Mathematical Modeling of Cutting Force and Temperature Distribution in Turning Steel Under High-Pressure Coolant Condition

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Declaration

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

A. K. M. Bashirul Khoda

This work is dedicated
to my loving

Parents.

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V_c	Cutting velocity
S_0	Feed rate
t	Depth of cut
ζ	Chip reduction coefficient
σ_u	Ultimate tensile strength of the work material
ε	Average cutting strain
β	Shear angle
τ_s	Dynamic yield shear strength of tha work material
a_2	Chip Thickness
a_1	Uncut chip thickness
C_N	chip tool contact length
C_p	length of sticking contact region
C_E	length of the sliding region
μ	co-efficient of friction
τ_{s1}	maximum shear stress
τ_0	shear stress
σ_0	normal stress
σ_{N1}	maximum normal stress
A_r	Real Area of Contact
A_a	Apparent area of contact
k	Thermal conductivity
c_p	Specific heat
ρ	Mass density
V_B	Flank wear length
φ	φprinciple cutting edge angle
V_f	Chip velocity
P_z	Main cutting force

P_x	Tangential force
F_1	Total frictional force
Q	Total heat generation
Q_s	Heat generated in shear zone
Q_f	Heat generated at rake surface
Q_w	Heta generated at flank wear land
F_2	Frictional force in wear land
α_0	Clearance angla
γ_0	Rake angle
MRR	Material Removal Rate

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Abstract

The present work deals with development of mathematical model of temperature distribution in chip-tool-work piece interface and cutting force in turning of medium carbon steel using high-pressure coolant jet and subsequently verify it with experimental investigation.

To determine the temperature distribution and force in metal cutting is very laborious and time intense through experiment. By using FEM, the temperature distribution in chip-tool-work piece interface can be achieved very accurately. The mathematical model for cutting temperature has been developed and MSC Nastran/Patran simulation software was used to illustrate the temperature distribution. The results were then verified with the experimental data for dry machining. As the results satisfy with acceptable margin, the model then applied for high-pressure coolant condition to find out the temperature distribution in chip-tool-work piece interface. A force model has been developed to determine the cutting force for turning operation.

In high-pressure coolant condition the average cutting temperature reduced by 16% and the cutting force reduced up to 30% then dry condition The both model provides reasonably acceptable results in terms of deviation from actual result, with 12% deviation for temperature model and 10% deviation for force mode Thus both the model prove its validity. As the temperature at the chip-tool interface and the cutting forces are the two most important factors influencing the machining process, so high-pressure coolant condition is complimentary for machining process.

Chapter-1

Introduction

1.1 High Production Machining

Any manufacturing process for its fruitful implementation essentially needs to be technologically acceptable, technically feasible and economically viable. The fourth dimension that has been a great concern of the modern industries and society is environment-friendliness in and around the manufacturing shops.

The performance and service life of engineering component depends on their material, dimensional and form accuracy and surface quality. The preformed blanks are finished by machining and grinding to attain the desired accuracy and surface integrity.

The growing demand for higher productivity, product quality and overall economy in manufacturing by machining and grinding, particularly to meet the challenges thrown by liberalisation and global cost competitiveness, insists high material removal rate and high stability and long life of the cutting tools.

However, high production machining and grinding with high cutting velocity, feed and depth of cut is inherently associated with generation of large amount of heat and high cutting temperature. Such high cutting temperature not only reduces dimensional accuracy and tool life but also impairs the surface integrity of the product.

Longer cuts under high cutting temperature cause thermal expansion and distortion of the job particularly if it is slender and small in size, which leads to dimensional and form inaccuracy On the other hand, high cutting temperature accelerates the growth of tool wear and also enhances the chances of premature failure of the tool by plastic deformation and thermal fracturing. The surface quality of the products also deteriorates with the increase in cutting temperature due to built-up-edge formation, oxidation, rapid corrosion and induction of tensile residual stress and surface micro-cracks. These problems are more predominant in grinding where cutting temperature is, as such, very high due to much higher specific energy requirement and cutting velocity Such problem becomes more acute and serious if the work materials are very hard, strong and heat resistive and when the machined or ground part is subjected to dynamic or shock loading during their functional operations. Therefore, it is essential to reduce the cutting temperature as far as possible.

In industries, the machining temperature and its detrimental effects are generally reduced by:

- proper selection of process parameters and geometry of the cutting tools

- proper selection and application of cutting fluid
- using heat and wear resistant cutting tool materials like carbides, coated carbides and high performance ceramics (CBN and diamond are extremely heat and wear resistive but those are too expensive and are justified for very special work materials and requirements where other tools are not effective)

Cutting fluid not only cools the tool and job but also provides lubrication and cleans the cutting zone and protects the nascent finished surface from contamination by the harmful gases present in the atmosphere But the conventional types and methods of application of cutting fluid have been found to become less effective with the increase in cutting velocity and feed when the cutting fluid cannot properly enter the chip-tool interface to cool end lubricate due to bulk plastic contact of the chip with the tool rake surface. Besides that, often in high production 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 which application of high cooling type water base cutting fluids are generally avoided in machining steels by brittle type cutting tools like carbides and ceramics But what is of more serious concern is the pollution of the working environment caused by use of cutting fluid, particularly oil-based type.

The major socio-economic problems that arise due to conventional type and method of application of cutting fluids are.

- inconveniences due to wetting and dirtiness of the working zone
- possible damage of the machine tool by corrosion and mixing of the cutting fluid with the lubricants
- environmental pollution due to break down of the cutting fluid into harmful gases
- biological hazards to the operators from bacterial growth in the cutting fluids
- requirement of additional systems for local storage, pumping, filtration, recycling, re-cooling, large space and disposal of the cutting fluid, which causes soil contamination and water pollution

The modern industries are, therefore, looking for possible means of dry, clean, neat and pollution free machining and grinding.

Ample researches have been carried out and are still going on in this direction. Cryogenic cooling by agents like liquid nitrogen appears to be a promising technique for effective cooling without the problems associated with conventional cutting fluid applications. However, it is also essential to be assured that productivity and overall economy are not affected while deriving the environmental benefits of cryogenic cooling. Rather it is necessary to explore the possible technological benefits of such cryogenic cooling and optimise it for maximum overall socio-economic benefits.

1.2 Literature Review

Until now, ample research and investigations have been done in different parts of the world on machinability of different materials mainly in respect of chip morphology, cutting forces, cutting temperature, chip tool interaction, dimensional accuracy, surface integrity and wear and life of cutting tool with and without (dry machining) using cutting fluid. Environmental pollution arising out of conventional cutting fluid applications has been a serious concern of the modern machining industries. Research has also been initiated on control of such pollution by cryogenic cooling 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.

1.2.1 On causes, effects and control of cutting temperature

Machining is inherently characterized by generation of heat and high cutting temperature. At such elevated temperature the cutting tool if not enough hot hard may lose their form 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.

It was observed [**Jawahir and van Luttervelt 1993**] that, in machining ductile metals producing long chips, the chip-tool contact length has a direct influence on the cutting temperature and thermo-chemical wear of cutting tools. The cutting temperature becomes 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.

In addition to usual flank wear and crater wear the cutting tools often attain notching on the flanks and grooving on the rake surface at the outer ends of the engaged portions of the cutting edges On the major cutting edge, the grooving wear occurs at the extreme end of the depth of cut and is characterized by deeper abrasion of the tool edge. On the end cutting edge, the grooving wear is characterized by smaller multiple notches. Several mechanisms have been proposed **[Solaja 1958]** to explain grooving wear such as

i) development of a work-hardened/abrasive oxide layer on the cut surface
ii) formation of thermal cracks due to steep temperature gradient
iii) presence of side-spread material at the edges of a newly cut surface and
iv) fatigue of tool material due to cutting force fluctuations at the free surface caused by lateral motions of the edges of the chip.

Trent **[1983]** 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 then crater wear begins and grooves intensively.

Kosa et al [**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.

The heat generated during machining [**Trent 1984**] also raises the temperature of the cutting tool tips and the work-surface near the cutting zone. Due to such high temperature and pressure the cutting edge deforms plastically and wears rapidly, which lead to dimensional inaccuracy, increase in cutting forces and premature tool failure. On the other hand, the cutting temperature, if it is high and is not controlled, worsens the surface topography and impairs the surface integrity by oxidation and introducing residual stresses, micro-cracks and structural changes

Reed et al. [**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 high cutting temperature also causes mechanical and chemical damage of the finished surface.

Vleugels et al [**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. Maximum temperature is found to develop on the rake face of the tool, at a certain distance from the cutting edge, where cratering occurs. The amount of energy dissipated through the rake face of the tool also raises the temperature at the flanks of the tool

The high specific energy required in machining under high cutting velocity and unfavourable 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 and Singh et al. 1997**]. On the other hand, such high temperature, if not controlled, impairs the surface integrity of the machined component by severe plastic flow of work material, oxidation and by inducing large tensile residual stresses, micro cracks and subsurface cracks. This problem is further intensified while machining for faster material removal in bulk and finishing very hard, strong and difficult-to-machine materials, which are gradually adventing with vast and rapid developments in the modern areas, like aerospace technology and nuclear science.

Past research has been focused on the temperature and its distribution in the cutting zone because it is believed that it has a direct impact on tool life **[Chao and Trigger 1955]**. The primary function of cutting fluids is to reduce this cutting temperature and increase tool life [**Shaw et al. 1951]**. The cutting fluids are believed to reduce cutting temperature either by removing heat as a coolant or reducing the heat generation as a lubricant. In addition, the cutting fluid has a practical function as a chip-handling medium [**Beaubien 1964**]. Cutting fluids also, help in machining of ductile materials by reducing or preventing formation of a built-up edge (BUE), which degrades the surface finish **[Heginbotham and Gogia 1961]**.

Usually the high cutting temperature is controlled by profuse cooling [**Alaxender et al. 1998, Kurimoto and Barroe 1982 and Wrethin et al. 1992]**. However, 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. With the advent of some modern machining process and harder materials and for demand for precision machining, the control of machining temperature by more effective and efficient cooling has become extremely essential.

Generally, suitable cutting fluid is employed to reduce this problem through cooling and lubrication at the cutting zone. However, it has been experienced [**Cassin and Boothroyed 1965]** that lubrication is effective at low speeds when it is accomplished by diffusion through the workpiece and by forming solid boundary layers from the extreme pressure additives, but at high speeds no sufficient lubrication effect is evident. The ineffectiveness of lubrication of the cutting fluid at high speed machining is attributed **[Shaw et al. 1951]** to the inability of the cutting fluid to reach the actual cutting zone and particularly at the chip-tool interface due to bulk or plastic contact at high cutting speed

The cooling and lubricating effects by cutting fluid [**Merchant 1958 and Kitagawa et al. 1997**] influence each other and diminish with increase in cutting velocity. Since the cutting fluid does not enter the chip-tool interface during high speed machining, the cutting fluid action is limited to bulk heat removal only. Mazurkiewicz **[1989]** 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.

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**].

The effect of the heat generated at the primary shear zone is less significant for its lesser intensity and distance from the rake surface. However, the heat generated at the chip-tool interface is of much greater significance, particularly under high cutting speed conditions where the heat source is a thin flow-zone seized to the tool [**Trent 1984**]. The coolant cannot act directly on this thin zone but only externally cools the chip, workpiece and the tool, which are accessible to the coolant. Removal of heat by conduction through the chip and the workpiece is likely to have relatively little effect on the temperature at the chip-tool and work-tool interface.

A cutting fluid may impart two more actions, namely the mechanical strength reducing action and the electro-chemical action. The mechanical strength reducing action (known as the Rehbinder effect) seemed to be negligible when steel jobs are machined at moderate cutting speeds with carbide tools [**Kurimoto and Barroe 1982**] The influence of the electric current flowing through the cutting zone on the rate of tool wear is also well known [**Ellis and Barrow 1969**]. However, most commercial cutting fluids are non electro-conductive, and as such the situation with respect to current flow will not vary significantly from the dry cutting case. The electrochemical action is treated as a corrosion phenomenon in respect of tool wear.

The machining temperature could be reduced to some extent by improving the machinability characteristics of the work material metallurgically, optimizing the tool geometry and by proper selection of the process parameters [**Muraka 1979, Dieter 1981 and Jawahir 1988**]. Some recent techniques have enabled partial control of the machining temperature by using heat resistance tools like coated carbides, CBN etc. The thermal deterioration of the cutting tools can be reduced [**Narutaki and Yamane 1979**] by using CBN tools. If properly manufactured. selected and used, CBN tool provides much less cutting forces, temperature and hence less tensile residual stresses [**Davies et al. 1996**]. However, CBN tools are very expensive.

A tribological experiment was attempted **[Farook et al. 1998]** to modify the contact surface of turning inserts by deposition of a soft bearing material by EDM. It was observed that although the modified inserts offer reduced cutting force, their beneficial effect on surface finish is marginal. At higher cutting velocities the brought on layers are fast depleted with cutting time and makes no contribution to wear resistance of the tool, especially at the flanks. It was reported **[Alaxender et al. 1998]** that coolant injection offers better cutting performance in terms of surface finish, tool force and tool wear when compared to flood cooling.

A recent development [**Chandrasekaran et al. 1998**] in this context is the use of CO_2 snow as the coolant in machining. This is feasible if CO_2 in liquid form under pressure (60 bars) is fed to the cutting zone and diffused through a capillary jet. This results in a change of state and the formation of CO_2 snow (endothermic reaction resulting in a temperature of -79^{O}C). Earlier investigations **[Thoors and Chandrasekaran 1994]** observed that CO_2 snow could function as a good cutting fluid/coolant under certain circumstances, which are very much related to the tool-work combination and the actual mode of feeding the coolant to the cutting zone.

1.2.2 On adverse effects of conventional cutting fluid applications

Technological problems

Traditionally, the manufacture of a product had been attempted to be done as quickly 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 application of cutting fluid may not always reduce the cutting tool wear as is commonly believed. Rather some conditions like machining steels by carbide tools, the use of coolant may increase tool wear.

It has been experienced [**Shaw et al. 1951**] that there was more tool wear when cutting with coolant than cutting dry in case of machining AISI 1020 and AISI 4340 steels by M-2 high speed steel tool cutting.

Seah et al. [**1995**] also reported that at the first stage of machining (first 40 seconds or so), tool wear was faster in wet cutting than in dry cutting. Later on, the wear rate stabilized and was somewhat the same for both dry and wet cutting.

During mechining, the cutting tool generally undergoes [**Trent 1983**] both flank wear and crater wear. 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

Another experimental investigation was conducted [**Cozzens et al. 1995**] on single point boring. This was aimed 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 had 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.

Proper selection and application of cutting fluid generally improves tool life. At low cutting speed almost four times longer tool life was obtained [**Satoshi et al. 1997**] by such cutting fluid. However, surface finish did 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. 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 [**Sheng and Munoz 1993**].

Environmental problems

Manufacturing by machining constitutes major industrial activities in global perspective. Like other manufacturing activities, machining also leads to environmental pollution [**Ding and Hong 1998 and Hong et al. 1999**] mainly because of use of cutting fluids. These fluids often contain sulfur (S), phosphorus (P), chlorine (Cl) or other extreme-pressure additives to improve the lubricating performance. These chemicals present health hazards Furthermore, the cost of treating the waste liquid is high and the treatment itself is a source of air pollution. The major problems that arise due to use of cutting fluids are **[Aronson 1995]**:

- environmental pollution due to breakdown of the cutting fluids into harmful gases at high cutting temperature,
- biological hazards to the operators from the bacterial growth in the cutting fluids
- requirements of additional systems for pumping, local storage, filtration, temporary recycling, cooling and large space requirement
- disposal of the spent cutting fluids which also offer high risk of water pollution and soil contamination.

Since beginning of twentieth century people [**Peter et al.1996, Welter 1978, Kennedy 1989 and Thony et al. 1975**] were concerned with possible harmful effects of various cutting fluid application.

It has been estimated [**Bennett 1983**] that about one million workers are exposed to cutting fluids in the United States alone. Since cutting fluids are complex in composition, they may be more toxic than their constituents and may be irritant or allergenic. Also, both bacteria and fungi can effectively colonize the cutting fluids and serve as source of microbial toxins. Hence significant negative effects, in terms of environmental, health, and safety consequences, are associated with the use of cutting fluids. The effects of exposure to the fluids on health have been studied for over 50 years; beginning with the concern that cutting fluid (oil) is a potential etiologic factor for occupational skin cancer (Epidemiological studies indicate that long-term exposure to metalworking fluids can lead to increased incidence of several types of cancer) The international Agency for Research on Cancer has concluded that there is sufficient evidence that mineral oils used in the workplace are carcinogenic [**Peter et al.1996**]. Basically, workers are exposed to metal cutting fluids via three routes [**Bennett et al. 1985**]; skin exposure, aerial exposure and ingestion.

Skin exposure is the dominant route of exposure, and it is believed that about 80 percent of all occupational diseases are caused by skin contact with fluids [**Bennett et al.1985**]. Cutting fluids are important causes of occupational contact dermatitis, which may involve either irritant or allergic mechanisms. Water mixed fluids generally determine irritant contact dermatitis and allergic contact dermatitis when they are in touch with workers skin. Non-water-miscible fluids usually cause skin disorders such as foliculitis, oil acne, keratoses and carcinomas.

Iowa Waste Reduction Centre [**1996**] reported that besides potential skin and eye contact, inhalation is also a way to occupational exposure. Mists are aerosols comprised of liquid particles (less than 20 μm) During machining process, a considerable amount of heat is generated for which the cutting fluid may attain a temperature sufficiently higher than the saturation temperature. The vapour is produced at the solid-liquid interface as a result of boiling. Vapour may be generated also at the liquid-air interface when the fluid vapour pressure is less than, the saturation pressure, namely as evaporation phenomene. Vapour generated then may condense to form mist. The non-aqueous components of the cutting fluid, such as the biocide additives, appear as fine aerosol that can enter the workroom air. Additionally, the cutting fluids impact with both stationary and rotating elements within the machine tool system, which leads to mechanical energy being transmitted to the fluid Thus, the cutting fluid has higher surface energy and becomes less stable and disintegratas into drops (atomization). The spray from the fluid application also may generate mist. A total fluid loss of 5 to 20 percent may occur due to evaporation, atomization, splashing and dragout processes. Whether formed by atomization or evaporation/condensation, small droplats may be suspended in the air for several hours even several days in the workers breathing zones. These drifting droplets tend evaporate further. Inhaled particles (with aerodynamic diameters less than 10 µm) deposit in the various regions of the respiratory system by the complex action of the different deposition mechanisms The particulates below 2.5 µm aerodynamic diameter deposit primarily in the alveolar regions, which is the most sensitive region of lung. The particulates in size ranging from 2 5 µm to 10 µm deposit primarily in the air-ways. The potential health effects of exposure to cutting fluid mists have been the subjects of epidemiological studies in the automotive industry. The mist droplets can cause throat, pancreas, rectum, and prostate cancers, as well as breathing problems and respiratory illnesses One acute effect observed is mild and reversible narrowing of airways during exposure to cutting fluid mist [**Kennedy 1989**].

Several other epidemiological studies have also suggested that exposure to fluid mist may be associated with increased risk of airway irritation, chronic bronchitis, asthma and even laryngeal cancer [**Bennett et al. 1985 and Eisen et al. 1994**]. The Occupational Safety and Health Administrations (OSHA) standard for airborne particulate (largely due to fluid mist) is 5 mg/m^3, and the United Auto Workers (UAW) has proposed a reduction in the standard to 0.5 mg/m^3. The oil mist level in a plant ranged from 4.2 to 15.6 mg/m^3 but fell to between 0.47 to 1.68 mg/m^3 when a different cutting fluid was substituted in the system [**Welter 1978**].

Anti misting compounds, such as a polymethaacrylate polymer, polyisobutylene and poly-n-butane in concentrations of 0.2% as well as poly (1, 2-butene oxide) have been suggested for addition into cutting fluids [**Bennett et al. 1985**]. However, consideration must be given to the effects of these chemicals upon humans The most effective way to control mist exposure is to use mist collector to prevent mist from entering plant air [**Leith et al. 1996**]. Many collectors use several stages of filters in series for the purpose. Other collectors use centrifugal cells or electrostatic precipitators as intermediate stages. Any collector using a 95% Dioctyl Phthalate (DOP) or High-Efficiency

Particulate Air (HEPA) filter as a final collection stage has been tested as high efficiency when new. However, its efficiency will decrease with time. Moreover, the oil droplets may undergo partial or complete evaporation as they travel to collector **[Raynor et al. 1996]**. The generated organic vapours may return to the room and affect work health, and may recondense on the cool surface causing safety and maintenance problems.

Pollution free manufacturing is increasingly gaining interest due to recent development of pollution-prevention legislation, European initiatives on product take-back or recycling, which affect many export industries in the US, and a growing consumer, demand for green products and production processes. 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 cryogenic machining process as one of the viable alternative instead of using conventional cutting fluids.

Economical aspects

Cutting fluids are widely used in machining operations to obtain accuracy of part dimensions, longer tool life and in some cases better surface finish. The research literature identifies two primary functions of cutting fluids in machining operations: lubrication to reduce process friction and cooling to remove process generated heat. A secondary function of the cutting fluid is to transport the chips from the cutting zone. Cutting fluid systems are used in industry to deliver fluid to the cutting process, recirculate fluid, separate chips, and collect fluid mists. The machining costs (labour and overhead) in the US alone is estimated to be $300 billion/year [**Komanduri and Desai 1983**]. The costs associated with the use of cutting fluids is estimated to be about 16% of the manufacturing costs [**Byrne and Scholta 1993**] which is many more times than the labour and overhead figures quoted above. A recent study in Germany found that 16% of machining cost in the high volume manufacturing industries is associated with the use of cutting fluids (procurement, maintenance and disposal) while only 4% of the cost was associated with cutting tools [**Aronson 1995**]. The use of cutting fluids also requires additional equipmant for plant housekeeping.

1.2.3 On methods and effects of high-pressure cooling in machining

Growing demand for high MRR in machining necessitated much increase in cutting velocity, which eventually required the efficiency of cooling to be increased in order to cope with the increase in the cutting temperature. On the other hand, legislation in many countries are restricting much use of coolants, because of environmental issues. There are limits on the amount of coolant mist, and some coolants and coolant-coated chips have been treated as toxic materials. Outside the plant, the rising cost of chip disposal and the potential secondary effects of coolant vented to the atmosphere are new concerns [**Aronson 1995**]. In some applications, the consumption of cutting fluids has been reduced drastically by using mist lubrication However, mist in the industrial environment can have a serious respiratory effect on the operator [**Kennedy 1989**]. Consequently, high standards are being set to minimize this effect. Use of cutting fluids will become more expensive as these standards are implemented leaving no elternative but to consider environmentally friendly manufacturing.

Recently 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 significantly reduce the temperature generated at the tool-workpiece and tool-chip interfaces when cutting at higher speed conditions. This is achieved by directing coolant under high pressure at the chip-tool interface. This process can also achieve high chip breakability and control through increased chip up curl and compressive stress **[Ezugwu 2004]**. Ezugwu [**2004**] stated that ability to deliver coolant at high pressure very close to the critical point on the secondary shear zone can improve machinability at higher speed conditions. The credibility of this technique of coolant delivery has been thoroughly investigated over the years. The high-speed coolant jet traverses the surface faster, thus significantly lowering the film boiling action of the coolant at the cutting area. This consequently minimizes heat transfer to the cutting tool. The high-pressure coolant jet creates a hydraulic wedge between the tool and the workpiece, penetrating the interface with a speed exceeding that required even for high speed machining and also alters the chip flow conditions [**Mazurkiewicz 1989**] The penetration of the high energy jet into the tool-chip interface reducas the temperature gradient and eliminates the seizure effect, offering an adequate lubrication at the tool-chip interface with a significant reduction in friction [**Ezugwu 2004]**.

The heat 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 **[2001**] found better solution from it and he states that HPC systems generates high velocity coolant streams moving at several hundred mph. 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 longstanding process, which has always produced dark 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.

Heat from the drill may also work harden or "heat treat" the workpiece in the vicinity of the hole. Friction from the drill heats the workpiece, and when coolant finally reaches the heated material, the coolant quenches it. On the subsequent peck, the drill encounters the hardened material, causing excessive tool wear or a broken tool and damaged part. The high pressure of the coolant breaks up chips and forces them up the flutes and out of the hole. Cycle times go down. because the pecking process is eliminated while spindle speeds and feed rates can be increased. With higher feed rates, chips tend to form better

The need for high pressure and high volume coolant in drilling became apparent when gun drills came into use over 100 years ago. The essence of the problem (then and now) with standard low pressure coolant systems is that so much heat is produced that the coolant boils away before it can reach the chip-tool interface where metal is actually cut. The super heated steam forms a barrier that low-pressure coolant cannot penetrate. Effective cooling does not occur and there is little real lubrication provided. Unfortunately, the vapor barrier that forms is not powerful enough to keep chips from falling back into the chip-tool interface and causing damage. Properly applied high pressure and high volume coolant prevents this vapor barrier from forming by causing a localized pressure increase. So much liquid is forced into the cutting zone that heat is removed and no vapor can form because of the pressurization. When machinists tried high-pressure coolant on standard drilling operations, they found that the benefits of increasing coolant pressure improved the performance of these operations as well. Properly applied high-pressure, high-volume coolant prevents the formation of a vapor barrier by causing a localized pressure increase. This force liquid into the cutting zone, removing heat, providing lubrication, and flushing chips away from the cut. Damage from heat and chips is eliminated, and tools can cut until they wear out. High-pressure coolant discourages chip welding, prevents the damaging chemical reactions that may occur at high temperatures, and allows drills to last longer [**Gregory 1999**]

High-pressure coolant also provides lubricity by blasting lubricating fluid between the chip and the cutting edge at hundreds of miles per hour. Combined with much lower temperature, this increased lubricity often causes surface finishes to be twice as good. With conventional coolant, the cutting edge comes up to a very high temperature as it enters the cut, and stays hot until it finishes the cut and is exposed to an extreme thermal shock as the coolant quenches the exposed tool.

Coolant is supposed to cool and lubricate but it can only perform these functions at the point of chip formation if the coolant actually reaches the cutting zone. When coolant is turned to steam or otherwise fails to reach the target, it does not perform its two essential functions. High-pressure is often the solution to getting the coolant 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 [**Frederick Mason 2001**]. Frederick Mason [**2001**] slates that high-pressure coolant reduces or eliminates the random tool failure from chip damage, resulting in much improved consistency of the machining process.

Cutting fluids have the dual tasks of cooling the cutting surface and flashing chip. In some operations such as drilling, for example, cutting fluid is important to remove the chips from inside the holes, thus preventing drill breakage [**Klocke 1997 and Derflinger 1999**]. They 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 to deburr [**Robert 2004**]. Possibility of controlling high cutting temperature in high production machining by some alternative method has been reported. High-pressure coolant injection technique not only provided reduction in cutting forces and temperature but also reduced the consumption of cutting fluid by 50% [**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.

1.2.4 Summary of the review

A review of the literature on machinability of different commercial steel highlights the immense potential of the control of machining temperature and its detrimental effects. It is realized that the machining temperature has a critical influence on chip reduction coefficient, cutting forces, tool wear and tool life. All these responses are very importent in deciding the overall performance of the tool. At the elevated temperature, the cutting tools mey undergo plastic deformation and attain rapid tool wear because by adhesive, abrasive, chemical and diffusion wear at the flanks and the crater. The dimensional accuracy and surface integrity of the workpiece also deteriorate due to high temperature. The conventional cutting fluids are not that effective in high speed machining particularly in continuous cutting of materials likes steels. Further, 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 problems.

Enormous efforts are, therefore, being made from the viewpoint of cost, technological and ecological issues to reduce or eliminate the use of cutting fluid or lubricant in metal cutting. In this context, high-pressure coolant, which uses a high-pressured spray of cooling medium like soluble and vegetable oils, appears to be a promising technique for effective cooling without the problems associated with conventional cutting fluid applicetions

1.3 Objectives of the Present Work

It is revealed from the aforesaid literature survey that 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 jet. The growing demands for high MRR, precision and effective machining of exotic materials is restrained mainly by the high cutting temperature. The objectives of the present investigation, keeping in view the overall improvement in productivity and quality in machining steel by the industrially used uncoated carbide insert at different speeds and feed rates combinations, are

(a) Experimental investigation of high-pressure coolant jet in respects of

  i. cutting force

  ii. average chip-tool interface temperature

(b) Develop a mathematical model for cutting force and cutting temperature distribution from the characterization of the physical processes.

(c) Validation of Developed mathematical model.

1.4 Organization of the Thesis

The thesis is subdivided into five chapters including this one. The chapters are organized in the following way.

Chapter 2 describes the experimental procedure of the present work and the method to achieve the desired result. The cutting parameters were set from two sets of cutting velocity (V_c= 93 m/min and 133 m/min), feed rate (S_0= 0.1 mm/rev & 0.14 mm/rev) and two different cutting condition (dry & high-pressure coolant condition) combination.

A mathematical modeling of cutting zone temperature along with numerical evaluation of chip-tool-work piece interface by using FEM has been performed in Chapter 3. Also cutting force modeling has been developed and validity test has been carried out for both the temperature and force modeling.

Chapter 4 narrates the discussion on results that have been found through experiment It depicts the deviation from the measured value of average cutting temperature and cutting force with the predicted results. Also the improvement of cutting temperature and force due to high-pressure coolant condition has been represented in this chapter.

In Chepter 5 concluding remarks of the present high-pressure coolant condition along with the developed mathematical model are presented.

Chapter-2

Experimental Investigations

2.1 Experimental Procedure and Conditions

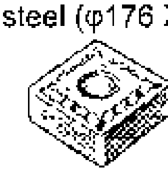
The concept of high-pressure coolant presents itself as a possible solution for high speed machining in achieving slow tool wear while maintaining cutting forces/power at reasonable levels, if the high pressure cooling parameters can be strategically tuned. It has the benefits of a powerful stream that 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 have been carried out by straight turning of medium carbon steel on a lathe (10 hp: China) by standard uncoated carbide insert at different cutting velocities (V_c) and feeds (S_o) and constant depth of cut

(t) under dry and high pressure coolant conditions. The experimental conditions have been given in Table-2.1.

Effectiveness of cooling and the related benefits depend on how closely the high pressure coolant jet can reach the chip-tool and the work-tool interfaces where, apart from the primary shear zone, heat is generated. The tool geometry is reasonably expected to play significant role on such cooling effectiveness. Keeping this view tool configuration namely SNMG-120408 has been undertaken for the present investigation. The insert was clamped in a PSBNR-2525 M12 type tool holder.

Table-2.1 Experimental conditions

Machine tool	: Lathe Machine (China) 10hp	
Work material	: Medium carbon steel (φ176 X 580 mm)	
Cutting tool (insert)	 SNMM 120408	
Cutting insert	: Uncoated Carbide, (P-30 grade), Sandvick	
Tool holder	: PSBNR 2525M12(ISO specification)	
Working tool geometry	: Inclination angle	: -6^{o}
	Orthogonal rake angle	: -6^{o}
	Orthogonal clearance angle	: 6^{o}
	Auxiliary cutting edge angle	: 15^{o}
	Principal cutting edge angle	: 75^{o}
	Nose radius	: 0. 8 mm
Process parameters		
Cutting velocity, Vc	: 93, 133, 186 and 266 m/min	
Feed rate, So	: 0.10, 0.14, 0.18 and 0.22 mm/rev	
Depth of cut, t	: 1.0 mm	
High-pressure coolant	: 80 bar, Coolant: 6.0 l/min through external nozzle	
Environments	: Dry and High-pressure coolant	

The positioning of the nozzle tip with respect to the cutting insert has been settled after a number of trials. The final arrangement made and used has been shown in Fig.2.1. The high-pressure coolant jet is directed along the auxiliary cutting edge at an angle 30° 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.2.2.

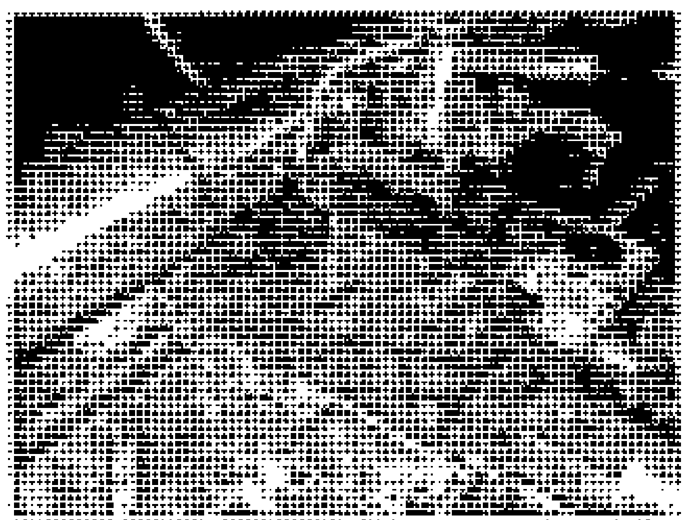


Fig.2.1 [illegible] nozzle injecting coolant during machining

Fig.2.2 [illegible]

The ranges of V_c and S_o have been chosen based on the tool manufacturers recommendation and industrial practice for machining the steel by the carbides undertaken. The depth of cut was kept constant to only 1.0 mm, which would adequately serve the present purpose since it has much less significant role on the machining characteristics excepting the magnitude of the cutting forces, which simply increase proportionally with the increase in depth of cut. The machining responses have been monitored and studied using sophisticated and reliable equipment and techniques as far as possible.

In the present research work, the average cutting temperature has been measured by standard tool-work thermocouple technique. The tool-work thermocouple was calibrated before use The output from the thermocouple was in mV unit, which was then converted to the corresponding temperature from the calibration data.

The magnitude of the cutting force is a major index of machinability, which governs productivity, product quality and overall economy in machining. The cutting forces increase almost proportionally with the increase in chip load and shear strength of the work material. Apart from chip load and strength of the work material there are some other factors which also govern magnitude of the cutting forces. However, attempt should always be made to minimise the magnitude of the cutting forces without sacrificing MRR and product quality. In the present work, the magnitude of main cutting force (P_Z) has been monitored by a dynamometer (Kistler) for all the combinations of cutting velocities, feed rates and environments undertaken. The dynamometer shows the direct value of P_z, the main cutting force in Newton (N) to its output device with data collection rate 8 pulses per second And these data were stored in computer through a computer interface from dynamometer.

2.2 Experimental Results

2.2.1 Cutting Temperature

The machining temperature at the cutting zone is an important index of machinability and needs to be controlled as far as possible. Cutting temperature increases with the increase in specific energy consumption and material removal rate Such high cutting temperature adversely affects, directly and indirectly, chip formation, cutting forces, tool life and dimensional accuracy and surface integrity of the products. Therefore, application of high-pressure coolant jet is expected to improve upon the aforesaid machinability characteristics which play vital role on productivity, product quality and overall economy in machining particularly when the cutting temperature is very high.

In the present work, the average chip-tool interface temperature has been measured effectively under both dry and high-pressure coolant conditions very reliably throughout the experimental domain by tool-work thermocouple technique. The effect of high-pressure coolant on cutting temperature under different V_c and S_o have been graphically shown in Fig 2 3

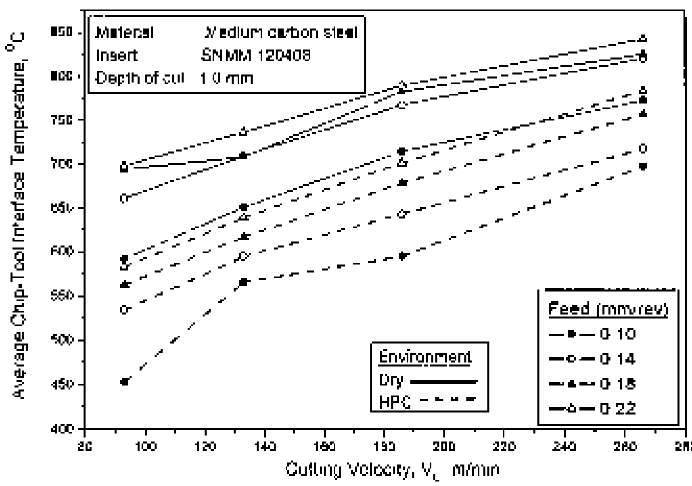


Fig.2.3 Variation in chip tool interface temperature with V_c at different S_o under dry and high-pressure coolant conditions

In the present work, the average chip-tool interface temperature could be effectively measured under dry machining very reliably throughout the experimental domain However, the distribution of temperature within the tool, work and chip cannot be determined effectively using experimental techniques. This necessitated development of finite element model of machining temperature, its validation using present experimental result and finally determining complete temperature distribution in the tool, work and chip under both dry and high-pressure coolant conditions. The approach, procedure and results of this computational evaluation of machining temperatures have been separately presented in the next chapter (Chapter-3).

2.2.2 Cutting Forces

Cutting forces are generally resolved into components in mutual perpendicular directions for convenience of measurement, analysis, estimation of power consumption and for design of Machine-Fixture-Tool-Work systems. In turning by single point tool like insert, the single cutting force generated is resolved into three components namely; tangential force or main cutting force, P_Z, axial force or feed force, P_X and transverse force, P_Y as has been indicated in Fig.2 4 Each of those interrelated forces has got specific significance.

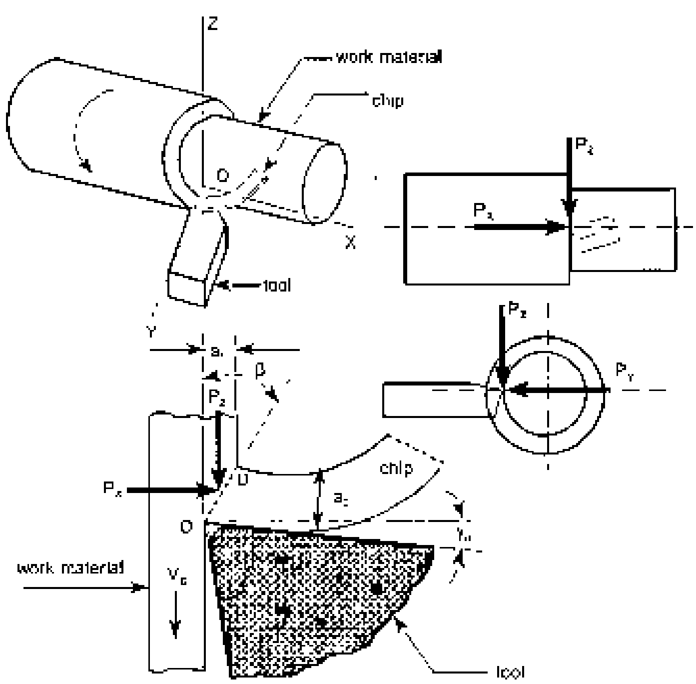


Fig.2.4 Components of cutting force acting on turning tool

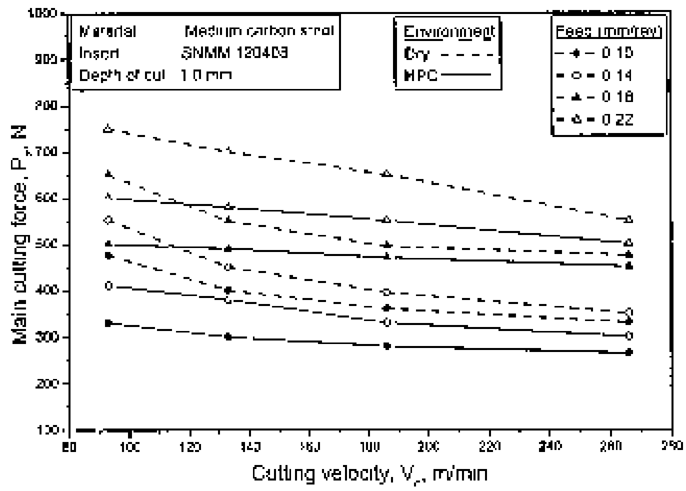


Fig.2.5 Variation in main cutting force, P_z with cutting velocity under dry and high-pressure coolant conditions

In the present work, the magnitude of main cutting force, P_z and feed force, P_x have been monitored by dynamometer for all combinations of cutting velocities, feed rates and environments undertaken. The effect of high-pressure coolant on P_z and P_x at different V_c and S_o under both dry and high-pressure coolant conditions have been graphically shown in Fig.2.5 and Fig.2.6 respectively.

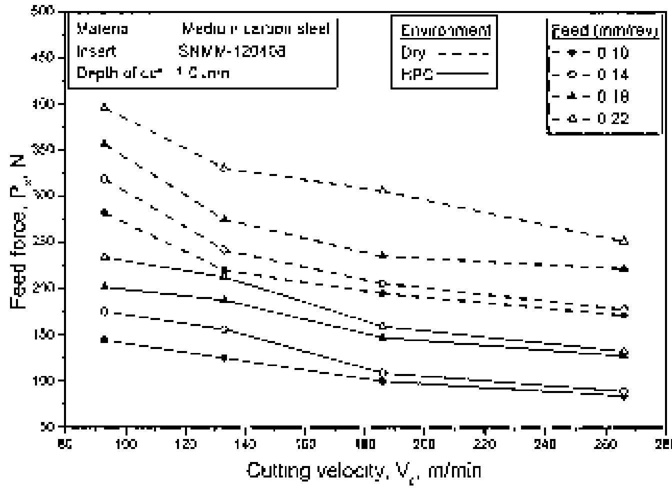


Fig.2.6 Variation in feed force, P_x with cutting velocity under dry and high-pressure coolant conditions

Chapter-3

Modeling of Cutting Temperature and Force

3.1 Numerical Evaluation of Cutting Temperature

3.1.1 Temperature Modeling in Work-Tool-Chip Domain

Earlier researchers [**Hahn 1951, Loewenand Shaw 1954 and Weiner 1955**] used Jeager's model of moving heat sources and block partition principle to estimate average temperature at the shear plane and at the chip-tool interface However, these models could not take into account variation in thermal properties of work and tool material with temperature, the elasto-plastic nature of chip-tool interaction, work-tool interaction at the wear land in flank etc. The aforesaid short comings of analytical approach were overcome [**Tay et al. 1974**] by using finite elemant modeling of machining temperature The refinement of the FEM models took place over the years [**Tay et al. 1976, Stevenson et al. 1983, Muraka et al. 1979, Strenskovski and Kyung-jin 1990, Ostafiev and Noschenko 1985 and Kagiwada and Kananuchi 1988**] with increasing reliability. Three dimensional FEM models are marginally accurate than two dimensional models, but are complex to develop and require more computational efforf [**Tay et al. 1976, Stevenson**

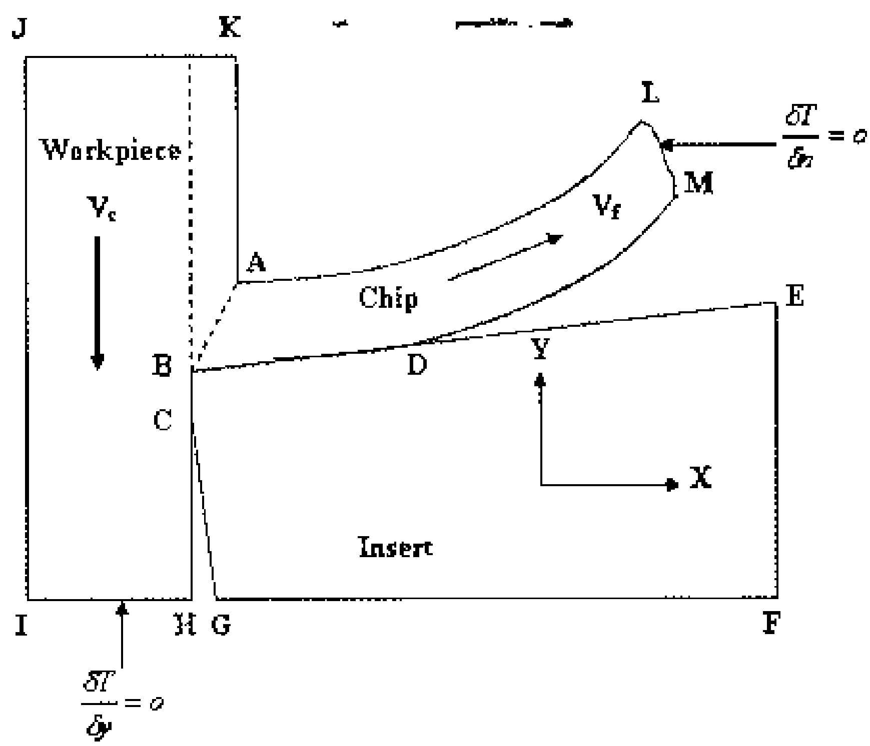
et al. 1983, Muraka et al. 1979, Strenskovski and Kyung-jin 1990, Ostafiev and Noschenko 1985 and Kagiwada and Kananuchi 1988]

In machining, where the chip thickness is much smaller than the chip width, the problem is reduced to a two-dimensional steady-state heat transfer with appropriate boundary conditions [**Tay et al. 1974, Stevenson et al. 1983, Muraka et al. 1979 and Strenskovski and Kyung-jin 1990**]. For the present work, a two dimensional model has been developed for computational evaluation of temperature distribution in the chip and tool for which the heat developed at the auxiliary flank has been neglected. In machining, heat is generated primarily in three different zones, namely primary shear zone, chip-tool interface and wear land on the principal flank. The mass and heat transport are governed by formation and separation of the chip, cutting velocity, chip velocity and heat conduction and convection. Being a two dimensional model the temperature distribution is calculated on the orthogonal plane and control volume includes the three regions; one is the workpiece moving at the cutting velocity, the second is the chip moving at the bulk chip velocity and the third one is the tool which is stationary The basic equation to be solved for the temperatures of this domain is of the type.

$$\rho c_p(T)\left(u\frac{\delta T}{\delta x}+v\frac{\delta T}{\delta y}\right)-k(T)\left(\frac{\delta^2 T}{\delta x^2}+\frac{\delta^2 T}{\delta y^2}\right)=Q \tag{3.1}$$

where ρ is the mass density, c_p is the specific heat, k is the thermal conductivity, $\dot{Q}$ is the internal heat generation rate, u & v represent the velocity components in the x and y directions and T is the temperature

The workpiece, chip and insert domain are discretised into appropriate elements for the steady-state heat transfer analysis using finite element methodology. The problem domain is defined with three types of material Starting from the shear plane, in the downstream direction, the whole length of the chip is treated as one type of material, the workpiece is treated as second type of material and the insert is treated as third type of material. This facilitates the specification of different mass flow rates. The velocity of flow of the chip has been assumed to be uniform through out, which is used to specify the mass flow rate in the chip region. The mass flow rate in the workpiece region is specified using the cutting velocity. These conditions would make the solution procedure simulate the thermal phenomenon in the cutting process more or less close to the actual cutting conditions with specified assumptions. The velocity boundary condition is shown in Fig.3.1.



boundary	Dry condition	High-pressure condition
IJ &JK	ambient temperature boundary	ambient temperature boundary
KA, AL,MD & DE	insulated boundary	convective boundary
EF & FG	200^oC temperature boundary	60^oC temperature boundary
GC & CH	insulated boundary	insulated boundary

Fig.3.1 Problem regions showing thermal boundary conditions

For all the cases, the mesh size was 0.05mm the shear plane BA and the chip-contact length BD in Fig 3.2 were divided into 10 elements and the wear land BC was divided into 4 elements. Since the chip-contact length varied with the cutting speed and feed, the element size for all the cases were not same.

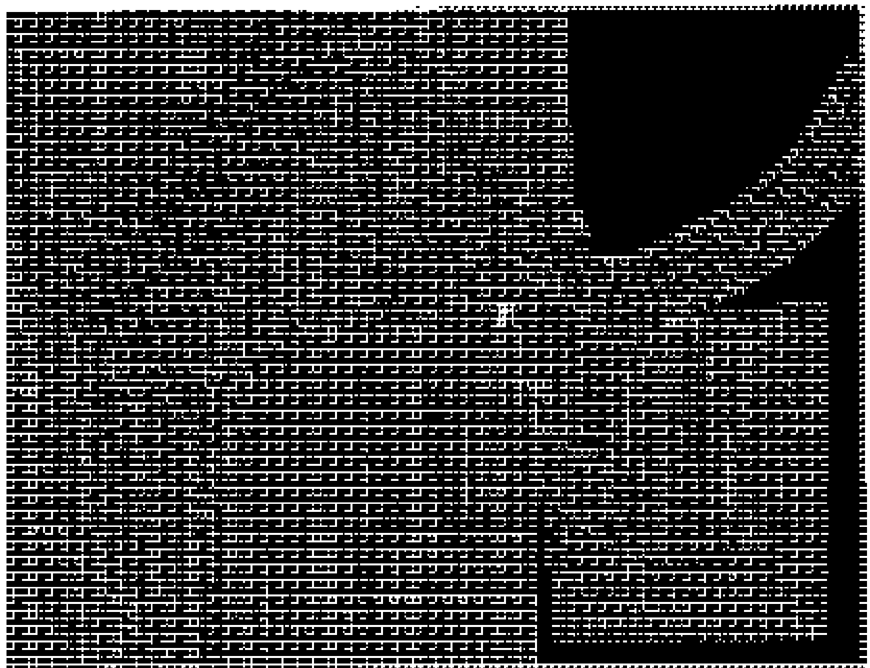


Fig.3.2 [illegible]

The dimensions of the part of the workpiece are so selected that the far boundaries are almost negligibly affected by the sources of heat. A constant gradient condition is imposed on these boundaries.

The length of the chip on the down stream side, from the point of separation from the shear plane has been taken to be equal to 12 mm. At such a distance from the frictional heat source, the temperature in the chip are found to stabilize in the flow direction. Thus, a zero thermal gradient condition has been specified at the outlet boundary of the chip. All the surfaces exposed to air are assumed to be insulated as the heat loss through these surfaces is negligibly small.

In the domain of the cutting insert, some surfaces will conduct the heat into the tool holder A constant temperature (200°C) boundary condition has been imposed at all the nodes on these surfaces [**Dhar et al. 2000**].

In dry machining condition, the thermal boundary condition as shown in Fig.3.1 can be categorized into three distinct groups, namely S_{T_n}, where the temperature is known to be ambient temperature (40°C), S_T, where the temperature is assumed to be a constant T, and S_n, which is assumed to be thermally insulated. T is set to 200°C for dry cutting. A zero temperature gradient ($\frac{\delta T}{\delta n} = o$ and $\frac{\delta T}{\delta y} = o$) is imposed on LM and HI respectively. Therefore, the following applies to the classification of thermal boundary conditions for dry machining.

$$\begin{Bmatrix} i. & S_{T_\alpha} \in IJ, JK \\ ii & S_{t} \in EF, FG \\ iii. & S_{n} \in KA, AL, MD, DE, GC, CH \end{Bmatrix} \tag{3.2}$$

Under high-pressure coolant condition, the boundary as shown in Fig.3.1 can be categorized into four distinct groups, namely $S_{T\alpha}$, where the temperature is known to be ambient temperature (40°C), S_T, where the temperature is known to be a constant T_N (T_N should be set to the cutting oil temperature 40°C for high-pressure cooling), S_n, which can be assumed to be thermally insulated and S_h, which is assumed to be convective heat transfer boundary by introducing cooling heat-transfer coefficients (0.02

W/mm^2) with temperature 40^{o}C into the boundary conditions. The convective heat transfer coefficient has been calculated assuming the flow of cutting oil over a flat plate maintained at a particular temperature [**Nashchokin 1979**]. The thermo-fluidic properties of the cutting oil has been taken from a handbook [Barron 1985] The heat fluxes for AB, BD, and BC (shear plane, chip-tool contact length and flank wear land) are given by the determined heat-generation rates along AB, BD, and BC respectively. The thermal boundary conditions of the solution region under high-pressure cooling condition are thus,

$$\left\{\begin{array}{l} i \quad S_{t_n} \in IJ, JK \\ ii. \quad S_T \in EF, FG \\ iii. \quad S_n \in GC, CH \\ iv. \quad S_h \in KA, AL, LM, MD, DE \end{array}\right\} \qquad (3.3)$$

Furthermore, by merging the boundaries of the tool and workpiece on the chip-tool interfece BD and tool-work interface BC, it is implicitly assumed that the tool rake and the chip face are subjected to the same temperature in that area. This is justified by the fact that high normal contact stress on the chip-tool interface produces only negligible thermal resistance.

Table-3.1 Thermal properties of the work materials **[Rothman 1988]**

Work material	Mass density, ρ (Kg/mm^3)	Thermal conductivity, k (W/mm-K)	Specific heat, c_p (J/Kg-K)
Medium carbon steel	7.2X10^{-06}	k=0.052-1.9X10^{-5} T	c_p=420+0 66 T

The variation of work material properties with temperature for different work materials have been considered in the present model

[Rothman 1988] The mass density, thermal conductivity and specific heat of the work material used in the analysis are given in Table-3.1. It was assumed that within an element, k and c_p were constant at values corresponding to the average temperature at the centroid of the element. As a consequence of this temperature dependence, it was necessary to perform the calculations iteratively. The thermal property of the tool material was taken to be temperature independent as given in Table-3 2.

Table-3.2 Thermal properties of tool materials **[Rothman 1988]**

Tool material	Mass density, (Kg/mm^3)	Thermal conductivity, k (W/mm-K)	Specific heat, c_p (J/Kg-K)
SNMM 120408 TTS	12×10^{-06}	0.047	251.00

The knowledge of the normal and tangential stress distributions on the tool rake face is essential for calculation of thermal load at the chip-tool interface. The magnitude and distribution of the frictional forces involved in a cutting process largely controls the temperature distribution over the rake surface

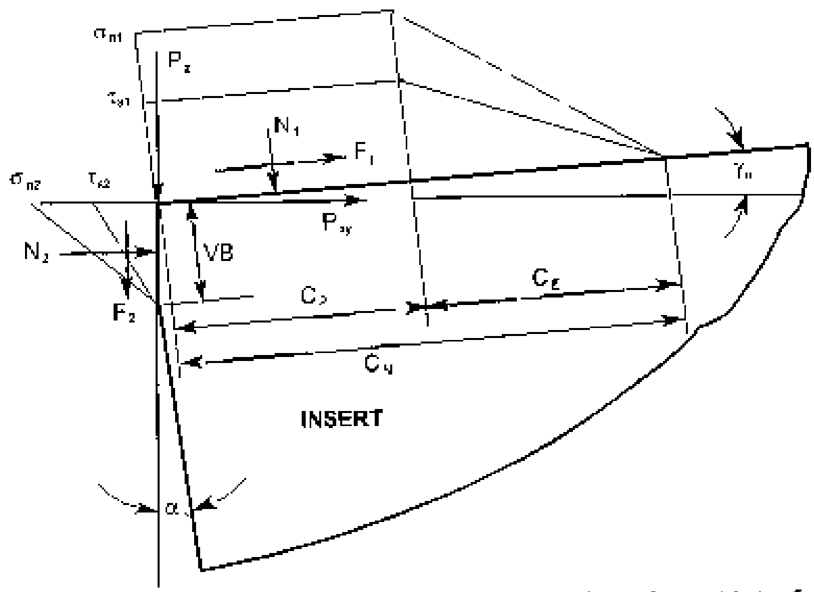


Fig.3.3 Stress distribution along the chip-tool and work-tool interface.

Previous investigations suggested that **[Kato et al. 1972, Barrow et al. 1982, Chen and Pun 1988 and Childs et al. 1989]** both the normal stress and the tangential stress remained uniform up to the plastic contact portion of the chip-tool contact area and then linearly decreased till the chip contact length to zero, as shown in Fig.3.3. Though there has been some difference of opinion regarding the apportionment of plastic to elastic contact length, in this work, the plastic contact length is considered as 60% of the total contact length **[Stephenson and Agaplou 1997]**

Under actual machining conditions, the tool never remains perfectly sharp and a small wear land usually exists on the flank surface. Considering such a wear land would always make the analysis represent conditions that are more realistic. Thus wear land of length of 0.2 mm [**Singamneni 1993**] has been taken to represent such realistic machining conditions in all the cases studied in this work. Based on the experimental results reported [**Stevenson et al. 1983**] earlier, the frictional force on the wear land is assumed as 20 N and the normal force as 40 N. A triangular distribution is assumed for these forces over the wear land as shown in Fig.3.3.

The chip velocity at the vicinity of the rake surface is usually less than the bulk chip velocity, V_f due to drag force generated by the secondary shear. The best approximation of such drag is to assume the velocity at the tool tip to be $\frac{V_f}{3}$ and then increasing to V_f with uniform acceleration within half the contact length [**Tay et al. 1974**]. However, in the present analysis, such effect has been neglected and the chip velocity has been taken to be uniform through the chip contact length.

Experimental determination of chip-tool contact length is often difficult. It may be assumed to be equal to a constant multiple of either the chip thickness [**Kato et al. 1972**] or product of the chip thickness and tool-chip friction coefficient [**Bhattacharyya 1984**]. Conventionally, the chip-tool contact length $C_{N'}$ for given rake angle and feed becomes almost proportional to a_2 as

$$C_N = a_2\left[1 + \tan(\beta - \gamma)\right] \tag{3.4}$$

where, β is the shear angle.

In machining, the major portion of the deformation energy gets converted into heat and a small portion remain frozen in the strained chips. The percentage of such frozen energy gradually decreases with the increase in cutting velocity. Hence, it may be assumed that the entire work done during the deformation process gets converted into heat [**Shaw 1984**]. Further, in the present work exothermic oxidation of the chips has also been neglected. Therefore, for the present analysis, the total heat generation, Q and the heat generation at the rake surface, Q_f per unit time have been evaluated as,

$$Q = P_z . V_c \text{ and } Q_f = F_1 . V_f \tag{3.5}$$

Where. F_1 is the total frictional force on the rake surface which could be determined from the known values of the tangential force P_Z and the axial force P_X by experimental force measurement.

The rate of heat generated in the shear zone Q_S is therefore,

$$Q_s = Q - Q_f \tag{3.6}$$

Q_S is essumed to be uniformly distributed over AB (Fig.3.1) both under dry and high-pressure cooling condition [**Ding and Hong 1998**] and specified over a strip of nodes along the shear plane. The total heat generated per unit time, Q_W due to friction at the flank wear land has been evaluated from,

$$Q_w = F_2 V_c \tag{3.7}$$

where, F_2 is the total frictional force at the wear land. The distribution of rate of heat generation at the chip-tool interface, Q_f and wear land, Q_W follow the shear stress distribution pattern as shown in Fig.3.3 and they are applied over BD and BC (Fig.3.1) respectively.

Unlike the previous approaches using apportionment coefficient for calculeting thermal loads on the cutting tool and analysis of only the tool [**Kagiwada and Kananuchi 1988, Bhattacharyya 1984 and Lo Casto et al. 1989**], the present analysis uses an integrated approach with a control volume consisting of work, tool and chip. The MSC NASTRAN/PATRAN software is used for implementing the model.

3.1.2 Results of Cutting Temperature Analysis

The correlation between the average chip-tool interface temperature obtained directly by measurement and that obtained by finite element analysis under dry machining heve been depicted in Fig.3.4 The estimated values of average chip-tool interface temperature appeared to be higher than the measured values expectedly for ignoring the part of the cutting energy that remains frozen in the chips as strain energy Such deviation has increased with the decrease in the energy level i.e. V_c and S_o when percentage of the residual strain energy in the chips increased.

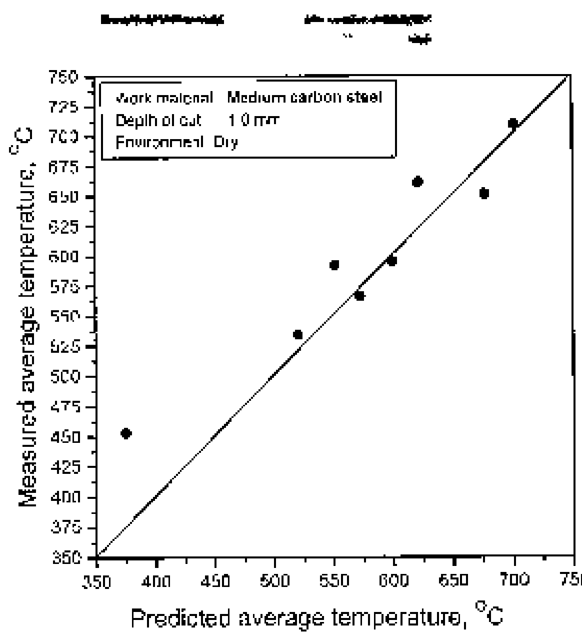
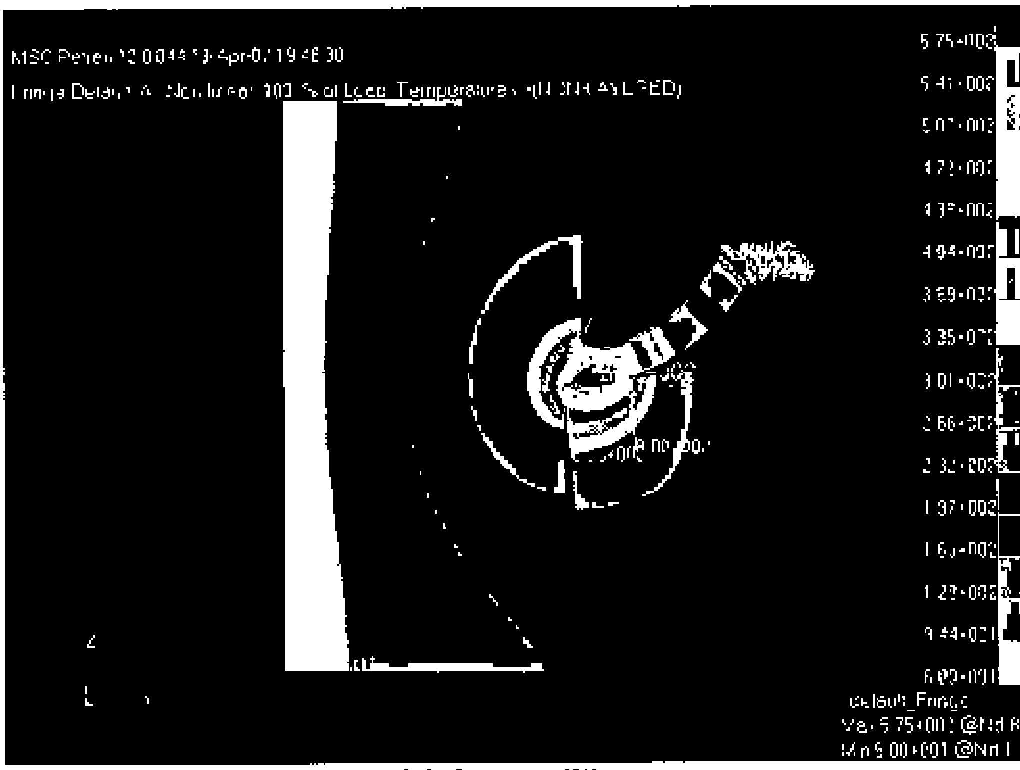
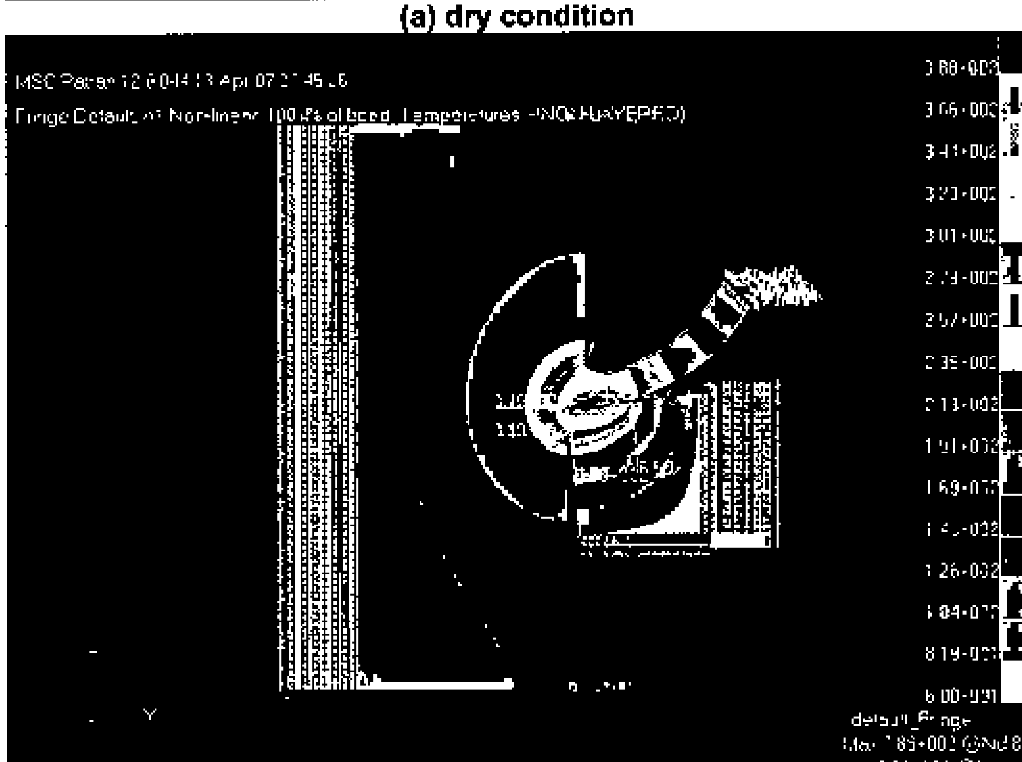


Fig.3.4 Comparison of measured and predicted average chip-tool interface temperature attained in dry machining

The finite element analysis provided distribution of temperature assuming steady state heat transfer in the workpiece, chip and tool Such analyses have been carried out for all the combinations of workmaterial-tool-V_c-S_o environment undertaken Fig 3 5 to Fig.3.8 are typically showing the temperature distribution in case of machining the medium carbon steel under dry and high-pressure cooling condition respectively by SNMM inserts.

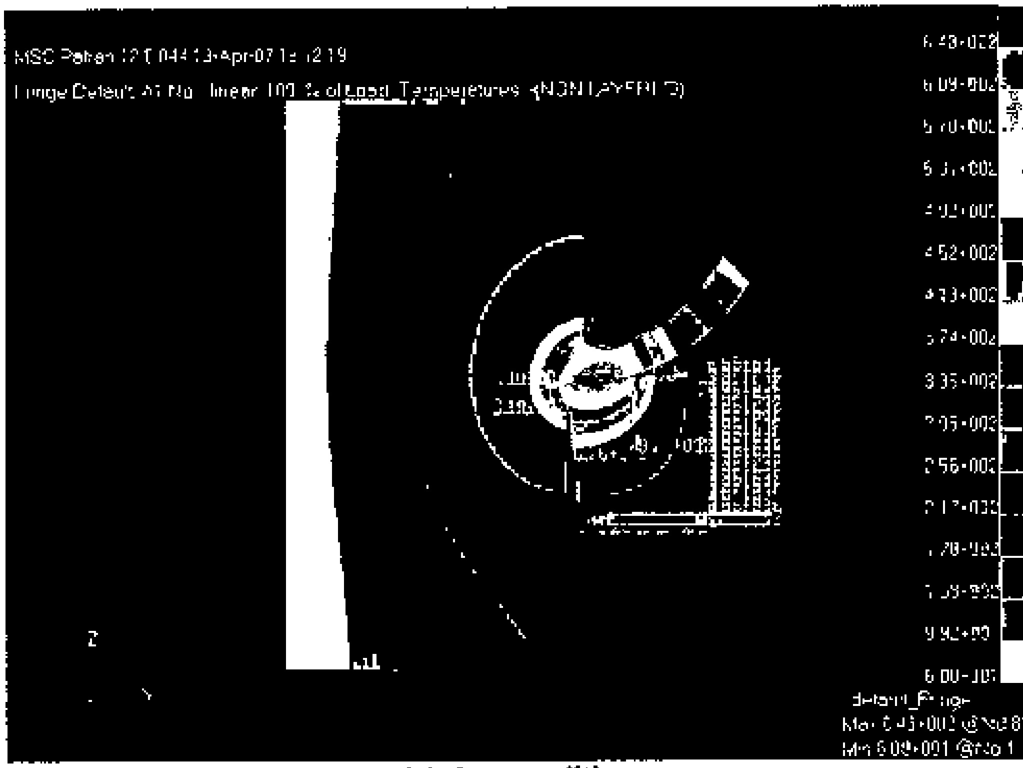


(a) dry condition

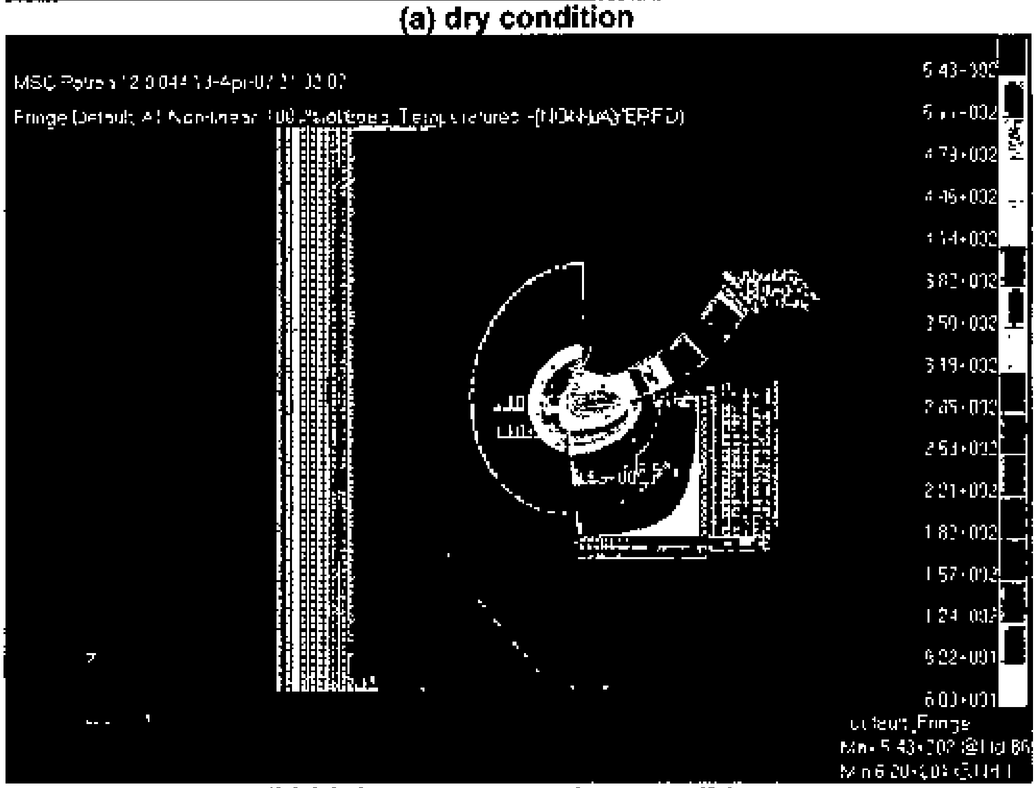


(b) high-pressure coolant condition

Fig.3.5 Computed temperature distribution in chip, tool and workpiece under (a) dry and (b) high-pressure coolant condition
[V_c= 93 m/min, S_o=0.10 mm/rev, t=1.00 mm]

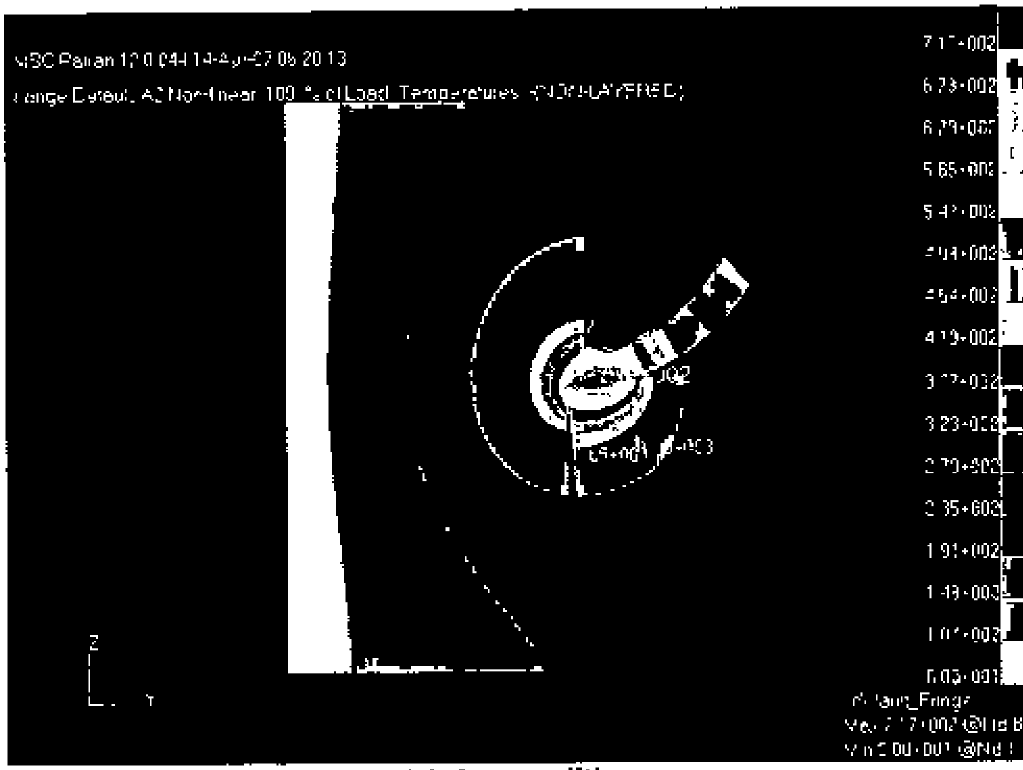


(a) dry condition

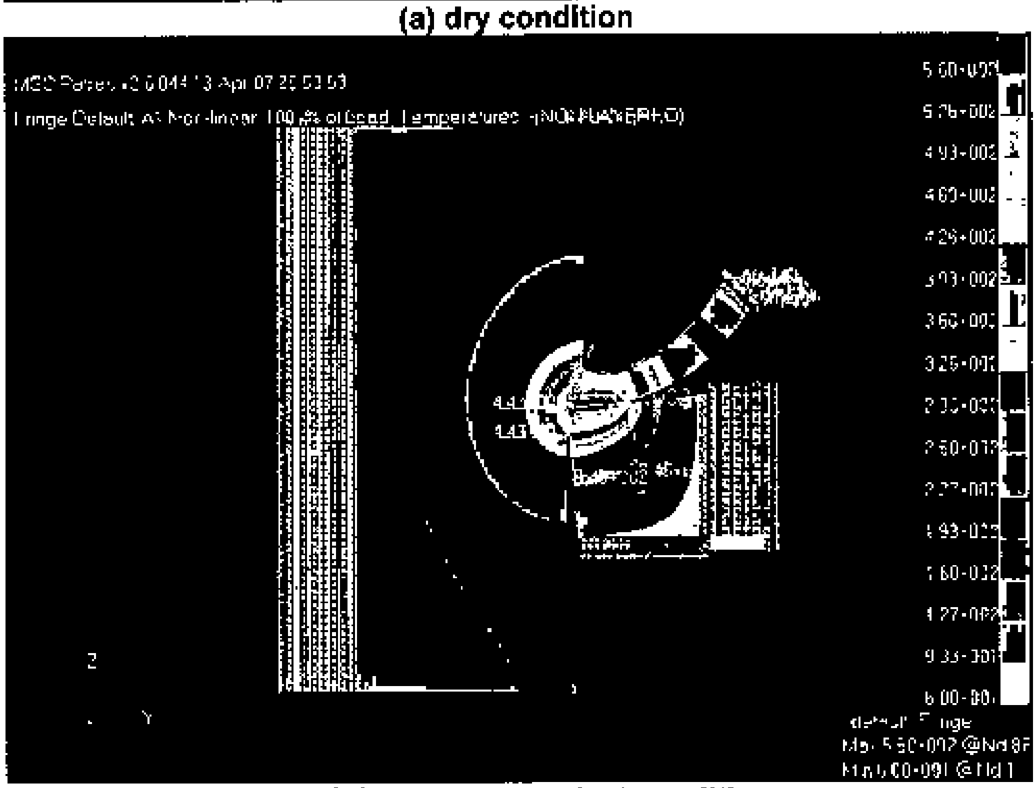


(b) high-pressure coolant condition

Fig.3.6 Computed temperature distribution in chip, tool and workpiece under (a) dry and (b) high-pressure coolant condition
[V_c= 93 m/min, S_o=0.14 mm/rev, t=1.00 mm]

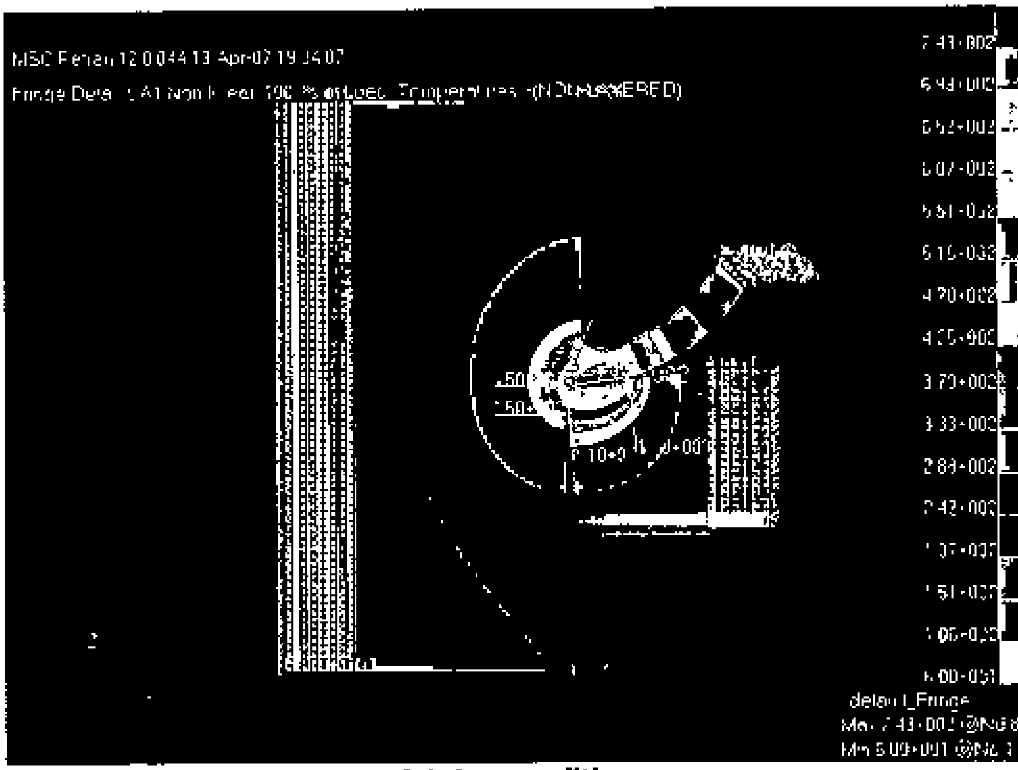


(a) dry condition

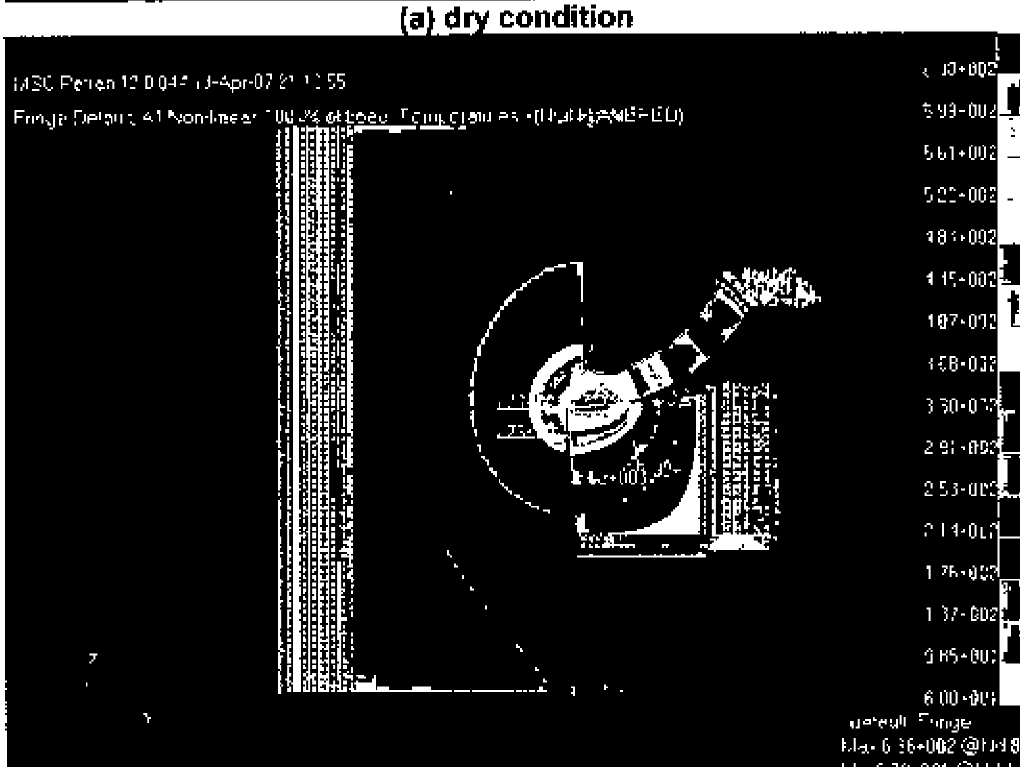


(b) high-pressure coolant condition

Fig.3.7 Computed temperature distribution in chip, tool and workpiece under (a) dry and (b) high-pressure coolant condition
[V_c= 133 m/min, S_o=0.10 mm/rev, t=1.00 mm]



(a) dry condition



(b) high-pressure coolant condition

Fig.3.8 Computed temperature distribution in chip, tool and workpiece under (a) dry and (b) high-pressure coolant condition
[V_c= 133 m/min, S_o=0.14 mm/rev, t=1.00 mm]

3.2 Mathematical Modeling of Cutting Force

The knowledge of cutting forces is a prerequisite to cutting temperature estimation, surface finish evaluation, tool life prediction, cutting process planning, and chatter analysis, etc. The mechanics of machining processes and the prediction of cutting forces have been extensively analyzed and modeled for decades by many researchers. Although a number of studies have been documented in the field, these models are not suited for high-pressure coolant condition without considering the effects of lubricating and cooling resulting from the small amount of cutting fluid transmitted to the cutting zone In order to support the planning, optimization, and control of high-pressure coolant machining process, it is necessary to establish a set of predictive thermo-mechanical models for estimating the cutting forces as functions of high-pressure jet parameters and cutting conditions.

Force modeling in metal cutting is important for thermal analysis, tool life estimation. chatter prediction, and tool condition monitoring purposes. Significant efforts have been devoted to understanding the force profiles in metal cutting. Along with a laborious experimental approach, several numerical and analytical approaches have been proposed to model the chip formation forces and the associated cutting forces Finite element method (FEM) has been applied to simulate machining process since the early 1970's [**Klamecki 1973**]. After that time, FEM with different derivatives has received widespread attention in the numerical modeling of machining processes [**Wang et al. 1988, Ng et al. 1999**]. Although some successes have been gained in modeling the chip formation forces in metal cutting by FEM, it is not yet ready to be applied due to the fact that it is laborious and not very easily extended to practical 3-D turning cases.

Analytical models have been favored for the modeling of forces in metal cutting because they are easy to implement and can give much more insight about the physical behavior in metal cutting. To model the chip formation forces in metal cutting, two fundamental approaches have been extensively researched: minimum energy principle [**Merchant 1945, Lee and Shaffer 1951**] and slip line field theory [**Oxley 1989**]. The former assumes that the plestic deformation occurred uniformly in the shear plane only so that the cutting energy can be calculated from the shear strain and stress at the shear plane. Minimizing this energy with respect to the shear angle yields the direction of the shear plane principle [**Merchant 1945, Lee and Shaffer 1951**]. Unfortunately, the solutions did not take into account factors such as flow stress varying with temperature, strain, and strain rate. Alternatively, by using plasticity theory for the plane strain case, slip line fields are constructed around the primary shear zone from experiments, and also by considering the effects of strain, strain rate and temperature on the flow stress a parallel-sided shear zone approach, which was presented by Oxley [**Oxley 1989**]. Numerous researchers have applied or modified these two approaches to model the force profiles afterwards in metal cutting.

Force difference is observed when using the same type of tools, but with different thermal properties. For example, under the same cutting condition there is force difference between using high and low CBN content tools, which are commonly used in turning hard steels. Unfortunately, among the documented approaches, the effect of tool thermal property on cutting forces hes not been addressed analytically. It is generally recognized that low CBN content tools have longer life than those of high CBN content tools in hard turning. Several mechanisms ere discussed for this phenomenon [**Konig et al. 1993, Barry and Byrne 2001**]. Unfortunately, very few effort has been made to determine the High pressure Coolant effect on the force distribution of chip formation process, although the stress and temperature distributions are considered the main factors in determining tool wear rate. Better analytical understanding of the effect of tool thermal property on chip formation process can help to improve the modeling of tool wear rate in turning operation.

In a recent study, it was shown that most documented studies on high pressure coolant machining were empirical and qualitative [**Liang and Sutherland 2002**] In this chapter, an analytical approach is taken to quantitetively model the cutting forces in high pressure coolant machining by including the cooling and lubricating effects in the Oxley's force model. The analysis is further expanded to use the obtained flow stress, contact length, and shear angle to predict the cutting forces due to tool flank wear based on Waldorf's model, considering that shear angle and chip thickness do not vary significantly with tool wear [**Boothroyd and Knight 1989**]. The cutting forces can be calculated as the summation of the forces attributed to the sharp tool and the forces attributed to the tool flank wear [**Waldorf 1996, Smithey and Kapoor 2001**].

The objective of this chapter is to estimate the cutting forces for high-pressure coolant machining under either sharp or worn tool conditions. Here instead of using empirical equations in estimating temperature of primary and secondary shear zones, modification to Oxley's predictive machining theory [**Oxley 1989**] is attempted by analytically describing the primary and secondary heat source behaviors.

The lubricant is applied to the tool rake surface with a pressure of 70 bar through the nozzle placed over the tool insert. Based on the physics of the high pressure coolant machining, modifications are made for Oxley's model [**Oxley 1989**] for sharp tools and for Waldorf's model [**Waldorf 1996**] for worn tools. First, the friction angle describing the ratio of tangential to normal forces at the tool-chip interface is calculated based on the boundary lubrication model presented by Kato et al. [**1998**]. The resulting friction angle is then used in Oxley's model for considering the lubricating effect in high pressure coolant machining. The predicted shear angle and flow stresses are then used in Waldorf's model for force prediction under the effect of tool flank wear

3.2.1 Force Modeling in 2-D Metal Cutting

The assumptions used herein to simplify the modeling of metal cutting are.

i) Cutting process is orthogonal

ii) No heat loss along the primary/secondary heat zones

iii) Uniform normal stress/shear stress distributions along all the tool-chip interface

iv) Preheating effect is negligible.

v) The machining variables or set up variables, such as cutting speed, feed rate, depth of cut are controllable and can be set up in advance.

vi) The tool geometry like nose radius, rake angle, side cutting edge angle, cutting edge angle, clearance angle etc depend on the tool to be chosen.

vii) Workpiece and their mechanical properfies is assumed unchanged during the operation

The cutting forces with the use of worn tools can be calculated by summing up the cutting forces attributed to the effect of the sharp tool and those attributed to the effect of the tool flank wear land [**Waldorf 1996**]. This section will discuss the methodology for finding the forces due to tool flank wear. The forces in the thrust force diraction P_x and in the cutting forca direction P_z can be calculated by integrating the normal flank stress and the shear flank stress respectively [**Waldorf 1996, Smithey and Kapoor 2001**]. The forces due to tool flank wear are depicted in Fig.2.4. Therefore, the cutting forces due to tool flank wear are given by

$$\left\{\begin{aligned} P_z &= t\int_0^{c_N}\sigma_{n1}\left(\frac{x}{c_N}\right)^{\xi}dx \\ &= \frac{\sigma_{n1}\,t\,c_N}{1+\xi} \end{aligned}\right\} \tag{3.8}$$

$$\left\{\begin{aligned} P_x &= t\left[\tau_{s1}c_P + \int_0^{c_N-c_P}\mu\,\sigma_{n1}\left(\frac{x}{c_N}\right)^{\xi}dx\right] \\ &= \tau_{s1}\,t\,c_P + \frac{\mu\sigma_{n1}\,t\left(c_N-c_P\right)^{1+\xi}}{c_N^{\ \xi}\left(1+\xi\right)} \end{aligned}\right\} \tag{3.9}$$

In order to estimate the cutting forces, the normal stress and the shear stress have to be found first. Waldorf [**1996**] proposed polynomial-shaped distributions for both the normal and shear stresses. Those stress distributions are also affected by chip tool contact length, c_N and length of the sticking contact region, c_P

Consideration of frictional behavior in the metal cutting has led to the model of orthogonal cutting with a continuous chip and no built-up edge as shown in Fig.2.4. Here the normal stress between the chip and the tool are sufficiently high to cause A_r/A_a to approach unity over the region of length c_P, adjacent to the tool cutting edge, termed the sticking region. In the length c_N-c_P, extending from the end of the sticking region to the point where the chip loses contact with the tool, the ratio A_r/A_a is less then unity. This region has been termed as sliding region [**Zorev 1963**]

Previous investigations suggested that [**Kato et al. 1972, Barrow et al. 1982, Chen and Pun 1988 and Childs et al. 1989**] both the normal stress and the tangential stress remained uniform up to the plastic contact portion of the chip-tool contact area and then linearly decreased till the chip contact length to zero, as shown in Fig 2.4. Though there has been some difference of opinion regarding the apportionment of plastic to elastic contact length, in this work, the plastic contact length is considered as 60% of the total contact length **[Stephenson and Agapiou 1997]**

In the sticking region, the shear stress become maximum τ_{s1} and from $x = c_N - c_P$ to $x = c_P$,

$$\tau_{s1} = \tau_0$$

At the point $x = c_N - c_P$ the normal stress is the function of c_N and c_P, which become

$$\sigma_0 = \sigma_{n1}\left(\frac{c_N - c_P}{c_N}\right)^{\xi}$$ and therefore

$$\tau_{s1} = \mu\,\sigma_{n1}\left(\frac{c_N - c_P}{c_N}\right)^{\xi}$$

Where the flow stresses σ_o and τ_o are obtained from the modified Oxley's force modeling for sharp tools. The required information, such as shear angle, for the Wardolf's model **[1996]** can be also obtained from the modified Oxley's machining theory [**1989**].

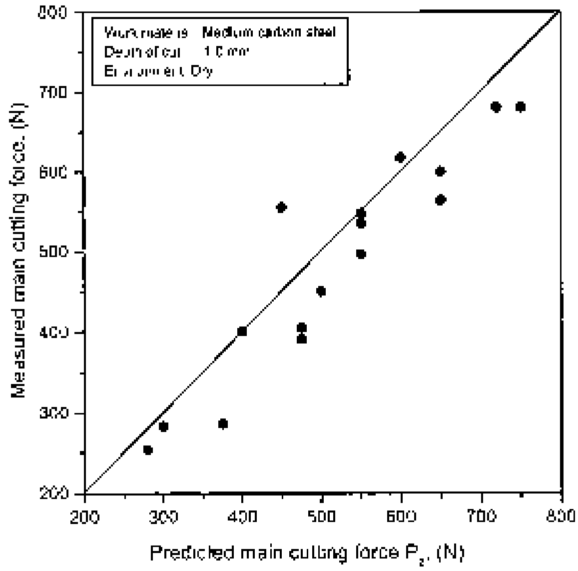


Fig.3.9 Comparison of measured and predicted main cutting force, P_z attained in dry machining

Chapter-4

Discussion on Results

4.1 Cutting Temperature

The machining temperature at the cutting zone is an important index of machinability and needs to be controlled as far as possible. Cutting temperature increases with the increase in specific energy consumption and material removal rate (MRR). Such high cutting temperature adversely affects, directly and indirectly, chip formation, cutting forces, tool life and dimensional accuracy and surface integrity of the products. Therefore, application of high pressure coolant is expected to improve upon the aforesaid machinability characteristics which 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.

Tool-work thermocouple technique is as such simple and reliable but limited to measurement of average cutting temperature and only dry machining when cutting fluids do not hamper measurement. Hence, finite element modelling has been essential for evaluation of cutting temperature under HPC and also for precisely determining the distribution of temperature in the cutting zone under any condition. But the modelling essentially need to be capable of predict temperature distribution reasonably accurately and reliably.

Fig.3.4 shows that the values of the average chip-tool interface temperature, predicted by the used model are in adequately close agreement with their measured values. The deviations may be attributed mainly to the assumption that the entire cutting energy is converted into heat. Actually, a small fraction of the cutting energy remains frozen in the chips as residual strain and its percentage decreases with the increase in the level of the cutting temperature due to increase in cutting velocity (V_c) and feed (S_o). As there is no analytical model available for the same, in the present finite element model this strain energy has been neglected. Possibility of incorporation of this residual strain could have improved the accuracy of the FE model.

However, the deviations between the predicted and the measured temperatures within the domain of the present study, excepting at few points, have been within around 0-20%, which is reasonably acceptable from engineering point of view [Ding and Hong 1998]. The pattern of temperature distribution at the cutting zone attained by the present FE model for dry machining are also matching with the corresponding results reported earlier **[Ding and Hong 1998, Muraka et al. 1979, Stevenson et al. 1983,**

Strenskovski and Kyung-jin 1990 and Tay et al. 1974]. Therefore, the presently used model could be considered reasonably accurate and valid for evaluation of cutting temperature.

The figures from Fig.3.5 to Fig.3.9 are showing that the pattern of estimated temperature distribution in the chip, tool and work have been quite similar in both dry and HPC but the later has resulted in much lesser value of temperature. Under both the machining environments, maximum temperature appeared at the chip-tool interface expectedly due to intensive sliding friction at higher speed. The temperature gradually increased along the rake surface from the cutting edge, attained maximum value and then again gradually diminished towards and away from the point of disengagement of the chips from the tool surface. This has been more or less true for all the work materials, inserts and cutting conditions undertaken. In machining ductile metals like steels, the chip first receives some heat at the shear plane (thin zone) due to primary deformation. The chip gets further heated due to intensive rubbing while sliding along the plastic chip-tool contact zone where stresses and friction are high. Heat addition and hence chip temperature starts decreasing from the elastic contact zone where stresses gradually decrease and ambient air or cutting fluid if any, is dragged in by capillary effect. Due to high-pressure coolant condition the temperature at the chip-tool interface decreased sizeably though in different degree for different tool-work combinations, V_c and S_o.

Also Fig.3.5 to Fig.3.9 demonstrate that under high-pressure condition maximum temperature zone shifted form the tool tip with respect to dry condition, which is obviously favorable. Again, the maximum temperature zone shifted from tool to chip region, which is complementary for any machining. The study also shows that the Chip-reduction co-efficient decreases in high-pressure coolant condition in respect with dry condition. And as a consequence the chip-tool contact length, C_N decreases and so as the cutting temperature and force.

It clearly apparent from the figures showing computed temperature distributions, that compared to chip-tool interface temperature, the shear zone temperature has all along been much less with average value around 350°C and this temperature level has not changed much expectedly, due to application of High pressure jets which were impinged in narrow streams primarily targeting the chip-tool and work-tool contact surfaces and aiming minimum bulk cooling and wastage of coolant.

4.2 Cutting Forces

It is already mentioned in the previous chapters that the magnitude of the cutting force is a major index of machinability which governs productivity, product quality and overall economy in machining. The cutting forces increase almost proportionally with the increase in chip load ($t \times S_o$) and shear strength of the work material. Apart from chip load and strength of the work material there are some other factors which also govern magnitude of the cutting forces. However, attempt should always be made to minimise the magnitude of the cutting forces without sacrificing MRR and product quality.

In general, the proposed model shows good estimation for the main cutting forces. In this study, although the predicted cutting forces have comparable errors with respect to the experimental data, the differences between the forces for dry and HPC cases are similar for both the predicted cutting forces and measured data. Fig.3.9 shows that the values of the measured main cutting force (P_z), and main cutting force predicted by the used model are in adequately close agreement with their measured values. However, the deviations between the predicted and the measured main cutting force within the domain of the present study, excepting at few points, have been within around 5-15%, which is reasonably acceptable from engineering point of view [Ding and Hong 1998]. The similar dissemblance of about 10% - 20% between cutting forces for dry and HPC machining was also observed by Rahman et. al. **[2001]** when cutting ASSAB 718H steel with a Sumitomo Electric Carbide 20 mm diameter single-tooth end mill.

For high-pressure coolant machining, the combination of the lubricating and cooling effects on machining medium carbon steel with uncoated carbide results in lower cutting forces in all directions. Since the cutting temperatures are higher in dry machining than those in high-pressure coolant machining, the cutting forces should be less under dry machining due to the material softening effect when only the cooling effect is considered. Thus, it is inferred that the lubricating mechanism has a stronger effect on cutting forces than the cooling mechanism when cutting medium carbon steel with uncoated carbide tools.

In addition to the lubricating and cooling effects, the temperature dependent material properties may play an important part in the cutting forces. The high cutting temperatures are usually observed in the cutting zone. As shown in the Fig.3 4, the predicted tool-chip interface temperatures can be as high as about 700 °C. The high temperature would affect the material properties such as yield stress, conductivity, elastic modulus and so on. The thermal softening of the material causes lower cutting forces in dry cutting than those in high-pressure coolant condition. This explains the overestimation of cutting forces in some cases in force predictions. Another temperature dependent property of materials is phase transformation. The high cutting temperature as predicted in the study may cause phase transformation of carbon steels. When the material phase transformation happens, these material properties should be reconsidered. They should be treated as different materials than the bulk materials. The change of the cutting forces due to the material phase transformation can be calculated according to the developed force model with the suitable material properties of the phase transformed materials.

Chapter-5

Conclusion

- The present investigation shows that the pattern of estimated temperature distribution in the chip, tool and work have been quite similar in both dry and high-pressure coolant but the later has enabled reduction in average chip-tool interface temperature upto 16%. Such reduction has been more effective for those tool-work combinations and cutting conditions, which provided higher value of chip reduction coefficient for adverse chip-tool interaction causing large friction and built-up edge formation at the chip-tool interface.

- Under both the machining environments, maximum temperature appeared at the chip-tool interface expectedly due to intensive sliding friction at higher speed. The present investigation also shows that under high-pressure coolant condition maximum temperature zone shifted form the tool tip and from tool to chip region, which is complementary for any machining.

- The study also shows that the chip-reduction co-efficient decreases in high-pressure coolant condition in respect with dry condition. And as a consequence the chip-tool contact length, CN decreases and so as the cutting force. High-pressure coolant cooling reduced the cutting forces by up to 30% of main cutting force.

- The values of the average chip-tool interface temperature, predicted by the used model are in adequately close agreement with their measured value, with an average deviation of 12%.

- The deviations between the predicted main cutting forces by the developed model and the measured main cutting force within the domain of the present study, excepting at few points, have been within around 10%.

- Hence high-pressure coolant cutting, if properly employed, can enable significant improvement in both productivity and product quality and hence overall machining economy even after covering the additional cost of high-pressure coolant cutting system

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