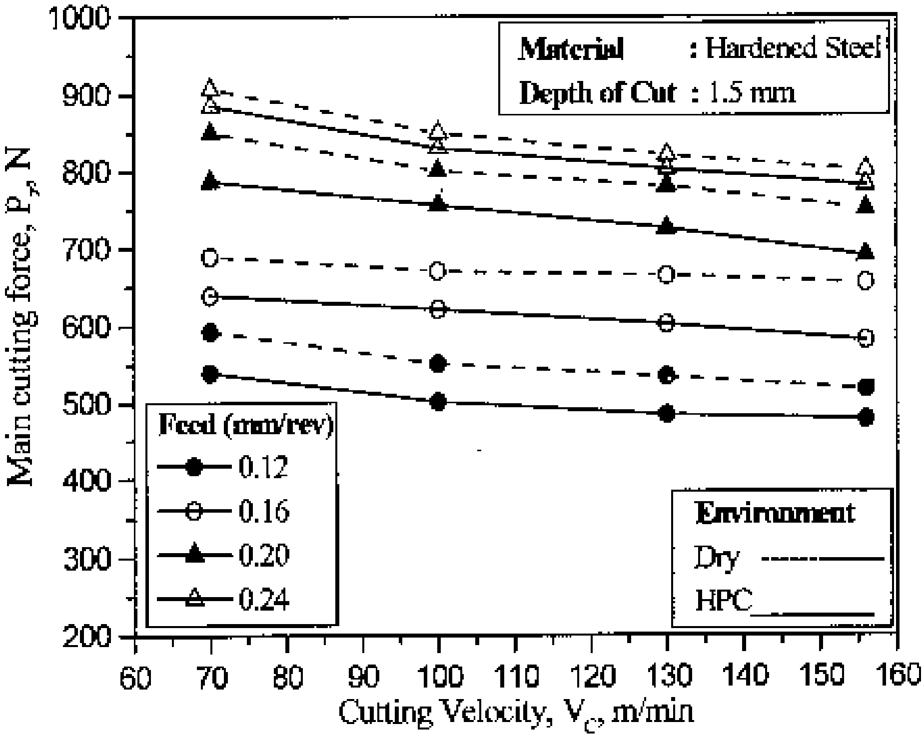


Fig. 4.4 Variation in main cutting force, P_z with cutting velocity, V_c and feed rate, S_o in turning hardened steel under **Dry** and **High-pressure coolant** condition

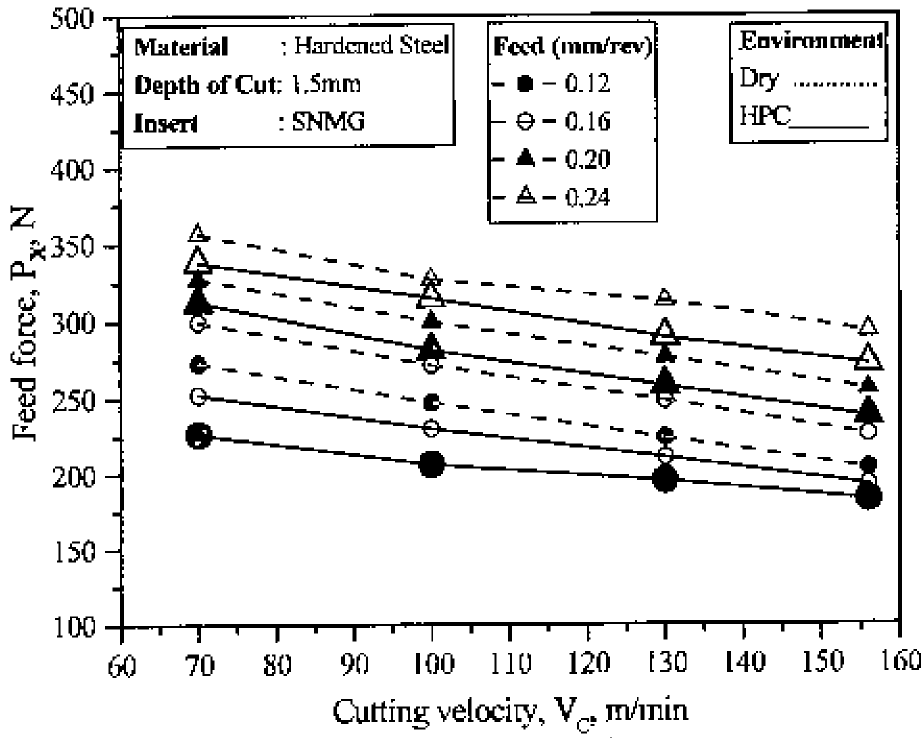


Fig. 4.5 Variation in feed force, P_X with cutting velocity, V_c and feed rates, S_o under **Dry** and **High-pressure coolant** condition.

4.4.4 Surface Roughness

Surface roughness values were recorded after each complete pass with a portable stylus type instrument known as Talysurf. Machining of hardened steel by the un-coated carbide SNMG insert, at different V_c and S_o combinations under dry and high pressure coolant conditions. Surface roughness is an important index of machinability, which is substantially influenced by the machining environment for given tool-work pair and cutting velocity-feed combinations. Surface roughness has been measured after a few seconds in after each cut of the machined surface. The average reading represents the surface roughness value of the machined surface. Variation of surface roughness with different cutting velocity, V_c and feed rates, S_o under dry and HPC environment in turning hardened steel by uncoated SNMG insert has been shown in Fig.4.6.

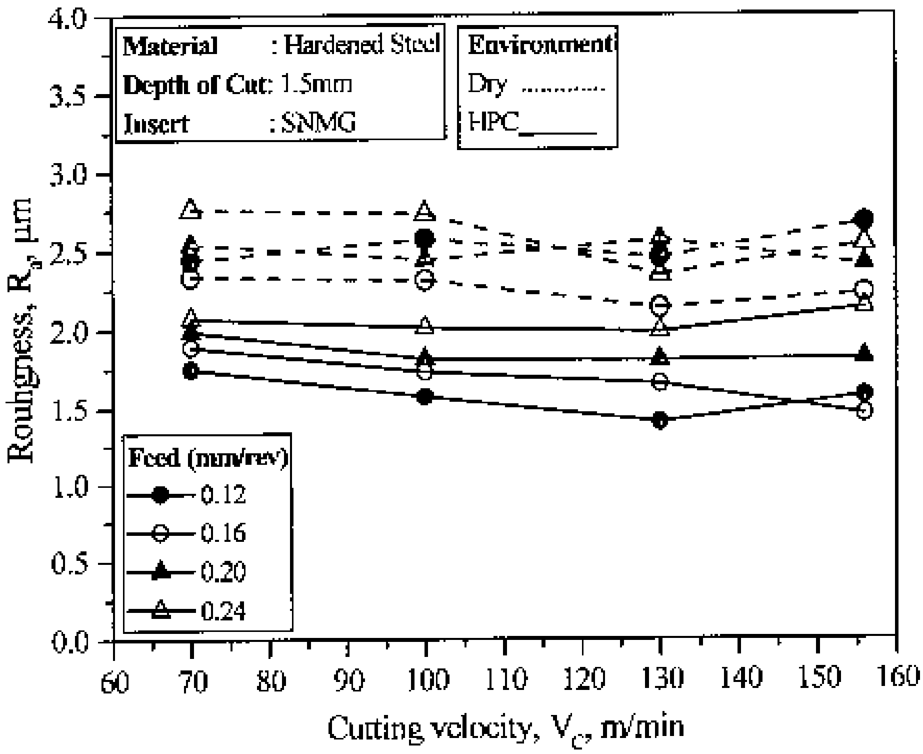


Fig. 4.6 Variation in surface roughness with cutting velocity, V_c and feed rates, S_o under **Dry** and **High-pressure coolant** condition.

Chapter-5

Results and Discussion

5.1 Cutting Temperature

During hard turning, the maximum heat generated at the chip-tool interface as a result temperature of chip-tool interface increased quickly. This temperature abruptly influences the cutting forces, surface finish and tool life. That is why; attempts are made to reduce this detrimental cutting temperature. In some cases dry cutting is preferable in machine to hard materials at low speed. But in case of high speed machining cutting fluid may apply. Conventional cutting fluid application may, to some extent, cool the tool and the workpiece in bulk but cannot cool and lubricate expectedly and effectively at the chip-tool interface where the temperature is maximum. This is mainly 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. Bulk contact does not allow the cutting fluid to penetrate in the 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 V_c when the chip-tool contact becomes almost fully plastic.

Therefore, application of HPC at chip-tool interface is expected to improve machinability characteristics that play vital role on productivity, product quality and overall economy in addition to environment-friendliness in machining particularly when the cutting temperature is very high. The average chip-tool interface temperature has been determined by using the tool work thermocouple technique and plotted against different cutting velocity, V_c under dry and HPC environment in turning hardened steel by uncoated SNMG insert.

With the increase in V_c and S_o, the average temperature increased as usual, even under HPC condition, due to increase in energy input. It can clearly be observed from Fig.4.3 that HPC is able to reduce average cutting temperature up to 11% compared to dry machining. At $V_c \leq 100$ m/min and all feed range, reduction in cutting temperature varies within 6~11%. Again, at $V_c > 100$ m/min and all feed range reduction in average temperature varies within 3~6%. It is evident from Fig.4.4 that as the cutting velocity and feed rate increases, the percentage reduction in average cutting temperature decreases. It may be for the reason that, the bulk contact of the chips with the tool with the increase in V_c and S_o did not allow significant entry of high-pressure coolant jet. Only possible reduction in the chip-tool contact length by the high-pressure coolant jet particularly that which comes along the auxiliary cutting edge could reduce the temperature to some extent particularly when the chip velocity was high due to higher V_c. So, at industrial speed-feed conditions, this amount of reduction in average cutting temperature is quite significant in pertaining tool life and surface finish.

5.2 Cutting Forces

The measurement of cutting force components is highly essential to evaluate the machinability characteristics of machine to hardened steel of hardness 52 HRC. During hard turning, the main cutting force, P_z acts in the direction of cutting velocity vector and the feed force, P_x in the direction of the tool travel. The main cutting forces, P_z were recorded by lathe tool dynamometer in both dry and HPC conditions where as feed force was recorded corresponded each P_z. From the Fig. 4.4 and Fig. 4.5 shows that in HPC machining. both the main cutting force and the feed force in HPC machining were decrease as compared to dry machining in corresponding cutting velocity and feed rates with depth of cut 1.5 mm in turning hardened steel by uncoated SNMG insert. Therefore the cutting forces in dry condition were more than that of HPC condition. Because of the coolant supply at high-pressure was able to access the cutting interface, ensuring effective cooling, lubrication and reducing the cutting interface temperature as well as cutting force. The reduction in cutting forces observed is also partly due to the chip segmentation.

Fig.4.4 is clearly showing that P_z has uniformly decreased with the increase in V_c more or less under all the feeds. for both the tool and environments undertaken as usual due to favourable change in the chip-tool interaction resulting in lesser friction and intensity or chances of built-up edge formation at the chip-tool interface. It is evident from Fig.4.4 that P_z decreased significantly due to high-pressure coolant jet more or less at all the V_c-S_o combinations. From Fig. 4.4 and Fig. 4.5, it was observed that at high feed rates main cutting force and feed force increases but when Vc increase significantly both the cutting forces decrease. Feed force, P_x increases more than that of main cutting force, P_z with high feed machining. It was also clearly been observed that under all feed rates and cutting velocity , HPC machining reduced 15-20% forces than dry machining. This improvement can be reasonably attributed to reduction in the cutting temperature particularly near the main cutting edge where seizure of chips and formation or tendency of formation of built-up edge is more predominant. In this respect, the high-pressure coolant jet impinged along the auxiliary cutting edge seems to be more effective in cooling the neighbourhood of the auxiliary cutting edge.

5.3 Surface Roughness

The quality of any machined product of given material is generally assessed by dimensional accuracy and surface integrity, which govern the performance and service life of that product. For the present study, only surface finish has been considered for assessment of quality of product under dry and HPC machining. Surface roughness is an important measuring criterion of machinability because performance and service life of the machined component are often affected by its surface finish, nature and extent of residual stresses and presence of surface or subsurface micro-cracks, if any, particularly when that component is to be used under dynamic loading or in conjugation with some other mating part. However, it is evident that HPC improves surface finish depending upon the work-tool materials and mainly through controlling the deterioration of the auxiliary cutting edge by abrasion, chipping and built-up edge formation.

From the Fig. 4.6 shows that the variations in surface roughness of machining of hardened steel at a particular set of cutting velocity, V_c feed rate, S_o under dry and HPC conditions by SNMG insert. Cutting velocity, V_c influence on surface roughness under dry and HPC machining. It was clear that the surface roughness quite decrease with increasing cutting velocity under dry machining. In case of HPC machining, surface roughness faster decrease with increases cutting velocity. This is mainly because of formation of built-up edge frequently and behaviour of materials to be machined in dry machining compared that of HPC.

It appears from Fig.4.6 that surface roughness grows quite fast under dry machining due to more intensive temperature and stresses at the tool-tips. HPC appeared to be effective in reducing surface roughness. However, it is evident that HPC improves surface finish depending upon the work-tool materials and mainly through controlling the deterioration of the auxiliary cutting edge by abrasion, chipping and built-up edge formation.It was also observed that the roughness of the machined surfaces were high at high feed rates and vice versa, under dry and HPC conditions. The factors influence in that phenomenon was the irregular deformation of the auxiliary cutting edge at the tool-tip due chipping, fracturing and wear.

Chapter-6

Conclusion

The overall findings from this investigation influenced the role of cutting temperature, cutting forces and surface roughness under dry and HPC environment in turning hardened steel by uncoated SNMG insert. The results obtained from this investigation show the present HPC is able to reduce average cutting temperature up to 11% compared to dry machining. At $V_c \leq 100$ m/min and all feed range, reduction in cutting temperature varies within 6~11%. Again, at $V_c > 100$ m/min and all feed range reduction in average temperature varies within 3~6% and even such apparently small reduction, unlike common belief, enabled significant improvement in the major machinability indices.

The application of high pressure coolant jet, the cutting forces reduced up to 15-20% compared to dry machining. Feed force, Px decreased more predominantly than main curting force, Pz. Favorable change in the chip-tool interaction and retention of cutting edge sharpness due to rednction of cutting zone temperature seemed to be the main reason behind reduction of cutting forces by high pressure coolant jet.

Surface finish also substantially improved mainly due to significant reduction of wear and damage at the tool tip by the application of high pressure coolant jet.

Finally, the results achieved by this investigation were very encouraging. By the application of high-pressure coolant jet, cutting temperature and cutting forces were reduced, surface quality and tool life improved, thereby increasing the metal removal rate, and improving the overall performance of the machining.

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