ANALYTICAL MODELING OF CUTTING FORCE AND CUTTING TEMPERATURE IN TURNING STEEL UNDER CRYOGENIC COOLING CONDITION

By

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

Md. Ahasan Habib

This work is dedicated to my
Loving Parents

Md. Fazlur Rahman
and
Asia Begum

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ABSTRACT

In the machining operation the energy dissipated is converted into heat which raises the temperature in the cutting zone. The increase of cutting temperature results tool wear, surface roughness, dimensional inaccuracy significantly. Not only is the cutting temperature, cutting force also increases with tool wear which results the increase of power and specific energy consumption. The cutting temperature restrains productivity, quality and hence machining economy, can be controlled by the application of cutting fluid. But conventional cutting fluids are ineffective to control the temperature in maximum cutting zones. So cryogenic cooling is environmental friendly new approach to control the temperature desirably. Cryogenics is the study of the production of very low temperature (-196°C) and the behavior of materials at that temperature. The physical behavior during metal cutting has been changed because of cutting condition, cutting environment and work/tool material.

The aim of the present work is to investigate the role of cryogenic cooling on the formation of chip, cutting temperature and force and then develop analytical model for cutting temperature and force in turning 42CrMo4 steel under cryogenic cooling condition. The m.files of matlab has been used to determine the modeled value of cutting force and cutting temperature under cryogenic cooling condition. From an economic viewpoint, it is evident that having knowledge about the machining responses such as, cutting forces, cutting temperature and work piece surface integrity at different cutting conditions would be highly desirable as a means of realizing cost savings, increased productivity, efficiency and for preventing any hazard occurring to the machine, cutting tool or the deterioration of the quality.

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LIST OF SYMBOLS

a_1 : Uncut chip thickness
a_2 : Chip thickness
A : Percent of this energy is converted into heat
$\bar{A}$: Area factor
BHN : Brinell Hardness number
b_1 : Width of chip
c, : Specific heat
c_1, c_2 : Partition Coefficient
C_n : Natural contact length
e : Error
E_f : Rate of expansion of friction energy
E_s : Rate of expansion of share energy
F : Component of frictional force directed along the tool rake face
HSM : High speed machining
J : Mechanical equivalent of heat in kg.cm/cal
K_y : Coefficient, the effect of rake angle for x, z direction
$K_{\emptyset}$: Coefficient, the effect of principle cutting edge for x, z direction
K_{hf} : Coefficient, the effect of tool wear for x, z direction
K_{cf} : Coefficient, the effect of cutting fluid used for x, z direction
K_m : Material transfer coefficient for x, z direction
K_o (u) : Modified Bessel function of second kind and zero order
K_o (x) : Modified Bessel function of second kind of order zero
l : Natural contact length
l : Distance along x-axis
L,L_1 : Dimensionless velocity parameter
MRR : Material removal rate
n : Exponent of feed rate
N : Normal force
m : Distance along y-axis
m_1 : Exponent of BHN
M : Resultant force

L_2 : Dimensionless velocity parameter for friction
p : Exponent of t
P_s : Shear force
P_x : Feed force
P_y : Thrust force
P_z : Main cutting force
q : Heat flux
q_s : Heat generated due to intensive plastic deformation
q_r : Heat source generated due to tip radius of the cutting tool
q' : rate of heat liberated at chip-tool interface
q_1, q_2 : The heat liberated at the interface
r : Nose radius
R : Resultant distance of cutting point
R_1, R_2 : Constant
S_o : Feed rate
T : Time
T_{mod} : Modified temperature
T' : Time for a specific point
t : Chip thickness
u_f : Specific energies involved in shear
u_s : Specific energies involved in friction
u_{cf} : Energy per unit volume going to the chip on chip-tool interface
u_{cs} : Energy per unit volume going to the chip on the shear plane
V : Velocity of moving heat source
V_c : Cutting velocity
V_f : Chip flow velocity
V_s : Volume of shear zone
X : Dimensionless velocity parameter along x-axis
Y : Dependent response variable
θi : Chip-tool interface temperature
θavg : Average temperature
θm : Maximum temperature

θs : Final shear zone temperature

$\overline{\theta_0}, \theta c$: Ambient temperature in ^{0}C

$\overline{\theta}_s$: Mean temperature of the shear plane

$\emptyset_1, \emptyset_2$: Inclination angle

$\emptyset_i$: Angle of the arbitrary radial plane

Ψ_i : Angle of inclination formed by the tangential

$\Delta\theta$: Temperature rise

φ : Principal cutting edge angle

α : Rake angle

$\emptyset$: Shear angle

β : Friction angle

η : Mean angle of friction at the rake surface

δ : Thermal diffusivity

$\varphi(T)$: Heat liberation rate

λ : Thermal conductivity

ρc : Volume specific heat

ρ, ρ_1 : Density

τ_s : Dynamic yield shear strength

ε : Shear strain

μ : Mean angle of friction at the rake surface

ξ : Chip reduction co-efficient

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Chapter-1

Introduction

The most promising inclination of the modern metal cutting operation is high material removal rate (MRR) with good surface finish and high machining accuracies. All the machining on the metal as well as on the alloy where plastic deformation is related to form chip, huge energy is required and this energy is converted into heat and finally increase the cutting-zone temperature. This is a great concern of the performance of the cutting tool and the excellence of the workpiece. Temperatures in cutting zone depend on contact length between tool and chip, cutting forces and friction between tool and workpiece material. A significant amount of heat generated during machining is transferred into cutting tool and workpiece and other portion of the heat is removed with chip. So the cutting condition and the performance of tool and tool life depend on contact length between the tool and chip.

Chip-tool interface temperature, chip morphology, chip-tool interaction, cutting forces, wear and life of cutting tool, dimensional accuracy and surface integrity along with surface finish under different cutting environments with or without using cutting fluids are potential topics to research in the modern world. As the usages of different conventional cutting fluids are creating health hazard and intend to create pollution so research are expanding with completely dry cutting using high heat and wear resistant cutting tools, cryogenic machining, high-pressure coolant jet assisted machining and minimum quantity lubricant machining and their technological effects particularly in temperature intensive machining and grinding.

A summary of this promising topics and the background of this research will be represented in this chapter. The bad effect of rising temperature at the cutting zone, effect of cryogenic condition on cutting forces and cutting temperature will be discussed thoroughly in this chapter. Related literature of research works with different necessary parameters will also be described in this chapter.

1.1 High Speed Machining

A material will be defined as good machinability if it is easy to cut it according to the desire shape and size with respect to tooling and machining process involved. This machinability is measured with respect to the tool life; MRR, cutting force and power consumption, surface finish generated and surface integrity of the machined component as well as the shape of the chips. The machinability index can also significantly be exaggerated by the properties of the material being machined, properties and geometry of the cutting tool, cutting conditions employed and cutting environment etc. Machining productivity can be significantly improved by employing the right combination of cutting tools, cutting conditions, machine tool and cutting environment that will promote high speed machining without compromising the integrity and tolerance of the machined components.High-speed machining is one of advanced production technologies with great future potential.The most obvious rationale for pursuing a study of high-speed machining (HSM) is the promise of increased MRR, which is the product of surface speed, depth of cut, and feed rate. While HSM generally means high surface speed, most practical applications also require some minimum chip load and this means a feed rate above a minimum value. A speed above which shear-localization develops completely in the primary shear zone is known as high-speed. For the creation of such type of shear localization, a huge amount of heat generates at the chip tool interface, which leads a very high cutting temperature [**Kitagawa et al. 1997**]. This huge amount of cutting temperature not only reduces dimensional accuracy and tool life but also impairs the surface integrity of the product [**Chattopadhyay and Chattopadhyay 1982**]. The rapid wear rate of cutting tools due to high cutting temperature is a critical problem to be solved in HSM of hardened steels. In recent years, HSM technology is becoming matured owing to the advance of machine tool and control system. In comparison with the conventional methods, HSM not only exhibits a higher metal removal ate but also results in lower cutting force, better surface finish, no critical heat of the workpiece, etc.

Reduction of finishing operations, elimination of part distortion, achievement of high metal removal rates and lower machining costs as well as improved surface integrity are some great advantages of HSM. It can also be used when huge temperature and stress are required at the position of tool-workpiece interface. Still cost effective application of this technology requires a fundamental understanding of the relationships between process variables. So the understanding of how amount of temperature and stress are produced during machining operations. This will really reduce the requirement of time and cost [**Sekhon and Chenot 1993**]**.**

The places where high speed looks intricate in action, there depth of cut can be a good solution. This can be accomplished only with a high-power, adequately rigid machine tool. The part should also be stiff enough to yield the required accuracy and finish under these cutting conditions. All these experiments have given a proof and undoubtedly accepted in modern time that HSM has a good efficiency in cost, time and accuracy.

1.2 Machining under Cryogenic Cooling Condition

Cryogenics is the field related to technology at deep freezing temperatures. Traditionally, the field of cryogenics is taken to start at temperatures below -196°C. The definition includes the more common cryogenics such as helium, hydrogen, neon, nitrogen, oxygen, argon, krypton, xenon, methane, ethane, and propane. Carbon dioxide is commonly added to the list even though a pressure over 50 KPa is required to maintain it in liquid form. Even the term "cryogenics" seem like an esoteric field, it plays a major role in modern industry and science. Some of the applications are: air separation plants for breaking it down into its components for industrial and medical uses, liquefied helium has become unavoidable cooling element of magnetic resonance imaging systems in modern hospitals, in space technology where cryogenics are through the liquefied hydrogen and oxygen used as fuels, food freezing and cooling, purging and blanketing, etc.The beginning of cryogenic is going back in the beginning of the nineteenth century where there was a “race" in liquefying gases and reaching ever lower temperatures. This started with the announcement of the liquefaction of oxygen by Pictet and Cailletet [**1887**]. James Dewar [**1898**] first liquefied hydrogen. He also developed the vacuum-insulated flask for containing cryogenic liquids that are still frequently used and are called "Dewars". The last and most difficult gas to be liquefied was helium, liquefied by **Kamerlingh Onnes of Lieden** [**1908**]. As a twentieth century progress, industrial application of cryogenics increased, particularly in the area of air liquefaction and industrialization.

The most practical and effective way to enhance the machining performance in cutting difficult-to-cut materials is to reduce the cutting temperature. One way of reducing the cutting temperature is to use a cutting coolant. Cutting fluids are used in conventional machining to extend tool life by reducing tool temperature and friction between the tool, the chip and the workpiece in the cutting process. However, conventional coolants contain different chemicals that may cause water pollution, soil contamination and health problems if disposed without required treatments. Another way of reducing the cutting temperature is to use a cryogenic coolant. In Cryogenic machining, liquid nitrogen (LN_2) is used as a coolant, is considered a viable option to conventional machining. Having a temperature as low as −196 °C at 101.325 KPa, super cold LN_2 is a good coolant. After absorbing the heat dissipated from the cutting process, it evaporates into nitrogen gas and becomes part of the air (79% of the air is nitrogen). It leaves no harmful residue to the environment. Therefore, it is considered to be environment friendly due to this natural recycling.

Wang et al. [**1996**] have carried out turning of ceramics (Si_3N_4) with polycrystalline cubic boron nitride (PCBN) under cryogenic cutting conditions and reported that liquid nitrogen cooling system reduced the cutting tool temperature and tool wear over dry machining. Hong and Ding [**2001**] conducted an experiment with various cooling approaches in cryogenic machining of Ti-6Al-4V. Temperatures in cryogenic machining were compared with conventional dry cutting and emulsion cooling. It was showed that a small amount of liquid nitrogen applied locally to the cutting edge is superior to emulsion cutting in lowering the cutting temperature. Hong et al. [**2001**] have carried out experimental investigation into the role of cryogenic cooling by liquid nitrogen on friction and cutting force in machining of Ti-6Al-4V. The experimental results indicated that cutting force was increased in cryogenic machining. It was also found that the friction coefficient on the tool-chip interface was considerably reduced in cryogenic machining. Dhar et al. [**2002**] involved experimental investigation of cryogenic cooling on tool wear, surface roughness and dimensional deviation in turning of AISI 4140 steel by two different geometries of carbide inserts. Substantial benefit of cryogenic cooling on tool wear, surface roughness and dimensional deviation was reported. Dhar and Kamruzzaman [**2007**] conducted an experiment on cryogenic machining and stated that benefits of cryogenic cooling are mainly by substantially reducing the cutting temperature, which improves the chip-tool interaction and maintains sharpness of the cutting edge and also shows better surface finish and higher dimensional accuracy as compared to dry and wet machining.

Paul et al. [**2006**] investigated the tool wear and tool life of carbide inserts in turning of Ti-6Al-4V alloy under dry, wet and cryogenic environment. It was found that tool wear parameters are less in cryogenic environment. Ahmed et al. [**2007**] conducted the experiment in cryogenic machining of AISI 4340 steel with modified tool holder. Two different flow outlets were tested for this modified tool holder. It was found that this modified tool holder for cryogenic cooling is more effective when the coolant out flow is directed away from the cutting edge of the carbide insert. Kumar and Choudhury [**2008**] studied the effect of cryogenic cooling on tool wear and high frequency dynamic cutting forces generated during high speed machining of stainless steel. It was showed that cryogenic cooling was effective in bring down the cutting temperatures that attributed for the substantial reduction of the flank wear. The main functions of cryogenic machining include (i) removing heat effectively from the cutting zone, hence lowering cutting temperatures, (ii) modifying the frictional characteristics at the tool/chip interfaces, and (iii) changing the properties of the workpiece and the tool material [**Uehara et al. 1970**].

In cryogenic machining, different cooling strategies are needed in order to solve the problems specific to the individual materials being machined. These strategies, which this may serve different purposes, include:

i) freezing the workpiece
ii) delivering the cryogen to the tool/chip or tool/work interface,
iii) cooling the cutting tool and chip

To choose cooling strategies, the properties of both the tool materials and the workpiece materials must be considered because they are fundamental in determining the machining characteristics. The desirable properties of tool materials generally include high hardness and wear resistance, high toughness and strength to resist various forms of fractures, and low chemical affinity with the workpiece. Properties of the workpiece materials become problematic when their hardness and strength are abrasive to cutting tools and these properties cause a high compressive stress to act on the cutting edge, raising the cutting temperatures. The materials' ductility and toughness affect the chip formation process. Highly ductile materials, for instance, are likely to produce continuous chips and built-up edges [**Hong et al. 1999 and Yildiz et al. 2008**].

Cryogenic machining of stainless steel, which is equivalent to AISI 304, has been studied in Japan. And it was reported that the cutting force was increased as the workpiece temperature was decreased to cryogenic temperatures [**Uehara et al. 1968**]. A milling study by Dillon et al. [**1990**] reported an increased difficulty in machining AISI 304 at reduced temperatures. Therefore, AISI 304 is considered to be a poor candidate for successful cryogenic machining. It was stated that if a new cryogenic cooling approach could provide effectiveness in machining this material, it would prevail in cutting other materials.

1.3 Literature Review

1.3.1 Effects of Conventional Cutting Fluids

A cutting fluid can be defined as any substance which is applied to a tool during a cutting operation to facilitate removal of chips. Cutting fluids have been used extensively in metal cutting operations for the last 200 years. In the beginning, cutting fluids consisted of simple oils applied with brushes to lubricate and cool the machine tool. Occasionally, lard, animal fat or whale oil was added to improve the oil's lubricity. As cutting operations became more severe, cutting fluid formulations became more complex. Today's cutting fluids are special blends of chemical additives, lubricants and water formulated to meet the performance demands of the metalworking industry.

The application of cutting fluids is another alternative to obtain higher material removal rates. Cutting fluids have been used widespread in all machining processes. However, because of their damaging influences on the environment, their applications have been in machining processes. New for elimination of cutting fluids application in machining processes has been examined and "dry machining" was presented as a important solution. The development of new cutting tool materials also helped dry machining method to be a positive solution for cutting fluids applications. However, the usage of cutting fluids has been increased due to high production levels in the world. According to Values [**1998**], $2.3x10^9$ liter cutting fluids have been used in the machining operations and its cost value was around \$ $2.75x10^9$. First study about cutting fluids had been determined by Northcott [**1868**]. In the middle of 1890's, F.W. Taylor emphasized that using cutting fluids would allow to use higher cutting speeds resulting in longer tool life and higher material removal rates. It had been concluded that the application of cutting fluids in machining processes would make shaping process easier. In this study, the studies about cutting fluid application in processes have been evaluated. The selection criteria of cutting fluids have been examined. Suitable cutting fluids for various material machining processes have been determined according to cutting tool materials. The cutting fluids applied in machining processes basically have three characteristics. These are:

i) cooling effect
ii) lubrication affect
iii) taking away formed chip from the cutting zone

The cooling effect of cutting fluids is the most important parameter. It is necessary to decrease the effects of temperature on cutting tool and machined workpiece. Therefore, a longer tool life will be obtained due to less tool wear and the dimensional accuracy of machined workpiece will be improved. The lubrication effect will cause easy chip flow on the rake face of cutting tool because of low friction coefficient. This would also result in the increased by the chips. Moreover, the influence of lubrication would cause less built-up edge when machining some materials such as aluminum and its alloys. As a result, better surface roughness would be observed by using cutting fluids in machining processes. It is also necessary to take the formed chip away quickly from cutting tool and machined workpiece surface. Hence the effect of the formed chip on the machined surface would be eliminated causing poor surface finish. Moreover part of the generated heat will be taken away by transferring formed chip.

1.3.2 Effects and Control of Cutting Temperature

Due to the excessive heat at the interface of tool-workpiece, the strength, hardness, stiffness and wear-resistance of the cutting tool are affected even the tool becomes soften goes through plastic deformation and as a result the dimension of the tool becomes changed and eventually results tool failure. So there is a great impact of tool-chip temperature on the rate of tool wear [**Usui et al. 1978**]. High temperatures at the tool–chip interface result in an increase of diffusion and chemical wear [**Endrino et al. 2006**]. The high specific energy required in machining under high cutting velocity and unfavorable condition of machining results in very high temperature [**Chattopadhyay and**

Chattopadhyay 1982, Singh et al. 1997]. At elevated temperature and pressure the cutting edge deforms plastically and wears rapidly, which lead to dimensional inaccuracy, increased cutting forces and premature tool failure [**List et al. 2005**]. Increasing cutting forces result the increase of power consumption. Tool wear and increased heat can induce thermal damage and metallurgical changes in the machined surface. The experimental results show that tool wear is a dominant factor affecting the values of induced residual stress, strain, subsurface energy, and the quality of the machined surface. The increase of tool wear caused an increase of residual stress and strain beneath the machined surface. It was also found that the overall energy stored in the machined subsurface increases as the tool wear increases and as the tool surface gets rougher. Rapid increase in notching occurs on carbide tools at higher cutting speed which usually leads to the premature fracture of the entire insert edge [**Ezugwu and Bonney 2004**]. Flank wear causes an increase in the cutting force and the interfacial temperature, leading normally to dimensional inaccuracy in the work pieces machined and to vibration which makes the cutting operation less efficient [**Bouzid et al. 2004**].

Innately high cutting zone temperature is generated at high production (high speed-feed rate). Uncoated carbide insert creates more cutting temperature than coated insert when turning different steels **[Sultana et al. 2009]**.Turning difficult to cut materials (Stainless steel, Titanium, Inconel etc.) using existing conventional techniques is an un-economical as the turning process results in high tool wear, takes longer time and require high cutting force [**Khan and Ahmed 2008**]. The generation of heat was very high while turning these materials due to strong adhesion between the tool and work material resulting from their low thermal conductivity, high work hardening rate, high viscosity, high reactivity, tendency to form built-up-edge (BUE) at tool edge compared to other alloy steels. 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 and it was observed by Vleugels [**1995]**. Strafford and Audy [**1997**] investigated the relationship between hardness and machining forces during turning of AISI 4340 steel with mixed alumina tools. The results suggest that an increase in hardness leads to an increase in the machining forces. Liu et al**.** [**2002**] observed that the cutting temperature is optimum when the work piece material hardness is HRC 50. With further increase in the work piece hardness, the cutting temperature shows a descending tendency. Liu et al. [**2002**] also suggests that, under different cutting parameters, the role of cutting force changes with work piece hardness. The main cutting force features an increasing tendency with the increase of the work piece hardness.

The hardness, plastic modulus and the fracture toughness of the tool decline with increase in cutting temperature, which accelerates tool wear rate was observed by Reed and Clark [**1983**]. Moreover, thermal stresses in the tool increase with the temperature resulting in more cracks in the tool and premature failure of the tool. The amount of energy dissipated through the rake face of the tool raises the temperature at the flanks of the tool [**Wu and Matsumoto 1990**]. The cutting temperature and force are tried to be controlled or reduced to some extent by

i) appropriate selection of process parameters
ii) appropriate selection of cutting tool geometry
iii) proper selection of cutting tools and
iv) proper selection and application of cutting fluids

Appropriate selection of the levels of the process parameters (cutting velocity, feed rate and depth of cut) can provide better machinability characteristics of a given work-tool pair even without sacrificing productivity or MRR. Amongst the process parameters, depth of cut, plays least significant role and is almost invariable compared to feed (S_o) variation of cutting velocity (V_c) governs machinability more predominantly. Increase in V_c, in general, reduces tool life but it also reduces cutting forces or specific energy requirement and improves surface finish through favorable chip-tool interaction. Some cutting tools, especially ceramic tools perform better and last longer at higher V_c within limits. Increase in feed raises cutting forces proportionally but reduces specific energy requirement to some extent. Cutting temperature is also lesser susceptible to increase in S_o than V_c. But increase in S_o, unlike V_c raises surface roughness. Therefore, proper increase in V_c, even at the expense of S_o often can improve machinability quite significantly [**Sun et al. 2005**]. Hasçalık and Çaydaş [**2008**] showed that feed rate and cutting speed were the most influential factors on the surface roughness and tool life, respectively. The surface roughness was chiefly related to the cutting speed, whereas the axial depth of cut had the greatest effect on tool life.

The geometrical parameters such as; tool rake angles, clearance angle, cutting angles, nose radius, inclination angle and depth, width, form of integrated chip breaker of cutting tools significantly affect the machinability of a given work material under given machining conditions. Increase in tool rake angles reduces main cutting force through reduction in cutting strain, chip reduction coefficient. Presence of inclination angle enhances effective rake angle and thus helps in further reduction of the cutting forces. The variation in the principal cutting edge angle influences feed force and the cutting temperature quite significantly. Feed force, if large, may impair the product quality by dimensional deviation and roughening the surface due to vibration. Inadequate clearance angle reduces tool life and surface finish by tool-work rubbing, and again too large clearance reduces the tool strength and hence tool life. Proper tool nose radius improves machinability to some extent through increasing in tool life by increasing mechanical strength and reducing temperature at the tool tip. Thus it reduces the surface roughness. Proper edge radius also often enhances strength and life of the cutting edge without much increase in cutting forces.

What the work material is not the factor, the cutting tool plays a significant role on the performance of the conventional machining operation. For instance, alterations in the cutting edge preparation will result in changes in tool wear rate, cutting forces, temperature, and machined surface finish. The results indicated that, in general, the turning force components are reduced with the tool nose radius and the specific cutting force decreased as feed rate is elevated, presenting values comparable to metallic alloys. Finally, for the elevation of feed rate and reduction of the nose radius the surface roughness will be increased [**Leonardo and Davim 2009**]. Tool geometry is another important factor affecting machining forces, above all the feed (axial) and thrust (radial) force components [**Thiele and Melkote 1999**]. The use of large nose radius together with low depths of cut lead to low true side cutting edge angle values, thus resulting in high thrust forces [**Muller and Blumke 2001**]. Rahman et al. [**1997**] investigated the machinability index of Inconel 718 subjected to various machining parameters including tool geometry, cutting speed and feed rate on flank wear, surface roughness and cutting force as the performance indicators for tool life. They observed that tool life increases with the increase in side cutting edge angle for the inserts and the heat generated during the cutting process is distributed over a greater length of cutting edge. This improves the heat removal from the cutting edge, distributes the cutting forces over a larger portion of the cutting edge, reduces tool notching and substantially improves tool life.

Ezugwu and Tang [**1995**] have shown that most of the major parameters including the choice of tool and coating materials, tool geometry, machining method, cutting speed, feed rate, depth of cut, lubrication, must be controlled in order to achieve adequate tool lives and surface integrity of the machined surface. In machining a given material, the tool life is governed mainly by the tool material which also influences cutting forces and temperature as well as accuracy and finish of the machined surface. The composition, microstructure, strength, hardness, toughness, wear resistance, chemical stability and thermal conductivity of the tool material play significant roles on the machinability characteristics though in different degree depending upon the properties of the work material. High wear resistance and chemical stability of the cutting tools like coated carbides, ceramics, cubic boron nitride (CBN) etc also help in providing better surface integrity of the product by reducing friction, cutting temperature and BUE formation in high speed machining of steels. Very soft, sticky and chemically reactive material like pure aluminium attains highest machinability when machined by diamond tools.

Two of great important materials cubic boron nitrate (CBN) and polycrystalline diamonds (PCD) cutting tools have been found important place in machining processes. Cubic boron nitride can maintain its hardness and resistance to wear at elevated temperatures and has a low chemical reactivity to the chip/tool interface [**Narutaki and Yamane 1979**].

The basic purposes of employing cutting fluid are to improve machinability characteristics of any work-tool pair through improving tool life by cooling and lubrication, reducing cutting forces and specific energy consumption and improving surface integrity, size accuracy by cooling, lubricating and cleaning at the cutting zone in metal cutting process. Cutting fluids also make chip-breaking and chip-transport easier. For reducing the cutting zone temperature through cooling and lubricating action a copious amount of fluid is flushed into the cutting zone to facilitate heat transfer from the cutting zone. Lubricants reduce friction and coolants effectively reduce high cutting temperature of tools/work pieces. It can flush chips away from the cutting zone, protect the machined surface from environmental corrosion and these factors improve tool life and help make a better more efficient cut [**Beaubien and Cattaneo 1964**]. On the other hand, using a cutting fluid may cause the material to become ‘curly’, which concentrates the heat closer to the tip. This is detrimental because it decreases the tool’s life. Some conditions like machining steels by carbide tools, the use of coolant may increase tool wear [**Paul et al. 2001**] though it can reduce temperature. In case of high speed-feed machining, which inherently generated high cutting zone temperature, cutting fluid can't reduce the temperature because fluid can't reach to the chip-tool interface [**Dhar et al. 2002**]. The favorable roles of cutting fluid application depend not only on its proper selection based on the work and tool materials and the type of the machining process but also on its rate of flow, direction and location of application. Proper selection and application of cutting fluid generally improves tool life. At low cutting speed almost four times longer tool life was obtained by such cutting fluid [**Satoshi et al. 1997**] but not improve significantly.

As conventional cutting fluids have some technological problems, additional cutting fluid systems are needed in industry to deliver fluid to the cutting process, re-circulate fluid, separate chips and collect fluid mist. Moreover, for using cutting fluid environment becomes polluted. Because, for improving the lubricating performance Sulfur (S), Phosphorus (P), Chlorine (Cl) or other pressure additives are mixed with cutting fluid [**Peter et al. 1996**]. If the cutting fluids are not handled appropriately, it may damage soil and water resource, which can cause serious environment pollution. Sokovic and Mijanovic [**2001**] have shown additionally, in the factory cutting fluid may cause skin and breathing problem of the operator. In flood cooling method, fluid is used in very large amount (6-10 l/hr). The cost associated with the use of cutting fluid is estimated to be about 16% to 20% of the total manufacturing costs [**Byrne and Scholta 1993, Brockhoff and Walter 1998**], where only 4% of the total manufacturing cost is associated with cutting tools [**Aronson 1995**]. So, in respect of costs, it is very important to reduce the amount of cutting fluid. Some conditions like machining steels by carbide tools, the use of coolant may increase tool life. In flood cooling method, fluid is used in very large amount (6-10 l/hr. So, in respect of costs, it is very important to reduce the amount of cutting fluid. Some conditions like machining steels by carbide tools, the use of coolant may increase tool wear [**Paul et al. 2001**].

Furthermore coolants and lubricants incur a significant part of the manufacturing cost. For instance in the production of camshafts in European automotive industry, the cost of coolants/lubricants constituted 16.9% of the total manufacturing cost, while the cost of tools was 7.5%. That is, the cost of purchase, storage, care and disposal of coolants are two times higher than the cost of tool. So, from the standpoint of cost, ecological and human health issues, manufacturing industries are now being forced to implement strategies to reduce the amount of cutting fluids used in their production lines [**Klocke 1997**]. Though dry machining takes the place [**Sreejith and Ngoi 2000, Popke et al. 1999**], but not being permanent because sometimes dry machining cannot show better performance if higher machining efficiency, better surface finish and other special cutting conditions are required. For these reasons many special techniques can be used as alternative of the traditional flood cooling method. Such as, mist lubrication system by water based fluids, cryogenic machining where nitrogen and carbon dioxide are used as a coolant, near-dry cooling/ minimum quantity lubrication (MQL) system with the application of a mist of a mixture of water and cutting fluid, high-pressure coolant (HPC) system, Coolant through the cutting tool system which allows a direct route for the coolant to the hot area. All these methods are proved as good for tool life, good for the environment.

Cryogenic machining with liquid nitrogen has improved machinability of steel to a certain extent in case of turning, grinding, milling, drilling operations. In high production machining, where conventional cutting fluids are ineffective in controlling the high cutting temperature, force, tool wear, dimensional accuracy and surface finish; cryogenic machining where the cutting tool is chilled by liquid nitrogen jets enhances tool hardness shows better effectiveness [**Paul and Chattopadhyay 1995**]. Favorable chip-tool and work-tool interactions can be achieved by this technique. Cooling the chip makes it brittle and aids removal. Moreover, by cryogenic cooling environmental pollution is reduced and it also helps in getting rid of recycling and disposal of conventional fluids [**Paul et al. 2000, Paul et al. 2001, Dhar et al. 2002, Dhar and Kamruzzaman 2007**].

If the coolant is applied at the cutting zone through a high speed nozzle, it could reduce the contact length and co-efficient of friction at chip-tool interface then cutting force and temperature may be reduced and tool life can be increased [**Mazurkiewicz et al. 1998, Kumar et al. 2002**]. Cryogenic is often the great solution to get 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. 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 condition in machining process as one of the viable alternative instead of using conventional coolant.

1.3.3 Modeling of Cutting Temperature

The importance of cutting temperature and to control it is great concern to examine both in practical and theoretical fields. The role of the cutting temperature in metal cutting has been studied in great detail, beginning as early as 1907 by Taylor. Since the early twentieth century, much of the work on the thermal aspects of metal cutting has been directly experimental, providing mostly temperature in an average sense. These works can be categorized as thermo-e.m.f (thermocouples), radiation (pyrometry, infrared photography, etc.) and thermo chemical reactions (thermo-colors) **[Barow, 1973]**. Other experimental methods have included the metallographic method [**Wright, et al 1973**] and the physical vapor deposition (PVD) in the method [**Kato et al, 1973**], to name just a few. Alternatively, the reverse estimation scheme has been tried to solve the cutting temperature problem based on the indirectly measured temperature information [**Yen et al, 1986**].

Numerical methods were also applied to determine the temperature distribution with some important results documented by Dawson and Malkin [**1984**]. On analytical modeling, the steady state temperature in metal cutting has been estimated by Hahn [**1951**], Trigger and Chao [**1951, 1953, 1955, 1958**], Loewen and Shaw [**1953**], Komanduri and Hou [**2000, 2001**] and most recently by Huang and Liang [**2002**] based on the premise of a moving heat source. This better understanding of the temperature distribution along the tool-workpiece interface at the presence of tool wear helps to provide insight into several important issues in metal cutting, such as tool wear progression, dimensional tolerance and workpiece surface integrity, etc. Unfortunately, most of the analytical studies documented thus far focus on thermal modeling only for a fresh tool, except that of Chao and Trigger [**1958**].

Usui et al. [**1978**] and Tlusty and Orady [**1981**] used the finite difference method to predict the steady-state temperature distribution in continuous machining by utilizing the predicted quantities, such as chip formation and cutting forces, through the energy method. The predicted temperatures were lower than the observed ones near the cutting edge and the chip leaving point. They correlated the crater wear of carbide tools to the predicted temperature and stresses in the tool. Smith and Armarego [**1981**] have predicted temperature in orthogonal cutting with a finite difference approach. Ren and Altintas [**2000**] applied a slip line field solution proposed by Oxley [**1989**] on high speed orthogonal turning of hardened mold steels with chamfered carbide and CBN tools. They evaluated the strain, strain rate and temperature dependent flow stress of the material, as well as the friction field at the rake face-chip contact zone from standard orthogonal cutting tests conducted with sharp tools. They showed a good correlation between the maximum temperature on the rake face and crater wear, which led to the identification of cutting speed limits for an acceptable tool life limits.

Strenkowski and Moon [**1990**] have developed an Eulerian finite element model to simulate the cutting temperature. This Eulerian formulation of the cutting model requires a constitutive law between the viscosity, second invariant of the strain rate tensor and uni-axial yield stress. An iterative computational scheme is also required for the solution. Numerical solutions, especially Finite Element (FE) methods require accurate representation of material's constitutive properties during machining. However, since the strain rates and strains are several magnitudes higher than those evaluated from standard tensile and Hopkinson's bar tests, FE methods mainly suffer due to lack of accurate material models. Shatla et al. [**1999**] used the material properties evaluated from orthogonal cutting and milling tests in the FE simulation of metal cutting. He reported improvements in predicting the temperature and cutting forces in both continuous turning and transient milling operations using a Finite Element method. There has been less research reported in the prediction of tool temperature in milling, where the chip thickness vary continuously, and the process is intermittent (i.e., the tool periodically enters and exits the cut). As a result, the shear energy, shear angle, and the friction energy changes continuously with time. Hence, the process does not stay in steady-state equilibrium like in continuous machining operations.

A model for the analytical calculations of average tool–chip interface temperature has been developed by McFeron and Chao [**1958**] for the plain peripheral milling process. They have instrumented a face mill with a thermocouple to measure the average transient temperature on the rake face of a carbide tool. Stephenson and Ali [**1992**] analyzed a special case of interrupted cutting with constant chip thickness. They have developed a model by considering a semi-infinite rectangular corner heated by a time varying heat flux with various spatial distributions to predict the average temperature on the rake face. They concluded that tool temperatures are generally lower in interrupted cutting than in continuous cutting under the same condition since temperature is dependent primarily on the duration of heating cycle and secondarily on the length of cooling time between cycles. Their analysis quantitatively underestimates the temperatures for short heating cycles.

A great work has been presented by Stephenson et al. [**1997**] on temperature prediction in contour turning. Redulescu and Kapoor [**1994**] analyzed the tool-chip interface temperature by solving the heat conduction problem with prescribed heat flux. The mechanistic force model was utilized in this analysis. Their results also indicate that the tool–chip interface temperature increases with cutting speed for both continuous and interrupted cutting. Jen and Lavine [**1994**] used a similar approach to Redulescu for tool temperature calculation and improved calculation speed relatively by using power law approximation for the exponential terms. For further information on the literature review and on methods to calculate the machining temperature, the publication by Tay [**1993**] is recommended. One of the biggest challenges in this research area is the lack of the experimental data to verify the mathematical models proposed in predicting the tool temperature. It is rather difficult to embed sensors close to the cutting edge. Infra-red temperature sensors provide average readings from the entire cutting zone. When the cutting is time varying like in milling, it is more challenging to put even simple sensors close to the cutting edge of the rotating tool. Most published articles rely on the few published experimental data from Trigger and Chao [**1951**], Boothroyd [**1963**] and Stephenson and Ali [**1992**].

A mathematical modeling using finite element method to predict the temperature and the stress distributions in micromachining has been presented by Kim et al. [**1999**]. The diamond cutting tool is used to machine the work material oxygen-free-high-conductivity copper (OFHC copper) and its flow stress is taken as a function of strain, strain rate and temperature in order to reflect realistic behavior in machining process. From the simulation, a lot of information on the micro-machining process like the effects of temperature and friction on micro-machining are investigated.

A numerical model based on the finite difference method is presented by Lazoglu and Altintas [**2002**] to predict tool and chip temperature fields in continuous machining and time varying milling processes. Continuous or steady state machining operations like orthogonal cutting are studied by modeling the heat transfer between the tool and chip at the tool-rake face contact zone. The shear energy created in the primary zone, the friction energy produced at the rake face-chip contact zone and the heat balance between the moving chip and stationary tool are considered. The temperature distribution is solved using the finite difference method. Later, the model is extended to milling where the cutting is interrupted and the chip thickness varies with time. The proposed model combines the steady-state temperature prediction in continuous machining with transient temperature evaluation in interrupted cutting operations where the chip and the process change in a discontinuous manner. Heat balance equations were determined in partial differential equation forms for the chip and for the tool. The finite difference method was utilized for the solutions of the steady-state tool and chip temperature fields. The simulation results both for continuous and interrupted machining processes agreed well with experimentally measured temperatures for different materials under various cutting conditions. The proposed algorithm can be utilized in selecting cutting speed, feed rate and tool rake and clearance angles in order to avoid excessive thermal loading of the tool, hence reducing the edge chipping and accelerated wear of the cutting tools. The mathematical models and simulation results are in satisfactory agreement with experimental temperature measurements reported in the literature.

Sundaram et al. [**2003**] investigated the influence of various grinding parameters like wheel speed, work speed and depth of cut on the grinding temperature at the surface of the Al-Si-C-P composite workpiece with different grinding wheels. The temperature distribution within the workpiece was studied by simulating the grinding process and using finite element analysis package with transient thermal analysis. Specific energy as the input, the temperature distribution for dry grinding condition and with coolant was analyzed. Even though partition ratio is lower for diamond, but the temperature developed at the surface is more for diamond compared with other wheels. The affinity to wheel loading is more for diamond wheels than other wheels. The CBN shows better results than other wheels. The influence of coolant is significant.

A proposition was given by Grzesik and Nieslony [**2004**] about physics based modeling concept has been applied to both the individual layer and the composite layer approach to develop an estimate of the average and the maximum steady-state chip-tool interface temperatures in orthogonal turning. Different approaches for determining the heat partition coefficient for sliding bodies of defined thermal properties were tested.

Attia and Kops [**2004**] developed a novel approach to cutting temperature prediction in multi-layer coated cutting tools. This approach is not based on the commonly used assumption of perfect contact at the tool-chip interface, but rather the contact mechanics at asperity level and the resulting thermal constriction resistance. A Micro-contact model was developed, and the correlation between the contact pressure and the thermal contact resistance of uncoated and multi-layer coated tools is established. The model was validated against analytical and experimental data. The thermal interaction and redistribution of heat between the workpiece, the chip and the tool were analyzed, supported by FE model, which considers thermal characteristics of multi-layer coating. It was found that coating causes reduction of the heat flow into the tool and reduction of the maximum temperature rise. These reductions can reach more than 50% and 120ºC, respectively. The importance of the present approach lies in the fact, that it can be used with a higher degree of confidence for the design of coated tools and other related issues, such as e.g. wear.

A FEM simulation model in order to obtain numerical solutions of the cutting forces, specific cutting energy and adequate temperatures occurring at different points through the chip/tool contact region and the coating/substrate boundary for a range of coated tool materials and defined cutting conditions was created by Grzesik et al. [**2005**]. Commercial explicit finite element code Third wave ADVANTEDGE has been used in simulations of orthogonal cutting processes performed by means of uncoated carbide and coated tools. The various thermal simulation results obtained were compared with the measurements of the average interfacial temperature and discussed in terms of various literature data.

A thermal model developed by Carvalho et al. [**2006**] which was about a numerical solution of the transient three-dimensional heat diffusion equation that considers not just the insert tip but also the shim and tool holder assembly. To determine the solution equation the finite volume method is used. Changing in the thermal properties with the temperature and heat losses by convection is also considered. Several cutting tests using cemented carbide tools were performed in order to check the model and to verify the influence of the cutting parameters on the temperature field.

Bareggi et al. [**2007**] present approaches for modeling the cooling influence of high velocity air jets using a supersonic nozzle during metal cutting on a lathe with the commercial package DEFORM 3D. Here, simulation results are consistent with the analytical results from other researchers. Cutting temperatures estimated with deform 3D are consistent with simulation undertaken with ADVANTEDGE. While simulation offers insights into the process which are not easily measured in experiments, careful engineering scrutiny of approaches and results remains necessary.

A brief historical perspective on the development of orthogonal cutting model was followed by Soo et al. [**2007**], including key work by Merchant and Oxley and concentrates on the use of finite element techniques to simulate two-dimensional orthogonal turning and the subsequent transition to three-dimensional formulations, thus enabling milling and drilling to be realistically modeled.

By using finite element method, the results reported in the paper by Mamalis et al. [**2008**] pertain to the simulation of high speed hard turning. For the finite element modeling a commercial program, namely the Third Wave Systems ADVANTEDGE, was used. This program is specially designed for simulating cutting operations, offering to the user many designing and analysis tools. The orthogonal cutting models provide results such as workpiece and tool temperatures which were compared to experimental results from the relevant literature. The 3D oblique cutting models represent a situation where the chip deforms not in plane as in the ideal case of orthogonal cutting but in all three dimensions; a more realistic approach is, thus, provided. Nevertheless, these models are more complicated and require the use of much more elements increasing this way the effort and the computational time required for the analysis. From the analysis it can be concluded that the proposed models are practical, since only a minimum amount of experimental work is needed, and produce reliable results, allowing for industrial use in pursue of optimal production.

A quantitative analyze about heat transfer problem in the cutting tool in a steady-state orthogonal cutting when using uncoated carbide tools and the AISI 304 stainless steel as a work material was given by Grzesik and Bartoszuk [**2009**]. Finite difference approach (FDA) is applied to predict the changes of temperature distribution, and both average and maximum temperatures at the tool-chip interface, resulting from differentiating the heat flux configuration. It was found that the assumption of an asymmetrical trapezoidal shape of heat flux configuration, similar to the distribution of contact shear stress, provides the simulated results closer to the experimental data.

Artificial Intelligence (AI) based models are developed using non-conventional approaches such as artificial neural network (ANN), fuzzy logic (FL) and genetic algorithm (GA). Machining process is very complex and does not permit pure analytical physical modeling. Thus, experimental and analytical models also known as explicit (empirical) models are developed by using conventional approaches such as Statistical Regression technique with combination of response surface methodology (RSM) had remained as an alternative in mathematical modeling for machining processes. Although statistical regression technique may work well for machining process modeling, this technique may not describe precisely the underlying non linear complex relationship between decision variables and responses. Jiao et al. [**2004**] applied FL technique based on fuzzy adaptive network (FAN) model for surface roughness prediction in turning operation; concluded that FAN network can estimate many parameters and even tune the network structure and thus is much more powerful than the usual multiple variables regression analysis. Jian and Ongxing [**2003**] in their work, focusing on modeling the system error of workpiece under cutting tool setting based on GA technique; presented that GA based method was better than the regression-modeling method in terms of accuracy and generalization ability. Recently, AI based models have become the preferred trend which are applied by most researchers to develop model for near optimal conditions in machining process. However, difference techniques labeled as AI may be suitable and could work well in certain modeling problems. Thus, this paper discusses the abilities, limitations with the applications of ANN technique in the modeling stage in order to find the optimal conditions in machining process. The features of the modeling approach and their application potentials are concluded based on the machining processes. The following section discusses one of the three non conventional approaches listed above, i.e. ANN technique to be used in developing the prediction models to predict the values of decision variables and responses in machining process.

1.3.4 Modeling of Cutting Forces

It is very significant to study the various approaches for simulating cutting forces in orthogonal and oblique cutting operations since they give a clear overview of the modeling of forces in any machining operation. Typical approaches for numerical modeling of metal cutting are Lagrangian and Eulerian techniques. Lagrangian techniques, the tracking of discrete material points, have been applied to metal cutting [**Sehkon and**

Chenot 1993, Obikawa and Usui 1996, Obikawa et al. 1997]. Techniques typically used a predetermined line of separation at the tool tip, propagating a fictitious crack ahead the tool. This method precludes the resolution of the cutting edge radius and accurate resolution of the secondary shear zone due to severe mesh distortion. To alleviate element distortions, others used adaptive re-meshing techniques to resolve the cutting edge radius [**Sehkon and Chenot 1993, Marusich and Ortiz 1995**]. Eulerian approaches, tracking volumes rather than material particles, did not have the burden of rezoning distorted meshes [**Strenkowski and Athavale 1997**]. However, steady state free-surface tracking algorithms were necessary and relied on assumptions such as uniform chip thickness, precluding the modeling of milling processes or segmented chip formation.

Chip formation, cutting temperatures, tool stresses and cutting forces from finite element method (FEM) simulations were predicted by Özel et al. [**1998**]. The experiments were conducted in a horizontal high speed milling center to measure cutting forces. Predicted cutting forces and chip shapes were compared with experimental results.

A methodology has been developed by Ozel and Altan [**2000**] for simulating the cutting process in flat end milling operation and predicting chip flow, cutting forces, tool stresses and temperatures using finite element analysis (FEA). As an application, machining of P-20 mold steel of hardness 30 HRC using uncoated carbide tooling was investigated. Using the commercially available software DEFORM-2D, previously developed flow stress data of the workpiece material and friction at the chip–tool contact at high deformation rates and temperatures were used. Comparisons of predicted cutting forces with the measured forces showed reasonable agreement and indicate that the tool stresses and temperatures are also predicted with acceptable accuracy. The highest tool stresses were predicted at the secondary (around corner radius) cutting edge.

The way of finite element modeling used by Marusich [**2001**], observed the influence of cutting speed and friction on cutting force. Simulations are validated by comparison of cutting forces and chip morphologies for the Al 6061-T6. Analysis of cutting forces over a wide range of cutting conditions suggests an important role of the secondary shear zone in the decrease of cutting force as a function of speed, even well into what is considered to be the adiabatic machining regime. The plan is supported by a decrease in chip thickness and significant increase in temperature at the tool-chip interface as the speed is increased. Temperatures in the primary shear zone rise only modestly and cannot account for the change in cutting force. Furthermore, the effect contributes to the nonlinear increase of forces with respect to feed as opposed to a plowing force by the cutting edge radius.

Patrascu and Carutasu [**2007**] presented a FEM model for 3D simulation of turning process with chip breaker tools. The model uses Oxley's machining theory to predict cutting forces for square inserts. Inserts were modeled with CATIA V5R8 and exported as STL files to import them in DEFORM 3D^{TM} software. A comparison made between predicted and experimental results shows good agreement.

The machining of aluminum T6061 alloys was presented by Otieno and Mirman [**2008**] by using a finite element analysis. The cutting forces and temperatures are predicted using Advantage Edge software. The results are used to guide machining operators to select machining conditions that produce favorable stresses on the tools, thus avoiding tool breakage. The preliminary results from this study can be used in an optimization process to determine optimum cutting conditions. Moreover, by studying the stresses in the tool material, it is possible to determine what the maximum recommended feeds and depths of cut should be forgiven cutting speeds.

The introduction of the use of molecular dynamics and dislocation theory as a link between nano-scale and meso-scale modules with the finite element method calculations serving as a bridge between the modules was carefully designed by Aly et al. [**2004**]. The purpose of this work is to fill the void between the nano-metric scale information required to model micro-cutting and the known macro-scale mechanical behavior of materials in metal cutting. The proposed study suggests several future perspectives for the use of alternative modules aiming to further our knowledge of material behavior modeling related to manufacturing processes.

The analytical models are based upon the theory of mechanics of cutting, orthogonal or oblique but they are complicated and mostly, they demand the a-prior knowledge of response magnitudes, as shear angle and friction angle [**Shaw 1989**].

In past, many researchers have investigated forces in metal cutting operations. Earlier cutting force models have been developed and simulated for orthogonal cutting operations by Merchant [**Merchant 1945**] who assumed the chip to be a rigid body held in equilibrium by the action of forces across the chip tool interface and shear plane. He also assumed that the shear plane angle would minimize the work done in cutting. 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 [**Lee and Shaffer 1945**] and slip line field theory [**Oxley 1989**]. Unfortunately, the solutions did not take into account factors such as flow stress varying with temperature, strain, and strain rate. Lee and Shaffer [**Lee and Shaffer 1951**] have applied slip line field theory to orthogonal metal cutting by assuming super plastic material behavior. Their solution required the construction of a slip-line field pattern and the shearing in the primary deformation zone is assumed to be concentrated on a narrow shear plane. Still neither of these models could incorporate the actual work piece behavior into the model structure in a realistic way. Therefore the predicted results were not quite in agreement with the experimental results obtained using different work piece material combinations. It is believed by Boothroyd [**1988**] that unique relationship of the form suggested by Merchant [**Merchant 1945**] or Shaffer [**Lee and Shaffer 1951**] for the prediction of shear and friction angle can never hold true for all materials. This is mainly due to the difference in the material properties, which have to be included into the relationship of shear plane and friction angle.

On the other hand, by using the 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 was presented by Oxley [**1989**]. Numerous researchers have applied or modified these two approaches to model the force profiles later in metal cutting. Furthermore, in order to generalize the modeling approach, a modified Johnson-Cook equation is applied in the chip formation model to represent the workpiece material properties as a function of strain, strain rate, and temperature.

Wright [**1982**] has attempted to include the work material strain hardening properties obtained through tension tests in calculating the shear plane and friction angle. However Bagci [**1973**] has shown that unless the secondary shear zone effects are included, Wright's [**1982**] model also would not hold for different combinations of tool geometries and work materials. Accordingly Bagci [**1973**] has proposed an experimental correction factor to take into account different cutting conditions. Similar concepts have been applied by other researchers [**Baily and Bhavandia 1973, Black 1979, Yellowly 1985**]. However no model has yet been developed that can incorporate the work piece material properties into the machining models without requiring additional experimental cutting force data.

It can be appropriately incorporated work material properties into machining models by applying the more complicated plasticity theory. This requires that no specific form of deformation pattern be assumed prior to solution and work piece material properties should be known as to the ranges of strains, strain rates and temperatures generated during the cutting action. Several researchers have attempted to apply principles of plasticity theory in metal cutting. But there are several numerical and technical problems involved in plasticity applications to metal cutting operations. As a result of very high strains and strain rates, high temperatures are generated during the deformation and the material properties apparently change from isotropic to anisotropic. However it is very difficult to represent material properties at high ranges of strains, strain rates and temperatures that are involved in metal cutting, since the material testing methods at these ranges of operating conditions can only give qualitative results [**Baily and Bhavandia1973, Campbell 1973**]. Therefore the results obtained from the plasticity analysis would also be qualitative. Thus, to improve the accuracy of the solutions obtained using plasticity theory, material property relationships and material testing methods at high strains, strain rates and temperatures must be improved.

An analytical modeling was developed by Tulsty [**1975**] of the end milling operations. In this work analytical expressions for tangential and radial cutting forces are framed and later these force components are resolved into the feed and normal direction cutting forces at the center of the cutter. The analytical expressions thus obtained are evaluated and plotted for various combinations of the cutting parameters and were found to produce satisfactory results. But eventually this model when tried for Micro end milling operations didn’t produce accurate simulated cutting forces in coincidence with experimental cutting forces. Analytical cutting force model for end milling operation has been developed by Wang [**2002**] considering the shearing and ploughing mechanisms.

The primary and secondary heat sources’ thermal modeling, modification to Oxley’s predictive machining theory is made by Huang and Liang [**2003**] to model the metal cutting behaviors. Temperature distributions along the primary and secondary shear zones are modeled with the moving heat source method. To generalize the modeling approach, the modified Johnson-Cook equation is applied in the modified Oxley's approach to represent the workpiece material properties as the function of strain, strain rate, and temperature. Although the (modified) Johnson-Cook equation cannot capture blue brittle phenomenon and history effect, the prediction results from this study show that the Johnson-Cook equation works well as the material constitutive equation, at least within the normal machining condition range. The proposed approach describes the effect of tool thermal property on cutting forces and it can facilitate tool design and process optimization. The model predictions are compared to the published experimental process data of hard turning AISI H13 steel (52 HRC) when using the low CBN content tool and the high CBN content tool. The proposed model and FEM predict lower tangential and thrust forces and higher tool–chip interface temperature when using the lower CBN content tool.

Jianwen Hu et al. [**2008**] developed an analytical model for cutting force simulations in finish hard turning by a worn tool, which includes both chip formation and flank wear-land contact forces. Due to the 3D nature of the cutting zone, both the uncut chip area and wear-land contact are considered as numerous thin slices and individually analyzed for cutting forces modeling. Using coordinate transformations, cutting forces due to individual slices can be projected and further integrated from the lead to tail cutting edge to calculate three components of cutting forces. The methodology was applied to simulate process parameter effects on cutting forces. The radial component is the most sensitive force to the change of process parameters, especially, flank wear-land and tool nose radius. Among all parameters tested, flank wear-land shows the most dominant effects on cutting forces and its existence will also augment the effects of other parameters, for example, the tool nose radius.

Cutting forces as well as heat generation to the thermo-mechanical process the presence of flank wear-land accompanies additional. There seems to be two schools of thought. One reported that total cutting forces can be treated as consisting of two uncoupled parts: forces due to chip formation regardless of the tool sharpness, and forces due to flank wear alone [**Waldorf et al. 1998, Smithey et al. 2000, Smithey et al. 2001, Elanayar and Shin 1996**]. But some other researchers still doubt the efficacy of this decoupling property. Wang and Liu suggested that chip formation forces are affected by wear-land interactions [**Wang and Liu 1998, Wang and Liu 1999**]. Elanayar and Shin also studied cutting forces due to wear-land using an indentation force model [**Elanayar and Shin 1996**]. The authors also reported that wear-land effects on chip formation forces are insignificant. Huang and Liang have applied the worn tool model from [**Waldorf et al. 1998, Smithey et al. 2000, Smithey et al. 2001**], expanding to three dimensional cutting, to model wear-land forces in hard turning [**Huang and Liang 2004**]. Wang and Liu [**1998**] developed a method to decouple wear-land forces and chip formation forces. The authors further characterized wear-land effects on heat transfer of chip formation and part surface micro-structural alterations in orthogonal cutting [**Wang and Liu 1999**].

Linear, power and exponential functions are the classification of the semi-empirical expressions which contain different cutting factor related constants. The most established cutting force relationship although old is that proposed by Kienzle and Victor [**1957**], also known as the specific cutting resistance model; it will be considered in the following. Over the last years, empirical models for the machinability parameters in various machining processes have been developed using data mining techniques, such as statistical design of experiments (Taguchi method) [**Davim 2003**], response surface methodology, computational neural networks [**Luo et al. 1998**] and genetic algorithms [**Suresh et al. 2002**]. All these techniques are, more or less, ‘’black box’’ approaches but possess the advantage of providing the impact of each individual factor and factor interactions, after an appropriate design of the experiment. Especially, for the Taguchi and response surface methodology, a minimum amount of experimental trials is combined to a reliable global examination of the variables interconnection, instead of one- factor- at- a – time experimental approach and interpretation [**Ross 1988**]. Turning operations are widely used in workshop practice for applications carried out in conventional machine tools, as well as in NC and CNC machine tools, machining centers and related manufacturing systems. All three cutting force components are of interest because apart from the tangential component that gives the cutting power and its determination is apparently necessary, the radial and in-feed components control dimensional and form errors in case of workpiece and tool deflections and tool wear.

Experimental techniques should be employed to improve the accuracy of the force predictions when quantitative knowledge about metal cutting operations is required. If the results of the experimental methods are expressed in the equation, these methods are called empirical methods. Since any metal cutting process involves many variables, empirical techniques require large number of experiments to arrive at a credible model. Empirical models cannot be extrapolated outside the experimentally tested domain. However forces can be related to the mechanics of the operation through a set of experimentally obtained model parameters [**Shaw et al. 1952, Nigm et al. 1977, Ueda and Mastsuo 1986, Rosenberg and Rosenberg 1987**]. These model parameters would be functions of a smaller number of variables than forces, and thus require a smaller number of experiments to obtain the parametric relationships. For example, the cutting forces are a function of the radial and axial engagements whereas the model parameters may not be affected by these geometric cutting conditions. These types of models are commonly called mechanistic force models. These mechanistic model parameters can be selected in multiple ways. For instance, shear plane angle, shear strength, friction, pressure, chip flow angle, direction of friction force, radial, tangential and axial force components are some of the commonly used model parameters in the mechanistic force models. The accuracy of mechanistic force models depends upon the accuracy of the empirical parametric relationships obtained through experiments.

A predictive model for cutting force components in longitudinal turning of constructional steel with a coated carbide tool was developed Petropoulos et al. [**2005**]. Taguchi method is used for the plan of experiments and the analysis is performed using response surface methodology. Next, a related comparison is attempted to results obtained using the Kienzle-Victor cutting force model.

Wenge Song [**2006**] was developed the wear land force and edge force models are developed by in empirical form for force prediction purpose. The orthogonal cutting force model allowing for the effects of flank wear is developed and verified by the experimental data. A comprehensive analysis of the mechanics of cutting in the oblique cutting process is then carried out. Based on this analysis, predictive cutting force models for oblique cutting allowing for the effects of flank wear are proposed. The predictive force models are qualitatively and quantitatively assessed by oblique cutting tests. The modelling approach is then used to develop the cutting force models for a more general machining process, turning operation. By using the concept of an equivalent cutting edge, the tool nose radius is allowed for under both orthogonal and oblique cutting conditions.

Empirical models for tool life, surface roughness and cutting force are developed by Al-Ahmari [**2007**] for turning operations. Process parameters (cutting speed, feed rate, depth of cut and tool nose radius) are used as inputs to the developed machinability models. Two important data mining techniques are used; they are response surface methodology and neural networks. Data of 28 experiments when turning austenitic AISI 302 have been used to generate, compare and evaluate the proposed models of tool life, cutting force and surface roughness for the considered material.

A model to correlate the cutting parameters with cutting force, using response surface methodology was developed by Sarma et al. [**2008**]. The results indicate that the developed model is suitable for prediction of cutting forces in turning of GFRP composites. The effect of different parameters on cutting forces are analyzed and presented in this study.

Sharma et al. [**2008**] constructed a model of cutting forces using neural networks. The data cutting forces at different cutting parameters such as approaching angle, speed, feed and depth of cut obtained by experimentation is analyzed and used to construct the model. Then the models are compared for their prediction capability with the actual values. The model gave overall 76.4% accuracy.

The prediction accuracy by Ibraheem et al. [**2008**] was calculated using Genetic network technique of the cutting force values in this research when (GN) are used is 92%. Genetic network (GN) has proved to be a successful technique that can be used to predict the longitudinal cutting force produced in end milling.

A new approach to obtain the specific coefficients for a mechanistic model from virtual FEM models has been presented by Gonzalo et al. [**2009**]. The main objective is the elimination of the experimental machining test to characterize the specific cutting coefficients needed in the mechanistic milling models. Two ways to get coefficients have been proposed:

i) The direct way, with improved accuracy but high computational costs and
ii) The hybrid way through spatial conversions, less accurate but faster for successive tests due to the use of 2D orthogonal cutting models the results of both methods have been presented and discussed.

The two ways proposed provide the same precision for the calculation of milling forces. The use of numerical FEM models instead of experimental data for the calculation of specific cutting coefficients only introduces an additional error of 4% in the calculation of the cutting forces in milling operations.

Khidhir et al. [**2010**] described a modification approach applied to a fuzzy logic based model for predicting cutting force where the machining parameters for cutting speed ranges, feed rate, depth of cut and approach angle are not overlapping. For this study, data were selected depending on the design of experiments. Response surface methodology was applied to predict the cutting force and to examine the fuzzy logic based model. The modification approach fuzzy logic based model produced the cutting force data providing good correlation with response surface data. In this situation the cutting force data were superimposed and results were adjusted according to their own ranges.

1.4 Summary of the Review

A brief review of the literature on machinability of different commercial steels shows the detrimental effect of temperature at different condition. It is realized that the machining temperature has a critical influence on chip formation, cutting forces, tool wear and tool life. All these responses are very important in deciding the overall performance of the tool. 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. Machining under cryogenic condition is a promising technology in high speed machining, which economically addresses the current processes, environmental and health concerns. In this unique process as cutting fluid these types of fluids are used which make very cool the cutting tool to eliminate the possible detrimental effects. The success of implementing this technology across the metal removal industries is therefore depend on increased research activities providing credible data for in depth understanding of cryogenic condition in turning supplies at the chip-tool interface and integrity of machined components. The growing demands for high MRR, precision and effective machining of exotic materials is restrained mainly by the high cutting temperature. It is revealed from the abovementioned literature survey that the cutting temperature, which is the cause of several problems restraining productivity, quality and hence machining economy, can be substantially controlled by machining under cryogenic condition.

The relationship between a big group of input independent parameters like speed, feed and depth of cut and resultant performance in efficient quantitative and predictive models in terms of cutting temperature and force are required for the wide spectrum of manufacturing processes, cutting tools and engineering materials currently used in the industry could contribute in industrial applications along with theoretical understanding. This research aims to develop Predictive models for cutting temperature and force for turning medium carbon steel with uncoated carbide insert by industrially recommended process parameters under cryogenic condition. The proposed model is verified based on the published experimental data in terms of cutting temperature and force are required for the wide spectrum of manufacturing processes, cutting tools and engineering materials currently used in the industry could contribute in industrial applications along with theoretical understanding.

1.5 Scope of the Thesis

A brief review of the literature on machinability of different commercial steels shows the detrimental effect of temperature at different condition. It is realized that the machining temperature has a critical influence on chip formation, cutting forces, tool wear and tool life. All these responses are very important in deciding the overall performance of the tool. 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. Application of liquid nitrogen jet not only can provide environment friendliness but also substantial technological benefits have been observed in machining different steels by different inserts.

Chapter 1 presents the survey of previous work regarding general requirements in machining industries, effect of cutting temperature and controlling method of the cutting temperature, technological-economical-environmental problems associated with the conventional cooling practices and expected role of cryogenic cooling machining, various methodologies and recent techniques in analytical modeling of cutting temperature and forces have been considered. Basic ideas of the modeling of cutting force, cutting temperature, beneficial effects of liquid nitrogen are realized through the literature review.

Chapter 2 presents the procedure and conditions of the machining experiments carried out and the experimental results on the effects of cryogenic cooling, relative to dry machining, on chip formation, cutting zone temperature and cutting forces in turning 42CrMo4 steel by uncoated carbide insert (SNMG 120804).

Chapter 3 and **Chapter 4** provide development of an analytical model for cutting temperature at the chip-tool interface and cutting forces from the characterization of the physical processes taking place during machining and its validation. **Chapter 5** contains the detailed discussion on the experimental results and possible interpretations on the results obtained.

Finally, a summary of major contributions and recommendation for the future work is given in **Chapter 6** and **references** are provided at the end.

1.6 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 cryogenic cooling. 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 work, keeping in view the overall improvement in productivity and quality in machining 42CrMo4 steel by uncoated carbide insert (SNMG 120408) at different speeds and feed rates combinations under cryogenic and dry condition, are

a) Experimental investigation on the role of liquid nitrogen jet in respect of
    i) average chip-tool interface temperature
    ii) main cutting force and
    iii) feed force
b) Develop a mathematical model for cutting forces and cutting temperature from the characterization of the physical processes.
c) Validation of developed mathematical model.

Chapter-2

Experimental Investigations

2.1 Experimental Procedure and Conditions

Physical behavior during metal cutting has been changed based on cutting condition and work/tool material. For cost savings, increasing productivity and for preventing any hazard occurring to the machine, cutting tool or the deterioration of the product quality it is highly desirable to have an idea about the behavior of machining. For optimization of process parameters, the prediction of the relation of process responses such as cutting temperature, cutting forces, surface roughness and tool life with the process parameter is necessary. In this research work 42CrMo4 steel were turned on a lathe machine with uncoated carbide insert (SNMG-120408) at industrial cutting speed and feed combination under dry and cryogenic cooling conditions. The evolution of high cutting temperature during machining is one of the most critical and primary level response during turning which not only reduces tool life but also impairs the product quality. The temperature behaves proportionally with the increased values of cutting process parameters and increased strength and hardenability of the work piece materials. Another primary level machining response which directly relates the amount of cutting power requirements is cutting force. Chips morphology has also been studied in order to examine and relate cutting temperature and cutting force effects on chip's color, breakability and shear angle. Cutting fluids are widely used to improve the machining responses. But due to its ineffectiveness in desired cooling and lubrication and corresponding health hazards, corrosion and contamination of natural environment, liquid nitrogen jet has been applied in machining through specially designed external nozzle in order to have better experimental results.

Effective control of the cutting zone temperature for high production machining of steel, is very essential. The concept of cryogenic condition presents itself as a possible solution for high speed machining in achieving slow tool wear while maintaining cutting forces/power at reasonable levels, provided that the cryogenic cooling parameters can be strategically tuned. It has the benefits of a powerful stream that can reach the cutting area because it provides strong chip removal. Liquid nitrogen injection technique not only provided reduction in cutting forces and temperature but also reduced the consumption of cutting fluid. A liquid nitrogen coolant applied at the cutting zone through a 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. It has been reported that the cooling and lubrication is improved in high speed machining of difficult-to-machine materials by the use of high-pressurized liquid nitrogen coolant/lubricant jet. The purpose of the experimental investigation in this present research work is to investigate on the behavior of cutting temperature, force and chips morphology experimentally under cryogenic coolant condition which is a pre-requisite in order to predict different machining phenomenon through predictive modelling.

Fig.2.1 Photographic view of the experimental set up

The machining tests were carried out by straight turning of 42CrMo4 steel, in a reasonably rigid and powered centre lathe at different cutting speeds (V_c) and feed rates (S_o) under both dry and cryogenic cooling condition. Keeping in view less significant role of depth of cut (t) on cutting temperature, saving of work material and avoidance of dominating effect of nose radius on cutting temperature, the depth of cut was kept fixed to only 1.0 mm. The tool geometry is reasonably expected to play significant role on such cooling effectiveness.

The nozzle tip's position with respect to the cutting insert has been settled after a number of trials. The liquid nitrogen jet is directed along the auxiliary cutting edge at an angle 30^o to reach at the principal flank and partially under the flowing chips through the in-built groove parallel to the cutting edges. The photographic view experimental set-up is shown in Fig.2.1

The ranges of cutting speed and feed rate chosen in the present investigation are representative of the current industrial practice for the tool-work material combination that has been investigated. The conditions under which the machining tests have been carried out are briefly given in Table 2.1

Table 2.1 Experimental conditions

Machine Tool	: Lathe (10 hp), China
Work Materials	: 42 CrMo4 (size: Ø102 X 485 mm)
Cutting Tool	
Cutting insert	: SNMG 120408 (ISO Specification)
Tool holder	: PSBNR 2525 M12, Sandvik
Working tool geometry	: -6^o, -6^o, 6^o, 6^o, 15^o, 75^o, 0.8 mm
Process Parameters	
Cutting speed, V_c	: 78, 112 and 156 m/min
Feed rate, S_o	: 0.12, 0.14 and 0.16 mm/rev
Depth of cut, t	: 1.00 mm
Environment	: Dry and cryogenic cooling

2.2 Experimental Results

2.2.1 Chip Formation

The machining chips were collected during all the treatments for studying their shape, colour and nature of interaction with the cutting insert at its rake surface. Shape and color of chip during turning 42CrMo4 steel by SNMG insert under dry and cryogenic cooling conditions are incorporated in Table 2.2.

Table 2.2 Shape and color of chips produced during turning 42CrMo4 steel by SNMG insert under dry and cryogenic cooling conditions

		Environment			
Feed (mm/rev)	**V_c (m/min)**	**Dry**		**Cryogenic Cooling**	
		Shape	**Colour**	**Shape**	**Colour**
0.12	78	tubular	blue	tubular	metallic
	112	spiral	blue	tubular	metallic
	156	tubular	blue	tubular	gray
0.14	78	tubular	blue	spiral	metallic
	112	tubular	blue	tubular	metallic
	156	tubular	gray	tubular	metallic
0.16	78	tubular	blue	tubular	metallic
	112	tubular	blue	tubular	metallic
	156	tubular	blue	tubular	gray

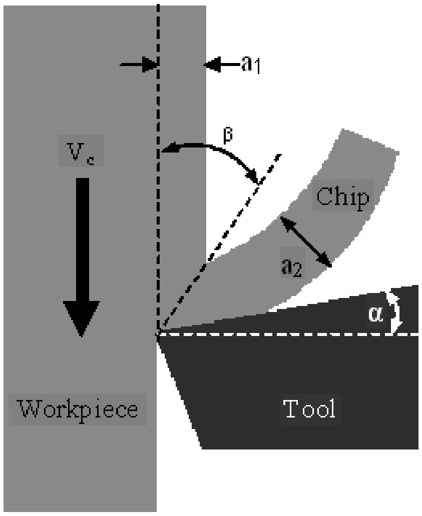


Fig.2.2 Schematic view of the formation of chip

The chip reduction coefficient, ξ (ratio of chip thickness after and before cut) is an important index of chip formation and specific energy consumption for a given tool-work combination. For specified tool geometry and cutting conditions, the value of chip reduction coefficient depends upon the nature of chip-tool interaction, chip contact length, curl radius and form of the chips all of which expected to be influenced by high-pressure coolant in addition to the level of cutting speeds and feeds. In machining conventional ductile metals and alloys producing continuous chips, the value of ξ is generally greater than 1.0 because chip thickness after cut (a_2) becomes greater than chip thickness before cut (a_1) due to almost all sided compression and friction at the chip-tool interface. Larger of ξ means larger cutting forces and friction and is hence undesirable. The thickness of the chips was repeatedly measured by a slide caliper to determine the value of chip thickness.

The schematic view of the formation of chip is shown in Fig. 2.2. The machining chips were collected during all the treatments for studying their shape, colour and nature of interaction with the cutting insert at its rake surface. Chips have been visually examined and their thickness has been measured by slide callipers at every run.

The variation in value of chip reduction coefficient, ξ with change in cutting speeds and feed rates as well as machining environment evaluated for 42CrMo4 steel have been plotted and shown in Fig.2.3 which depict some significant facts;

i) values of ξ has all along been greater than 1.0

ii) the value of ξ reduced by the application of cryogenic cooling

iii) the value of ξ decreased with increase in V_c and S_o

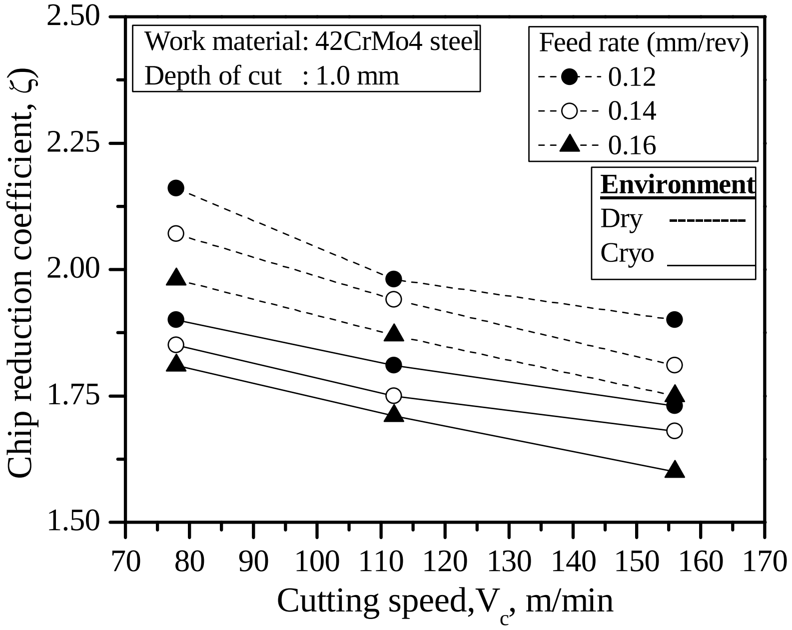


Fig.2.3 Variation in chip reduction coefficient (ξ) with that of V_c and S_o in turning 42CrMo4 steel by SNMG insert under dry and cryogenic cooling conditions

Fig.2.3 clearly show that throughout the present experimental domain the value of ξ gradually decreased with the increase in V_c though in different degree for the different tool-work combinations, under both dry and cryogenic cooling conditions. The value of ξ usually decreases with the increase in V_c particularly at its lower range due to plasticization and shrinkage of the shear zone for reduction in friction and built-up edge formation at the chip-tool interface due to increase in temperature and sliding velocity. With the increase in feed (i.e. uncut chip thickness) also the value of ξ decreases due to increase in effective rake angle of the tool with edge radiusing or beveling. In machining steels by tools like carbide, usually the possibility of built-up edge formation and size and strength of the built-up edge, if formed gradually increase with the increase in temperature due to increase in V_c and also S_o and then decrease with the further increase in V_c due to too much softening of the chip material and its removal by high sliding speed. Fig.2.3 is showing how and to what extent ξ has decreased due to cryogenic cooling condition under the different experimental conditions. With the increase in V_c and S_o, ξ increased as usual, even under cryogenic cooling condition, due to increase in energy input.

2.2.2 Cutting Temperature

The specific energy required in machining converted into heat and the heat generated during machining raises the temperature of the cutting tool tips and the work-surface near the cutting zone.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 liquid nitrogen jet is expected to improve upon the aforesaid machinability characteristics which play vital role on productivity, product quality and overall economy. The lubricating effect on cutting temperatures in cryogenic coolant machining is considered by the change of cutting forces which lead to different heat intensities in the cutting zone. For the temperature rise in the chip on the tool-chip interface, the effects of the shearing heat source on the shear plane and the frictional heat source on the tool-chip interface are considered. For the temperature rise in the tool on the tool-chip interface, the effects of the secondary heat source due to friction and the heat loss due to cooling on the tool rake face are influential.

The average cutting temperature (θ) was measured under all the machining conditions undertaken by simple but reliable tool-work thermocouple technique with proper calibration. The evaluated role of cryogenic cooling on average chip-tool interface temperature in turning cryogenic cooling steel by uncoated carbide SNMG inserts at different V_c–S_o combinations compared to dry condition have been shown in Fig.2.4.

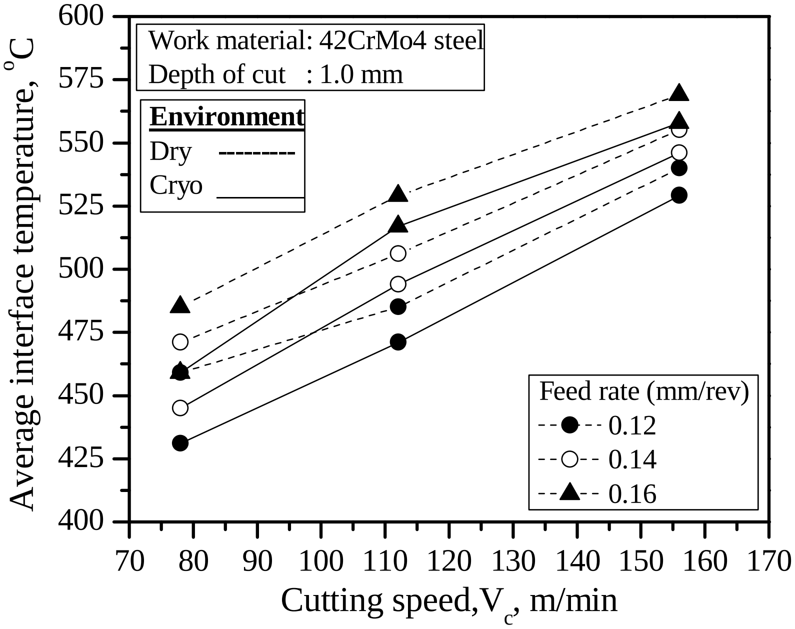


Fig.2.4 Variation in average interface temperature (θ) with that of V_c and S_o in turning 42CrMo4 steel by SNMG insert under dry and cryogenic cooling conditions

The cutting temperature generally increases with the increase in V_c and S_o, though in different degree, due to increased energy input and it could be expected that cryogenic cooling condition would be more effective at higher values of V_c and S_o. The average chip-tool interface temperature (θ) have been determined by using tool-work thermocouple technique and plotted against cutting speed for different work-tool combinations, feed rates and environments undertaken. Fig.2.4 is showing how and to what extent θ has decreased due to cryogenic cooling condition under the different experimental conditions. With the increase in V_c and S_o, θ increased as usual, even under cryogenic cooling condition, due to increase in energy input.

2.2.3 Cutting Forces

Cutting force is 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 tools like inserts, 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. Each of those interrelated forces has got specific significance. In the present work, the magnitude of P_z has been monitored by dynamometer for all the combinations of steel specimens, tool configurations, cutting velocities, feeds and environments undertaken.

In the present work, the magnitude of P_z and P_x have been monitored by dynamometer (Kistler) for all the combinations of steel specimen, tool configuration, cutting speeds, feed rates and environments undertaken. The effect of liquid nitrogen on P_z and P_x that have been observed while turning 42CrMo4 steel by SNMG insert at different V_c-S_o have been graphically shown in Fig.2.5 and Fig.2.6 respectively.

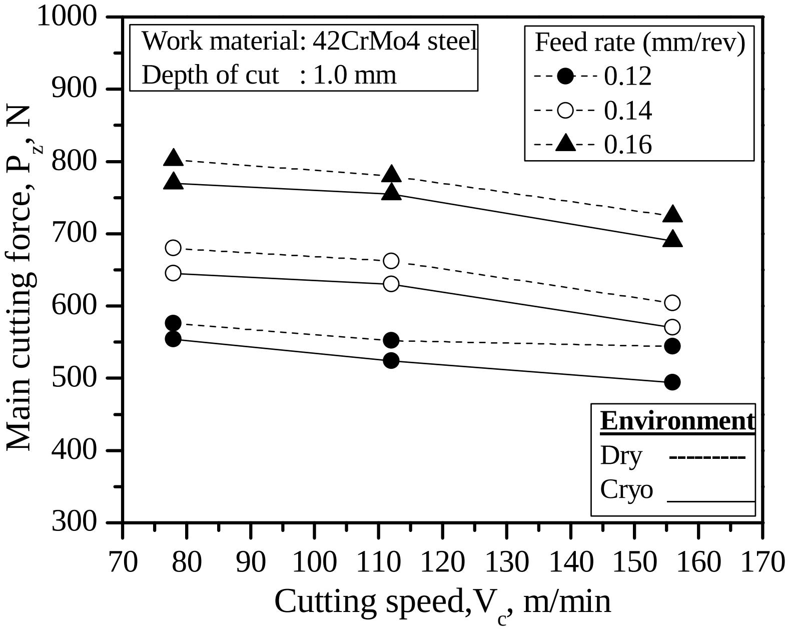


Fig. 2.5 Variation in main cutting force (P_z) with that of V_c and S_o in turning 42CrMo4 steel by SNMG insert under dry and cryogenic cooling conditions

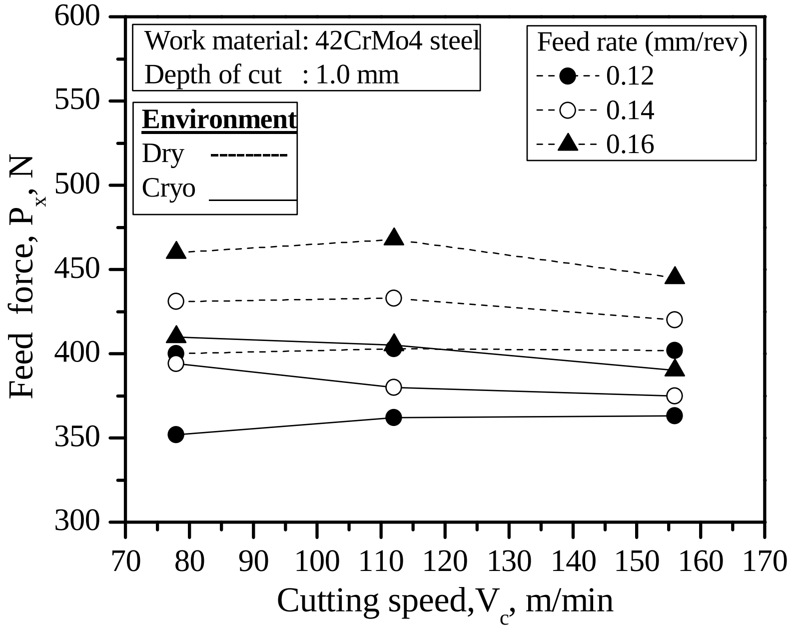


Fig.2.6 Variation in feed force (P_x) with that of V_c and S_o in turning 42CrMo4 steel by SNMG insert under dry and cryogenic cooling conditions

Chapter-3

Modeling of Cutting Temperature

The increasing customer needs for higher quality enlarge the significance of precision machining. It is a relatively new area of machine industry and requires intensive experimental and practical investigation activity referring to technological parameters and circumstances. One part of the research activity of our department is the scope of precision machining and the applicability of our results in the industry. The monitoring of cutting processes predestinates the investigation on the major technological variables determining the shape and dimensional accuracy of the machined parts. Among several influences cutting temperature plays an important role in metal cutting. 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 and 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. Normally the heat is produced for several reasons.

3.1 Temperature Rise due to Heat Source

If a certain amount of heat is suddenly liberated in unit area of a plane surface in a body, this surface becomes an instantaneous source of heat. If the heat is developed continuously instead of suddenly it is known as continuous source. The rate of heat release in continuous source may be constant or may be a function of time expressible as φ (T).

Furthermore the heat sources may be known a point, line, plane or cylindrical source. Another is moving source of heat.

Fourier equation of conduction of heat is given by

$$\frac{\partial^2\theta}{\partial x^2}+\frac{\partial^2\theta}{\partial y^2}+\frac{\partial^2\theta}{\partial z^2}=\frac{1}{\delta}\frac{\partial\theta}{\partial t}\ldots\ldots\ldots\ldots \qquad [3.1]$$

The equation is satisfied by a solution of the type,

$$\theta=\frac{q}{8(\pi\delta T)^{3/2}}\exp\left[\frac{\{(x-x')2+(y-y')2+(z-z')2\}}{4\delta T}\right]\ldots\ldots\ldots\ldots \qquad [3.2]$$

This equation can be extended for any type of heat source. For a continuous point source, when heat is liberated at the rate φ (T), pc per unit time, from $T=0$ to $T=T'$at the location x', y', z', the temperature rise at x, y, z at time T is

$$\theta=\frac{1}{8(\pi\delta)^{\frac{3}{2}}}\int_0^T \emptyset(T')e^{-r^2/\{4\delta(T-T')\}}\frac{dT'}{(T-T')^{3/2}}\ldots\ldots\ldots\ldots \qquad [3.3]$$

where

θ = Temperature at any location x', y', z' °C,

q = Strength of an instantaneous point source of heat liberated at x', y', z' at T=0

Total quantity of heat liberated at $T=0$ at x', y', z' is $q\,p\,c$

δ = thermal diffusivity $=\frac{\lambda}{\rho c}$ cm^2/second

in which

λ = thermal conductivity (cal/cm/second/°C)

ρc = volume specific heat (cal/°C/cm^3)

where $r^2=(x-x')^2+(y-y')^2+(z-z')^2$

If the rate of heat liberation is constant then

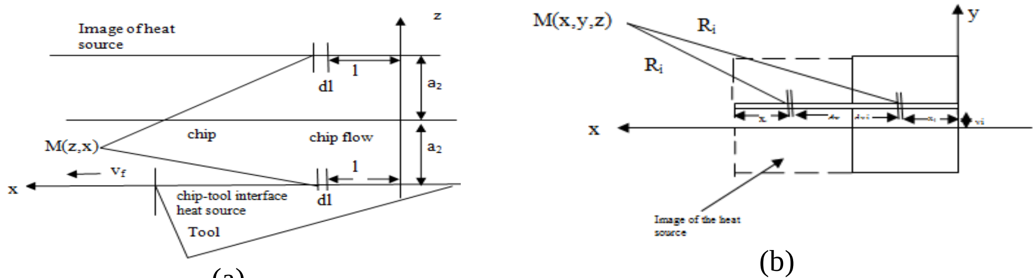
$$\theta=\frac{1}{8(\pi\delta)^{\frac{3}{2}}}\int_0^T \emptyset(T')e^{-r^2/\{4\delta(T-T')\}}\frac{dT'}{(T-T')^{3/2}}\ldots\ldots\ldots\ldots \qquad [3.4]$$

where $\mathrm{T_1}=(\mathrm{T}-\mathrm{T}')^{-\frac{1}{2}}$

hence $\theta=\frac{q}{4\pi\delta r}\operatorname{erfc}\frac{r}{\sqrt{(4\delta T)}}$

For a steady state distribution, when $T\to\infty$,

$$\theta=\frac{q}{4\pi\delta r}\ldots\ldots\ldots\ldots \qquad [3.5]$$



(a) (b)

Fig. 3.1 Schematic view of (a) the frictional heat source at chip tool interface (b) the frictional heat source at chip tool interface considering as a stationary rectangular heat source

For a continuous moving point source of heat when the heat is liberated at the rate of q cal/second at $x, y, z = 0$ for a time $dT'$and an infinite slider moves past this source with a velocity V parallel to axis, the temperature at a point x, y, z at time T can be calculated from

$$d\theta = \frac{q\,dT'}{8\rho c[\pi\delta(T-T')]^{3/2}} \exp\left[\frac{-\{x-V(T-T')\}^2+y^2+z^2}{4\delta(T-T')}\right] \ldots\ldots\ldots\ldots \quad [3.6]$$

Hence the temperature liberation between the period 0 and T is

$$\theta = \frac{1}{8\rho c(\pi\delta)^{\frac{3}{2}}} \int_0^T \frac{e^{-\{x-V(T-T')\}^2+y^2+z^2/[4\delta(T-T')]}}{(T-T')^{3/2}} dT' \quad [3.7]$$

$$= \frac{q}{2R\lambda\pi^{3/2}} e^{Vx/2\delta} \int_{R/\{2\sqrt{(\delta T)}\}}^{\infty} e^{-\xi^2-\{V^2R^2/(16\delta^2\xi^2)\}} d\xi \ldots\ldots\ldots\ldots$$

where $R^2 = x^2 + y^2 + z^2$

For steady state solution $T \rightarrow \infty$,

$$\theta = \frac{q}{4\pi\delta R} e^{-V(R-x)/(2\delta)} \ldots\ldots\ldots\ldots \quad [3.8]$$

For a linear source when the heat of emitted at the rate of q' per unit length along y axis and per unit length, and the temperature at the surface $(z = 0)$ is sought. The upper equation when integrated along y between $-\infty$ to ∞ provides the solution

$$\theta = \frac{q'}{2\pi\lambda} e^{Vx/2\delta} K_0 \left[\frac{Vx}{2\delta}\right] \ldots\ldots\ldots\ldots \quad [3.9]$$

where K_0 (X) is modified Bessel function of second kind of order zero, $X = \frac{Vx}{2\delta}$

Jaegar and Blok have derived out the solution for an infinite strip source$-l < x < l$, $-\infty < y < \infty$ the surface z=0, when heat flux is q cal/cm^2 /second and the surrounding medium moves a velocity in the direction of x.

Integrating the following equation

$$\theta = \frac{q'}{2\pi\lambda}\int_{-1}^{1} e^{V(x-x')/2\delta} K_0\left[\frac{V(x-x')}{2\delta}\right] dx' \ldots\ldots\ldots\ldots\ldots \quad [3.10]$$

In term of dimensionless parameters, $L = \frac{Vl}{2\delta}$, $X = \frac{Vx}{2\delta}$

This equation reduces to

$$\theta = \frac{q\delta}{\pi\lambda V}\int_{x-L}^{x+L} e^{u} K_0(u) du \ldots\ldots\ldots\ldots\ldots \quad [3.11]$$

where $K_0(u)$ = modified Bessel function of second kind and zero order

If L is large and greater than 0.2, then the maximum temperature θ_m is obtained occurring at $x = l$ from $\theta_m = \frac{ql}{\lambda\sqrt{(\pi L)}}$ and the average temperature is

$$\theta_{avg} = .754\frac{ql}{\lambda\sqrt{(\pi L)}} \ldots\ldots\ldots\ldots\ldots \quad [3.12]$$

3.2 Modeling of Cutting Temperature

Machinability of materials usually judged mainly in respect of chip morphology, chip-tool interaction, cutting temperature, cutting forces, dimensional accuracy, surface integrity and wear and life of cutting tool with using cutting fluid and without using cutting fluid. In cutting, nearly all of energy dissipated in plastic deformation is converted into heat that in turn raises the temperature in the cutting zone. Since the heat generation is closely related to the plastic deformation and friction, we can specify three main sources of heat when cutting.

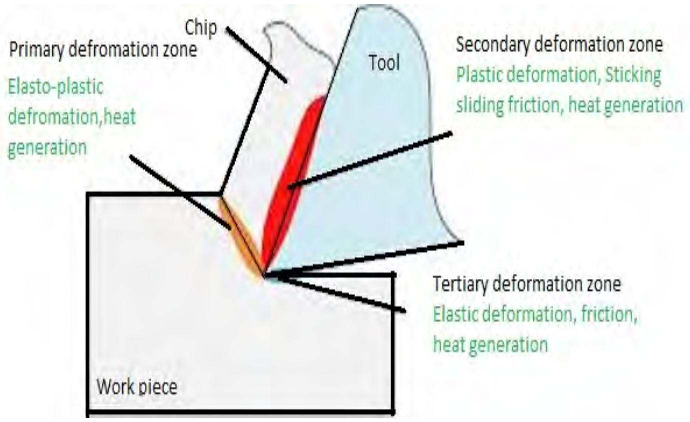


Fig. 3.2 Heat sources in metal cutting process

i) Primary shear zone: The chip formation takes place firstly and mainly in this zone as the edge of the tool penetrates into the work-piece. Material on this zone has been deformed by a concentrated shearing process. q_s is the heat, generated in the primary zone due to intensive plastic deformation. The shear plane temperature is very important because it influences flow stress of work piece material and temperatures on the tool face. In this area local heating due to plastic work can cause the temperature to become very high. This leads to softening of the material and allows greater deformation and further heating, which can lead to periodic shear band formation and serrated chips.

ii) Secondary shear zone: The chip and the rake face of the tool are in contact. When the frictional stress on the rake face reaches a value equal to the shear yield stress of the work-piece material, material flow also occur on this zone. Frictional heat source q_f localizes at the tool-chip interface heat source. The friction in this area causes generation of heat, which can lead to high temperatures. Temperature of rake face is the maximum temperature in real machining operations and it causes tool wear.

iii) Tertiary shear zone: When the clearance face of the tool rubs the newly machined surface deformation can occur on this zone. Heat source q_r is generated due to tip radius of the cutting tool. The surface roughness and integrity of the finished surface, produced by the cutting process, are of interest in this area.

The main assumptions employed in the model development are:

i) The cutting edge is assumed to be sharp so that the tertiary zone can be neglected.

ii) All energy involved in plastic deformation (in the shear zone and at the chip-tool interface) is converted into heat.

iii) The primary and secondary zones are plane surfaces.

iv) The heat generated along the friction interface and the heat generated along the shear zone is evenly distributed.

v) The chip formation takes place along a thin shear zone and moves as a rigid body along the rake face of the tool. The chip leaves the shear zone at a constant temperature equal to the shear plane temperature.

vi) Part of energy at the shear plane will be convected away by the chip and part will flow into the work. Also, part of the energy at the chip-tool interface will usually go to the chip and part to the tool. There are thus two partition coefficients to be evaluated. R_1 is the fraction of energy of the shear plane going to the chip; R_2 is the fraction of energy at chip-tool interface going to the chip.

vii) Another assumption is that none of the energy per unit volume going to the chip on the shear plane is $u_{cs} = R_1 u_s$ while the energy per unit volume going to the chip at chip-tool interface is $u_{cf} = R_2 u_f$ where u_s and u_f are the specific energies involved in shear and friction, respectively.

The rate at which the share energy is expand along the shear plane is given by $E_s = P_s V_s$. But from energy considerations

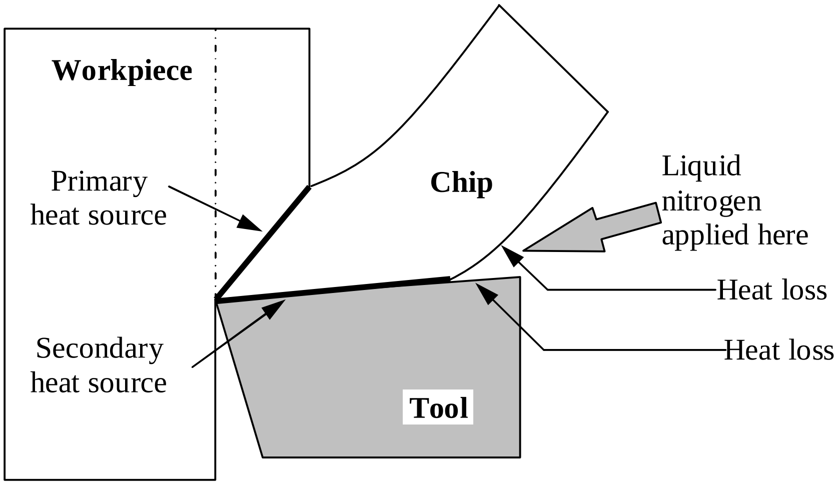


Fig. 3.3 Heat sources and heat loss for the 2D model

Assuming that ‘A’ percent of this energy is converted into heat, the share zone heat per unit time per unit area is given by

$q_1 = \frac{A[P_z V_c - F V_f]}{J a_1 b_1 \ cosec\beta}$ Cal/cm^2/second…………………………………….. [3.14]

where a_1, b_1 are in cm and, A= 0.98 to 1.0

Part of the heat will travel with the chip $c_1 q_1$ and rest of them $(1 - c_1 q_1)$ will flow back to the work piece. Total shear heat $c_1 q_1$ going to chip will be

$$Ac_1 \frac{[P_z V_c - F V_f]}{J}$$

While the heat is utilized in raising the temperature of the chip, when

$Ac_1 \frac{[P_z V_c - F V_f]}{J} = cp_1 \rho_1 V_c a_1 b_1 [\overline{\theta_s} - \overline{\theta_0}]$……………………………….. [3.15]

J= mechanical equivalent of heat in kg.cm/cal

A= 0.98 to 1.0

$cp_1 \rho_1$ =Volumetric specific heat of chip material at shear zone temperature, cal/cm^3/^{0}c

Hence

$\overline{\theta}_s = Ac_1 \frac{[P_z V_c - F V_f]}{J cp_1 \rho_1 V_c a_1 b_1} + \overline{\theta}_0$…………………………………………….. [3.16]

where,

$\overline{\theta}_0$ = Ambient temperature in ^{0}C

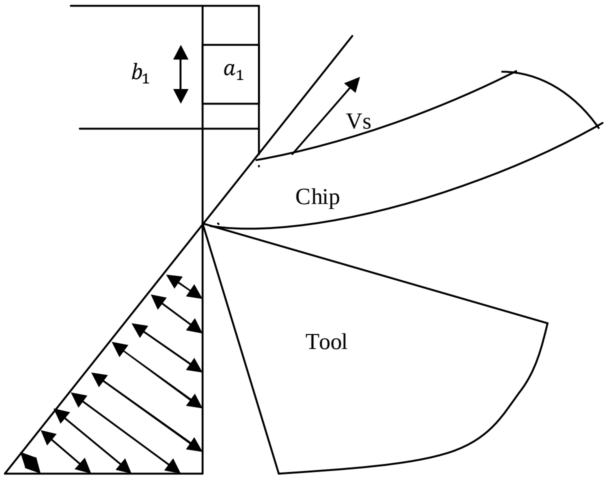


Fig. 3.4 Moving of source of shear plane

when

$$\bar{\theta}_s = \frac{0.754(1-c_1)q_1\left[\frac{a_1}{2}\mathrm{cosec}\beta\right]}{\lambda_1\sqrt{(L_1)}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [3.17]$$

From 3.16 and 3.17 $c_1 = \frac{1}{1+1.328\sqrt{\frac{\delta_1\varepsilon_1}{V_c a_1}}}$ and

$$L_1 = \frac{V_s\left[\frac{a_1}{2}\mathrm{cosec}\beta\right]}{2\delta_1} = \frac{V_c\varepsilon a_1}{4\delta_1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [3.18]$$

In which δ_1 is the thermal diffusivity of conducting surface in cm^2/second. Equating the both equation

$$\theta_s = \frac{A(P_zV_c - FV_f)}{\left[1+1.328\sqrt{\frac{a_1\varepsilon}{Vc\delta_1}}\right](J\rho_{1cp_1}V_c a_1 b_1)} + \theta_c \ldots\ldots\ldots\ldots\ldots\ldots \quad [3.19]$$

In an infinites solid initially at zero temperature, the temperature rise at the joint x, y, z at time T due to a quantity of heat q instantaneously liberated at x', y', z' at zero time is given by the equation

$$\Delta\theta = \frac{q\delta}{8\lambda(\pi\delta t)^{3/2}} \exp\left[\frac{\{(x-x')^2+(y-y')^2+(z-z')^2\}}{4\delta T}\right] \ldots\ldots\ldots\ldots\ldots \quad [3.20]$$

For the case of a continuous heat source extending over a finite area and for a steady state condition ($T \rightarrow \infty$) the equation for the rise of temperature due to a uniform heat source extending over $-l < x' < l$ and $-m < y' < m$ as shown in the following figure

$$\Delta\theta_{x,y,z} = \frac{q}{2\pi\lambda}\int_{-l}^{+l} dx' \int_{-m}^{+m} \frac{dy'}{\sqrt{[(x-x')^2+(y-y')^2+z^2]}} \ldots\ldots\ldots\ldots\ldots \quad [3.21]$$

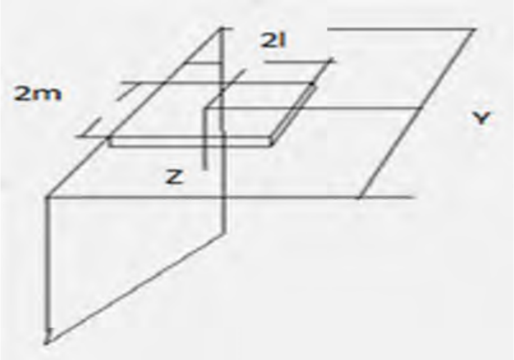


Fig.3.5 Stationary source of heat at chip tool interface

Hence

$$\Delta\theta = \frac{q}{2\pi\lambda}\left[(x + l)\left\{\sinh^{-1}\frac{y+m}{x+l} - \sinh^{-1}\frac{y-m}{x+l}\right\} + (x - l)\left\{\sinh^{-1}\frac{y-m}{x-l} - \sinh^{-1}\frac{y+m}{x-l}\right\} + (y + m)\left\{\sinh^{-1}\frac{x+l}{y+m} - \sinh^{-1}\frac{x-l}{y+m}\right\} + (y - m)\left\{\sinh^{-1}\frac{x-l}{y-m} - \sinh^{-1}\frac{x+l}{y-m}\right\}\right]\ldots \qquad [3.22]$$

The mean temperature rise is

$$\Delta\theta i|avg = \frac{\int_{-l}^{+l}\int_{-m}^{+m}(\Delta\theta)_{x,\ y,\ z=0}\,dxdy}{4lm} = \left(\frac{ql}{\lambda}\right)\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad [3.23]$$

where

$$A = \frac{2}{\pi}\left\{\sinh^{-1}\left(\frac{m}{l}\right) + \left(\frac{m}{l}\right)\sinh^{-1}\left(\frac{l}{m}\right) + \frac{1}{3}\left(\frac{m}{l}\right)^{2} + \frac{1}{3}\left(\frac{l}{m}\right) - \frac{1}{3}\left[\left(\frac{l}{m}\right) + \left(\frac{m}{l}\right)\right]\sqrt{1 + \left(\frac{m}{l}\right)^{2}}\right\}$$

For a cutting edge extending from $-\infty\ to\ \infty$; free cutting similar to orthogonal pipe turning where length of cutting edge is quite large compared to width of cut takes place when

$$\frac{m}{l} = \frac{t}{2l}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad [3.24]$$

where,

t = Depth of cut

l=C$_n$ = Natural contact length, mm

For a cutting edge extending from $-\infty$ to ∞; such as in ‘restricted’ cutting in conventional turning:

$$\frac{m}{l} = \frac{t}{l}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad [3.25]$$

The heat liberated at the interface is given by

$$q_2 = \frac{FV_f}{Jb_1 l}\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad [3.26]$$

The amount of this heat going to the chip is $c_2 q_2$ and heat going to the tool is $(1 - c_2)q_2$. Again, utilizing Jaeger's moving source of heat equation from previous

$$\theta_{avg} = .754 \frac{ql}{\lambda\sqrt{(\pi L_2)}} \ldots\ldots\ldots\ldots \qquad [3.27]$$

where $L_2 = \frac{V_f{}^{1/2}}{2\delta_2}$

and,

$\lambda_2, \delta_2 =$ thermal conductivity and thermal diffusivity at interface temperature of chip material.

$$\theta_i = \theta_s + \frac{0.377 c_2 q_2 l}{\lambda_2\sqrt{(L_2)}} \ldots\ldots\ldots\ldots \qquad [3.28]$$

But from the previous equation $\theta_i = \theta_0 + \frac{(1-c_2)q_2 l}{\lambda_3}\bar{A}$

and,

$\lambda_3 =$ thermal conductivity of tool at interface temperature.

Equating the both equation

$$c_2 = \left[\frac{\frac{q_2 l\bar{A}}{\lambda_3} - \theta_s + \theta_0}{\frac{q_2 l\bar{A}}{\lambda_3} + \frac{0.337}{q_2\lambda_2\sqrt{(L_2)}}}\right] \ldots\ldots\ldots\ldots \qquad [3.29]$$

It can be shown:

$$E_s = \tau_s \varepsilon$$
$$E_f = \frac{\mu\tau_s}{\xi \sin\beta}$$

Analytically the effect of cryogenic on cutting speed, feed rate is

$$\text{Effect}_{\theta_{i\,(cryo)}} = \frac{1.5 b_1\sqrt{\frac{a_1}{\xi}}}{1+\sqrt{\frac{a_2\xi}{v_c}}} + \frac{2.27}{(v_c S_o sin\varphi + 1.328)(1+\sqrt{\frac{a_2\xi}{v_c}})} \ldots\ldots\ldots\ldots \qquad [3.30]$$

The effect of cryogenic cooling condition in the following equation is when V_c is increasing then ξ is decreasing a large amount so the factor $\sqrt{\frac{a_2\xi}{V_c}}$ is decreasing and finally the factor $\frac{1.5b_1\sqrt{\frac{a_1}{\xi}}}{1+\sqrt{\frac{a_2\xi}{V_c}}}$ is increasing. Again with increasing V_c, $(V_c S_o \sin\varphi + 1.328)$ factor is increasing. So $\frac{2.27}{(V_c S_o \sin\varphi + 1.328)(1+\sqrt{\frac{a_2\xi}{V_c}})}$ factors will decrease, as the effect of $(V_c S_o \sin\varphi +$

$1.328)$ portion is much than $(1 + \sqrt{\frac{a_2\xi}{V_c}})$ so with increasing the V_c the cutting temperature is increasing not a large amount. Again when S_o is increasing $(V_cS_o\sin\varphi + 1.328)$ portion is increasing so $\frac{2.27}{(V_cS_o\sin\varphi+1.328)(1+\sqrt{\frac{a_2\xi}{V_c}})}$ portion will also decrease, but $1.5b_1\sqrt{\frac{a_1}{\xi}}$ portion will increase as a result the cutting temperature will increase a small amount.

Incorporating this cryogenic effect to the equation [3.28] the final equation is

$$\theta_i - \theta_o = \frac{\tau_s}{J}\sqrt{\frac{V_c a_1 \varepsilon}{\lambda_2 \rho_2 cp_2}}\left[\frac{0.934\mu b_1\sqrt{\frac{1.5a_1}{\xi\varepsilon \mathbf{l}\mathbf{sin}^{2\beta}}}}{1 + \frac{0.754}{\bar{A}}\left(\frac{\lambda_3}{\lambda_2}\right)\sqrt{\left(\frac{a_2\xi}{lV_c}\right)}} + \frac{1}{\left[0.44\sqrt{\left(\frac{V_c a_1}{\delta_1\varepsilon} + 1.328\right)}\right]\left\{1 + \frac{0.754}{\bar{A}}\left(\frac{\lambda_3}{\lambda_2}\right)\right\}\sqrt{\frac{a_2\xi}{lV_c}}}\right] \quad [3.31]$$

From this equation it is apparent that temperature is directly dependent on dynamic shear stress (τ_s) of the work material and is also dependent on the cutting speed, feed, cutting strain (V_c, S_o, ε) and thermal combination (λ, ρ, cp).

3.3 Experimental Model Validation of Cutting Temperature

In order to validate the model, the measured cutting temperature for turning 42CrMo4 steel by uncoated SNMG insert at different V_c-S_o-t combinations has been compared with the predicted temperature. Table 3.1 shows the combination of V_c-S_o-t for different test conditions.

Table 3.1 Test conditions for temperature validation

Test No.	**V_c (m/min)**	**S_o (mm/rev)**	**t (mm)**
1	78	0.12	1.00
2	78	0.14	1.00
3	78	0.16	1.00
4	112	0.12	1.00
5	112	0.14	1.00
6	112	0.16	1.00
7	156	0.12	1.00
8	156	0.14	1.00
9	156	0.16	1.00

In the Fig 3.5 predicted values from the analytical model and the measured values have been compared. It shows that the predicted values can follow the trend of the measured values very efficiently and can predict the value of the cutting temperature within reasonable error level.

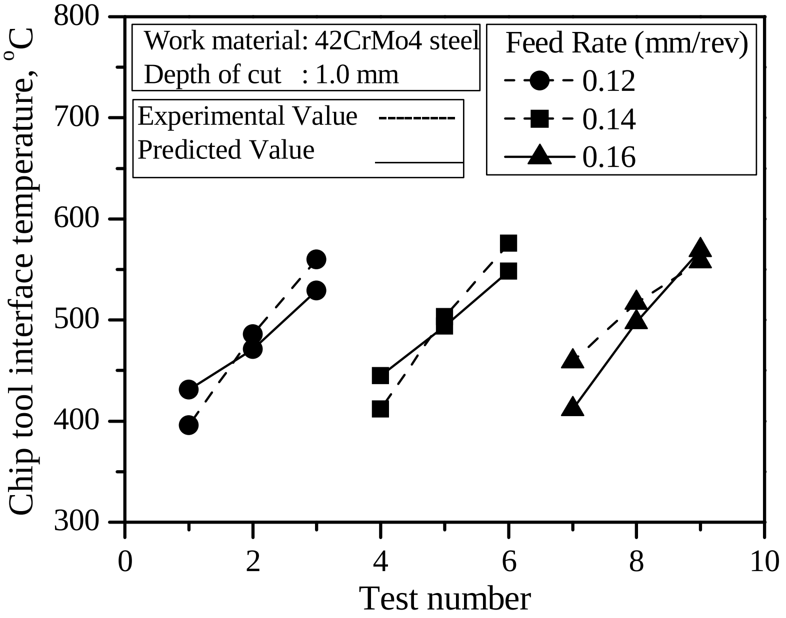


Fig.3.6 Comparison of actual and predicted cutting temperature for different combinations of cutting velocity and feed rate under cryogenic condition.

Chapter-4

Modeling of Cutting Force

Metal cutting is the process of removing a layer of metal in the form of chips from a blank to give the desired shapes and dimensions with specified quality of surface finish. In metal cutting, as shown in Fig.4.1, the chip is formed by a shear process mainly confined to a narrow plastic deformation zone that extends from the cutting edge to the work surface. This narrow zone is referred to as the primary shear zone since the chip is basically formed in the zone.

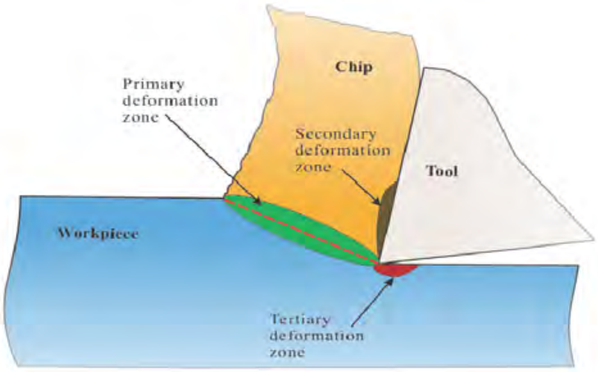


Fig. 4.1 Plastic formation zones of metal cutting

The secondary shear zone along the chip-tool interface due to the high normal stress on the tool rake face; the tertiary shear zone along the work-tool interface due to the high pressure at the tool tip.

Orthogonal and oblique cutting are the two most fundamental machining types. The analysis of other more complicated machining processes such as milling, drilling etc. can be derived from the study of these two basic processes. The cutting tool in orthogonal cutting, as shown in Fig.4.2 has a straight cutting edge, which is perpendicular to the cutting velocity direction. The cutting edge engages into the workpiece with the depth of cut "t" with both ends extending out of the workpiece. In oblique cutting, as shown in

Fig.4.3, the straight cutting edge is inclined with an acute angle (inclination angle) from the direction normal to the cutting velocity.

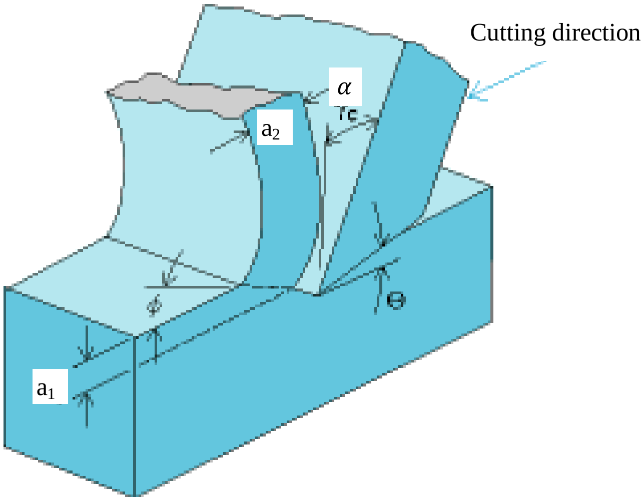


Fig 4.2 Orthogonal metal cutting process

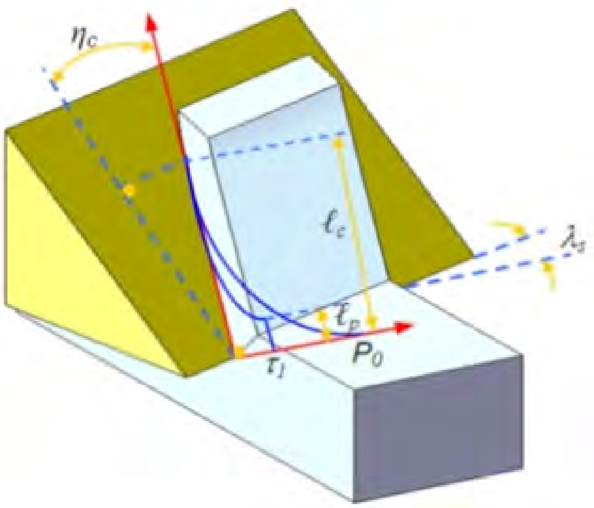


Fig. 4.3 Oblique metal cutting process

In industry, most of cutting processes are performed under oblique cutting conditions. However, the simplicity and adequacy of the orthogonal metal cutting in describing the mechanics of machining make it favorable to researchers during the investigation of chip formation processes. Furthermore, the orthogonal cutting is experimentally advantageous and able to produce a reasonably good approximation of material responses to metal cutting operation under various conditions.

4.1 Thin Shear Plane and Thick Deformation Zone Model

Piispanen's work, first published in 1937 and published in English in [**1948**], applied 'pack of cards' analogy to explain the deformation pattern during chip formation process.

As shown in Fig.4.4, the chip formation process is represented by a deck of cards inclined to the cutting direction with an angle ∅. As the tool moves relative to the workpiece, it engages one card at a time and causes it to slide over its neighbor. Each chip segment (each card) is represented by a small thin parallelogram. Slipping occurs between each chip segment along the shear plane. The assumption and simplifications of the card model can be summarized as:

i) Shear action occurs on a perfectly plane surface.

ii) Exaggerates the in homogeneity of strain.

iii) Does not account for the chip curl.

iv) Assumes no BUE formation.

v) Interprets the tool face friction as elastic rather than plastic.

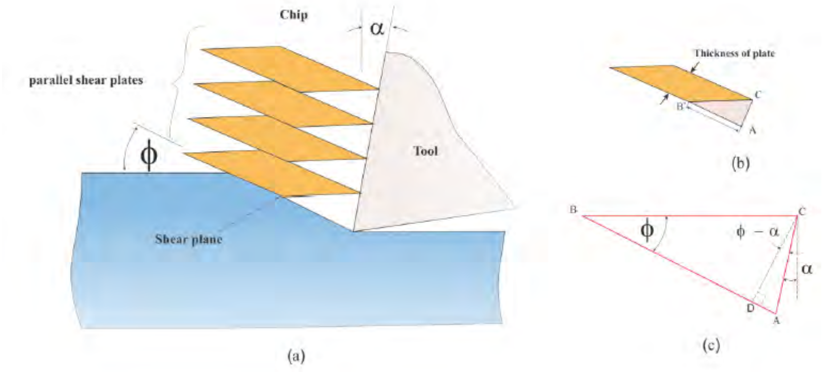


Fig.4.4 Deck-of-Cards chip formation model (a) Parallel shear plate (b) Thickness plate (c) Relation of angle [**Piispanen1948**]

In spite of the simplicity, limitations, and assumptions, this analogy of the chip formation process presents a good illustration of how the shearing action occurs.

The first quantitative analysis of the cutting forces based on the upper bound theory was made by Merchant [**1945**]. It was assumed that the chip of the rigid perfectly plastic material is formed as a result of the intensive shearing along a thin shear plane, which forms an angle $\emptyset$ with the cutting tool moving direction. The first and the most remarkable contribution from Merchant's analysis is that the geometrical relationships among the various pairs of perpendicular force components are defined in a circle with the diameter representing the resultant force R, as shown in Fig.4.5. The force components at the shear plane (P_s and P_n), the friction force and normal force at the chip-tool interface (F and N), the main cutting force (P_z) and thrust force (P_y) can be related through the shear angle $\emptyset$, the tool rake angle α and the friction angle β as shown.

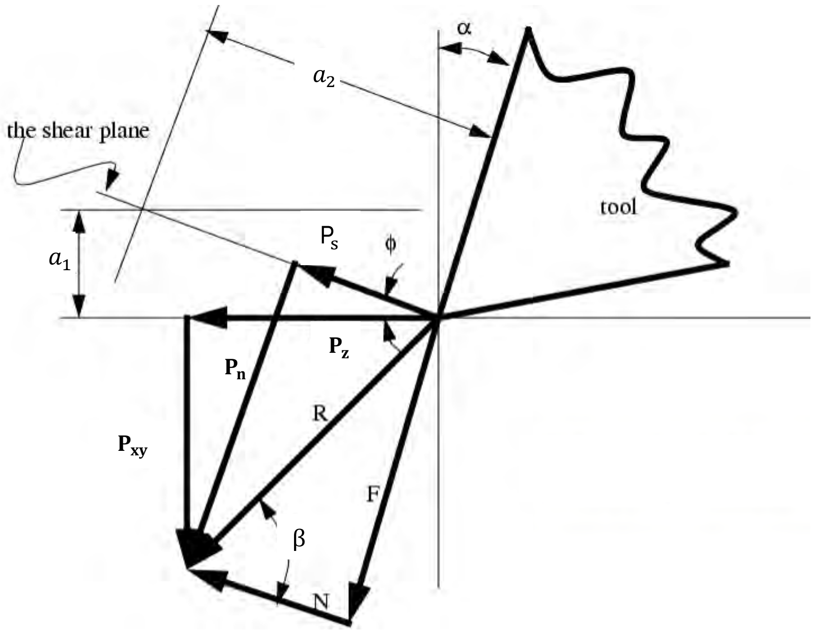


Fig. 4.5 Merchant's Shear plane force circle

The second contribution is that the shear angle $\emptyset$ is determined in terms of the rake angle α and the friction angle β by minimizing the energy consumption during the cutting process.

If the shear stress τ at the shear plane and the friction angle β at the chip-tool interface are known, with the given tool geometry and cutting conditions, the orthogonal cutting forces can be predicted.

The third contribution is the hodograph obtained based on the upper bound analysis. The assumption that all the deformation takes place at a single shear plane across which the work material turns into the chip, leads to the hodograph shown in the Figure 4. It can be seen that the work material with the initial cutting velocity U suddenly changes to the chip with the velocity V_c. This sudden change of the velocity produces a velocity discontinuity along the shear plane, the so-called shear velocity V_s. With this hodograph, the chip velocity and the shear velocity are able to be related to the known cutting velocity.

$$P_s = P_z\cos\emptyset - P_{xy}\sin\emptyset \ldots\ldots \quad [4.1]$$

$$P_n = R\sin(\emptyset + \beta - \alpha) \ldots\ldots \quad [4.2]$$

$$R = \frac{P_s}{\cos(\emptyset+\beta-\alpha)} \ldots\ldots \quad [4.3]$$

$$F = R\sin\beta \ldots\ldots \quad [4.4]$$

$$N = R\cos\beta \ldots\ldots \quad [4.5]$$

$$P_z = R\cos(\beta - \alpha) \ldots\ldots \quad [4.6]$$

$$P_y = R\sin(\beta - \alpha) \ldots\ldots \quad [4.7]$$

$$\emptyset = \frac{\pi}{4} - \frac{1}{2}(\beta - \alpha) \ldots\ldots \quad [4.8]$$

$$V_c = \frac{V\sin\emptyset}{\cos(\emptyset-\alpha)} \ldots\ldots \quad [4.9]$$

$$V_s = \frac{V\cos\alpha}{\sin(\emptyset-\alpha)} \ldots\ldots \quad [4.10]$$

So the co-efficient of friction is can be calculated according to equation 4.11

$$\mu = \frac{F}{N} = \frac{P_z sin\alpha + P_{xy} cos\alpha}{P_z cos\alpha - P_{xy} sin\alpha} = \tan\eta \ldots\ldots \quad [4.11]$$

The force circle, the shear angle equation and the hodograph have been serving as the foundation for the machining process research since then. The major limitations of Merchant's analysis are:

i) The material is assumed to be rigid perfectly plastic, so that the effects of the strain, strain rate and the temperature are not considered.

ii) The shear strain rate along the shear plane is infinite due to the sudden change of the velocity across the infinitely thin shear plane.

iii) During the derivation of the shear angle relation, the shear angle was isolated as a constant so that the interrelations among the shear angle and other processing parameters were not taken into account.

iv) The force circle, the shear angle equation and the hodograph have been serving as the foundation for the machining process research since then.

Lee and Shaffer **[1951]** introduced the slip-line field analysis dealing with the plane plastic flow problems in the plasticity theory into the area of metal cutting based on the following assumptions:

i) The work material is rigid perfectly plastic, meaning that during the deforming process, plastic strain overwhelmingly dominates and that the shear flow stress is invariant throughout the deformation zone.

ii) The deformation rate has no influence on the material behavior.

iii) The effect of temperature increase during deformation is negligible.

iv) The inertia effect as a result of material acceleration during deformation is neglected.

Under these assumptions, Lee and Shaffer constructed a slip line field that consists of two orthogonal classes of so-called slip lines, indicating the two orthogonal maximum shear stress directions at the specific point in the plastic deformation zone, as shown in Fig.4.6. The lower boundary of the field is formed by an idealized shear plane AC, extending from the tool cutting edge to the point where the chip and work material free surface intersect, and all the deformation is assumed to take place at this plane. It can be easily realized that this shear plane is very similar to that in Merchan’s analysis. Since AC is the direction of the maximum shear stress, a line AB on which the shear stress is zero is constructed along the direction 45 degree away from AC, and it serves as the upper boundary of the field. It should be noted that in the triangular plastic zone ΔABC, no deformation occurs but the material is stressed to its yield point. Finally, assuming that the stresses acting at AC the tool-chip interface are uniform, the principle stresses at AC will meet this boundary at the angle or $\beta + \frac{\pi}{2}$. The shear angle $\emptyset$ is then related to tool rake angle α and friction angle β using Mohr's circle as:

$$\emptyset = \frac{\pi}{4} - (\beta - \alpha) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad [4.12]$$

Although the plastic deformation zone was realized and proposed, Lee and Shaffer did not resolve the physics-related conflicts that result from the single shear plane model, that is, the infinite stress and strain rate gradient across the shear plane.

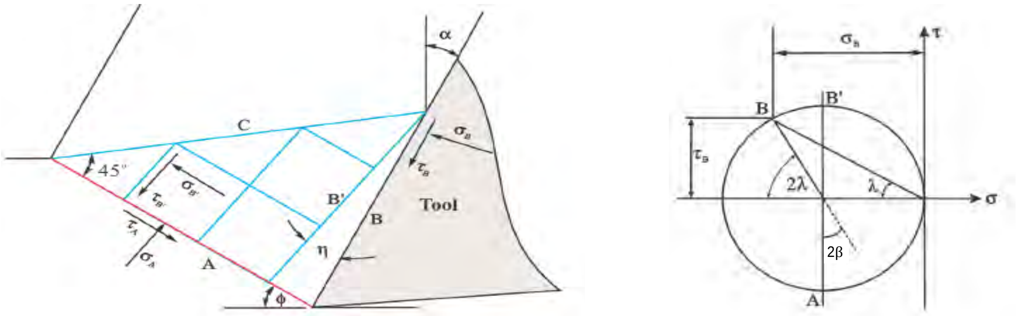


Fig. 4.6 Lee and Shaffer's slip line filed model [**Lee and Shaffer1951**]

Okushima and Hitomi [**1998**] assumed that rather than along a single shear plane, the shearing should fulfill a transitional region that transforms the work material to the steady chip. As shown in Fig 4.7, the transitional region AOB is bounded by straight lines OA and OB, where the plastic deformation initiates and finishes respectively. OC is the shear plane used by previous studies. Assuming the work material is rigid perfectly plastic, the stress in the area of AOB must be in the yield state and therefore the shear stresses on both boundaries must be equal to the yield shear flow stress,

$$\tau_{OA} = \tau_{OB} = \tau_o \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad [4.13]$$

$$\tau_{OB} = \frac{R\cos(\emptyset_2 - \alpha)\cos(\emptyset_2 - \alpha + \beta)}{ba_2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad [4.14]$$

Assuming the uniform distribution, the shear stresses on both boundaries and along the tool-chip interface OD is obtained by means of the resultant force R on the work material side and the chip side:

$$\tau_{OA} = \frac{R\sin(\emptyset_1-\alpha)\cos(\emptyset_1-\alpha+\beta)}{ba_1} \quad [4.15]$$

$$\tau_{OB} = \frac{R\cos(\emptyset_2-\alpha)\cos(\emptyset_2-\alpha+\beta)}{ba_2} \quad [4.16]$$

$$\tau_{OD} = \frac{R\sin\beta}{ba_1} = \tau_o \quad [4.17]$$

Where $\emptyset_1$ and $\emptyset_2$ are the inclination angles of the lower boundary and upper boundary of the shear zone to the cutting direction. β is the mean friction angle, is l the contact length of the tool-chip interface a_1 and a_2 are the uncut chip thickness and deformed chip thickness respectively.

Equating equations, the inclination angles of lower boundary and upper boundary can be determined.

$$\emptyset_1 = \frac{K_1}{2} - \frac{\beta}{2} + \frac{\alpha}{2} \quad [4.18]$$

$$\emptyset_2 = \frac{K_2}{2} - \frac{\beta}{2} + \frac{\alpha}{2} \quad [4.19]$$

$$K_1 = \sin^{-1}\left[\frac{2a_1\sin\beta}{l} + \sin(\beta-\alpha)\right] \quad [4.20]$$

$$K_2 = \sin^{-1}\left[\frac{2a_2\sin\beta}{l} + \cos\beta\right] \quad [4.21]$$

From the geometry, the shear strain inside the shear zone at any given transitional line can be expressed as follows:

$$\varepsilon_i = \frac{A''P}{A'Q} = \cot\emptyset_i - \cot(\emptyset_i - \alpha_i) \quad [4.22]$$

Where $\emptyset_i$ the inclination is angle of the arbitrary radial plane, and is Ψ_i formed by the tangential to the point of interest on the free surface and the cutting direction. In particular, the shear strain on the starting and ending boundary lines of flow region are given by:

$$\varepsilon_1 = \varepsilon_2 = \cot\emptyset_2 - \tan(\emptyset_2 - \alpha) \quad [4.23]$$

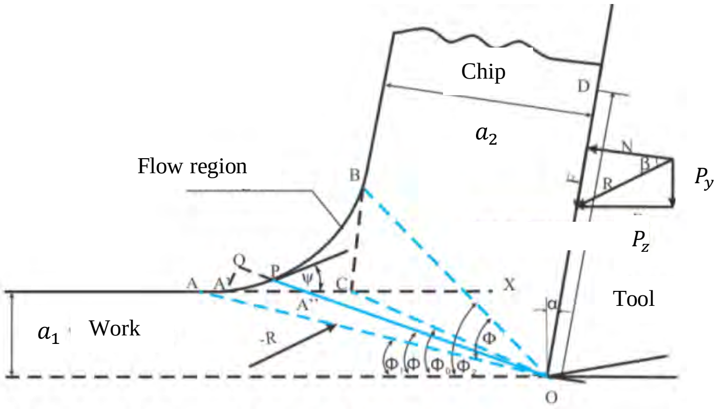


Fig.4.7 Okushima and Hitomi's model

The most distinguished contribution from this work is the gradual change of the shear strain, although in a discrete manner, can be expressed in terms of the tool rake angle and the average friction angle. However, the effect of work hardening and the thermal softening are still excluded.

Considering the fact that each plastic deformation is caused by shear and therefore characterized by lines of maximum shear stress (slip lines), Zorev [**1996**] depicted the shape of the deformation zone with the basic knowledge of plasticity.

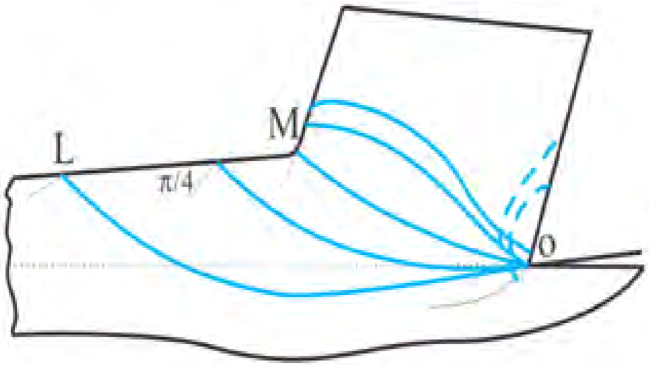


Fig. 4.8 Zorev's schematic representation of slip lines in chip formation **[Zorev1998]**

As shown in Fig.4.8, since LM is the free surface and slip lines stands for the planes of maximum shear stress, each slip line should meet the free surface with an equal angle of $\frac{\pi}{4}$. To satisfy this boundary condition, these lines must be curved instead of straight. For example, if line OL is straight, it would form an angle smaller than $\frac{\pi}{4}$ with the free surface. Furthermore, there must be a deformation zone (the dotted lines) around point O to initiate the deformation. The most part of this zone is on the chip-tool interface and called secondary deformation zone. The shape of this zone should be influenced by the friction boundary conditions at the chip-tool interface.

All models reviewed above only reflect a particular aspect of metal cutting. The impact of variations of cutting conditions of workpiece material is not considered.

Oxley and coworkers devoted great effort into the investigation of the influence of the material properties and the effect of strain, strain rate and temperature on the chip formation process in a series of work Oxley [**1989**], and all the achievement was crystallized in the excellent book Oxley [**1989**].

Two plastic deformation zones, namely the primary shear zone and the secondary shear zone are considered and the shearing process are analyzed in the model, as shown in following figures. In the primary shear zone, the so-called shear plane is opened up so that the continuous flow of the material can be considered. Once the material particles pass through the primary shear zone, further plastic shearing occurs in the secondary shear zone till the end of the tool-chip contact.

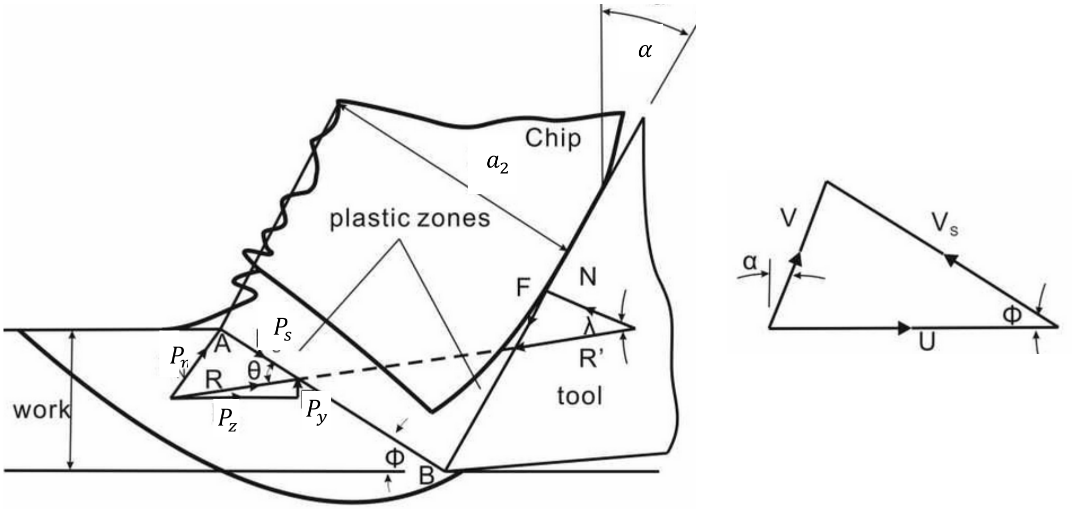


Fig. 4.9 Oxley's shear zone model **[Oxley1997]**

The basis of the theory is to analyze the stress distributions along the AB and tool-chip contact interface in terms of shear angle (angle made by AB and cutting velocity) based on the cutting conditions and work material properties. The effect of the work hardening and thermal softening on the plastic flow behavior was taken into account. The shear angle $\emptyset$ is selected in a manner that resultant forces transmitted by AB and the interfaces are in equilibrium. Once $\emptyset$ is determined, the various components of force can be determined from geometry relations. The most significant contribution is that Oxley and co-workers used the velocity modified temperature concept to describe material properties as a function of strain rate and temperature. The velocity modified temperature, defined as $T_{\mathrm{mod}} = T\left[1 - \mathrm{v}\lg\frac{\varepsilon_{\dot{A}B}}{\dot{\varepsilon_o}}\right]$ increases as the temperature increases and decreases as the strain rate increases. The parameters ν and $\dot{\varepsilon}_o$ are the constants for a given material. The flow stress is related to the strain through the power law $\sigma = \sigma_1(T_{\mathrm{mod}})\varepsilon^{n(T_{\mathrm{mod}})}$, where both strength coefficient and the strain hardening exponent, are functions of velocity modified temperature. The detailed demonstration of the methodology will be introduced later. The following is the list of assumptions and limitations in the Oxley's model:

i) The shear strain rate is constant through the shear zone.
ii) The shear stress is constant along shear plane AB.
iii) Half of the overall shear strain occurs at AB.
iv) The effect of temperature gradient is neglected.
v) The effect of strain rate gradient is neglected.
vi) The distribution of the hydrostatic pressure alone AB is linear with A B P.
vii) The distribution of normal stress at chip-tool rake interface is uniform.
viii) The shear stress along chip-tool rake interface is constant.
ix) Sticking dominates in secondary shear zone and the shear strength in the chip material adjacent to the tool-chip interface will be used to represent the friction parameter.
x) The hodograph is adopted from that for single shear plane model so that velocity discontinuity still exists.

Although sweeping assumptions and simplifications were utilized, Oxley's machining theory still serve as a great breakthrough toward the understanding of the machining process.

4.2 Modeling of Cutting Forces

The knowledge of cutting forces developing in the various machining processes under given cutting factors is of great importance, being a dominating criterion of material machinability, to both: the designer-manufacturer of machine tools, as well as to user. Also, their prediction helps in the analysis of optimization problems in machining economics, in adaptive control applications, in the formulation of simulation models used in cutting databases. In this regard, cutting forces being a substantial dependent variable of the machining system has been tested by many researchers in various cutting processes through formulation of appropriate models for their estimation. These are analytical, semi-empirical and empirical relationships, which connect cutting factors to forces.

Over the last years, empirical models for the machinability parameters in various machining processes have been developed using data mining techniques, such as statistical design of experiments, computational neural networks and genetic algorithms. These techniques possess the advantage of providing the impact of each individual factor and factor interactions, after an appropriate design of the experiment. Mainly, for the Taguchi and response surface methodology, a minimum amount of experimental trials is combined to a reliable global examination of the variables interconnection, instead of one factor at a time experimental approach and analysis.

The response surface methodology (RSM) is a collection of mathematical and statistical techniques useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response [**Montgomery 2005**]. The most extensive applications of RSM are in the particular situations where several input variables potentially influence some performance measure or quality characteristic of the process. The performance measure or quality characteristic is called the response. The input variables are sometimes called independent variables. The field of response surface methodology consists of the experimental strategy for exploring the space of the process or independent variables, empirical statistical modeling to develop an appropriate approximating relationship between the yield and the process variables, and optimization methods for finding the values of the process variables that produce desirable values of the response. In this work we will concentrate on the second strategy: statistical modeling to develop an appropriate approximating model between. The concept of the response surface involves a dependent variable (Y) called the response variable and several independent variables X_o, X1, X2, X3 ….X_n. If all of these variables are assumed to be measurable, the response surface can be expressed as follow

$$Y = f\left(X_o, X_1, X_2, X_3 \ldots X_n.\right) + e \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad [4.24]$$

Where, f is the response function which is unknown and perhaps very complicated and ‘e’ is the error which is normally distributed with zero mean according to the observed response. It is assumed that the independent variables are continuous and controllable by the experimenter with negligible error. Usually they are called the natural variables, because they are expressed in the natural units of measurement, such as degrees Celsius, pounds per square inch, etc. In much RSM work it is convenient to transform the natural variables to coded variables, which are usually defined to be dimensionless with mean zero and the same standard deviation.

Because the form of the true response function f is unknown, we must approximate it. In fact, successful use of RSM is critically dependent upon the experimenter’s ability to develop a suitable approximation for f. In many cases, either a first-order or a second order model is used.

The first-order model is likely to be appropriate when the experimenter is interested in approximating the true response surface over a relatively small region of the independent variable space in a location where there is little curvature in f. The form of the first-order model in the following equation is sometimes called a main effects model, because it includes only the main effects of the variables.

$$Y = \left\{ b_o X_o + b_1 X_1 + b_2 X_2 + b_3 X_3 + ... \right\} + e \quad .... \quad [4.25]$$

If there is an interaction between these variables, it can be added to the model easily as follows:

$$Y = \left\{ \begin{array}{l} b_o X_o + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_{12} X_1 X_2 \\ + b_{23} X_2 X_3 + b_{13} X_1 X_3 + ... \end{array} \right\} + e \quad .... \quad [4.26]$$

This is the first-order model with interaction. Adding the interaction term introduces curvature into the response function. Often the curvature in the true response surface is strong enough that the first-order model (even with the interaction term included) is inadequate. A second-order model will likely be required in these situations. The general second-order model is as given below:

$$Y = \left\{ \begin{array}{l} b_o X_o + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_{12} X_1 X_2 + b_{23} X_2 X_3 + \\ b_{13} X_1 X_3 + b_{11} X_1^2 + b_{22} X_2^2 + b_{33} X_3^2 + ... \end{array} \right\} + e \quad .... \quad [4.27]$$

Where Y is the estimate response based on second order equation. The parameters b_0, b_1, b_2, b_3, b_{12}, b_{23}, b_{13}, b_{11}, b_{22} and b_{33} are to be calculated by the method of least squares.

Response surface method is found the successful technique to perform the trend analysis of cutting force with respect to various combinations of design variables include the cutting speed, feed rate and depth of cut. It is a combination of experimental and regression analysis and statistical inferences. The concept of the response surface involves a dependent variable (P_z) called the response variable and several independent variables. If all of these variables are assumed to be measurable, the response surface can be expressed as Eq. (4.28):

$$P_z = f\left(V_c, S_o, t\right) + e \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [4.28]$$

Where, f is the response function and V_c, S_o, t are the cutting speed, feed and depth of cut and ‘e’ is the error which is normally distributed with zero mean according to the observed response. The observed response P_z as a function of the speed, feed and depth of cut can be written as in Eq. (4.29).

$$P_z = b_o + b_1\, V_c + b_2\, S_o + b_3\, t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [4.29]$$

Where P_z is the response, b_0, b_1, b_2 and b_3 are the constants.

The non-linear relationship between the cutting force and machining independent variables represented in the following equation. The equation is,

$$P_z = C\, V_c^{\ a}\, S_o^{\ b}\, t^c \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [4.30]$$

Where C is a constant and a, b and c are the exponents. A logarithmic data transformation can be applied to convert the nonlinear form of equation into to the linear form. This is one of most popularly used data transformation techniques in empirical model building. The above function can be represented in linear mathematical form as follows:

$$\mathrm{lnP_z} = \mathrm{lnC} + \mathrm{alnV_c} + \mathrm{blnS_o} + \mathrm{clnt} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad [4.31]$$

The above equation can be compared with the first order linear model like Eq. [4.25]. The constants and exponents C, a, b and c can be determined by the method of regression analysis.

Designs of all kinds of machine tools involving operations with single point tools required analysis of cutting force at cutting edge during turning, boring parting, grooving etc. There are several approaches for estimating the cutting forces. An empirical method based on data Granovsky [**2005**] is described here to facilitate computation of forces in order to aid design work as well as for calculating power consumption.

The force system in general case of conventional turning process has been shown in Fig.4.10.

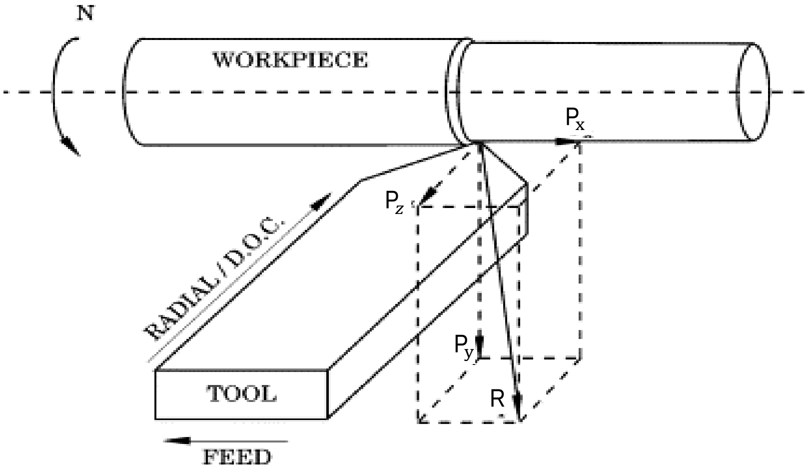


Fig.4.10 Force components of conventional turning process

The resulting cutting force R can be expressed by its components: P_x, known as the feed force, P_y called as radial thrust force in the direction perpendicular to the produced surface and the P_z, the main cutting force acting at the direction of cutting velocity vector. Thus the resultant force R, can be evaluated from Eqn. (4.32)

$$R = \sqrt{P_x^2 + P_y^2 + P_z^2} \quad \ldots\ldots \quad [4.32]$$

The component Pz is in the direction of velocity vector v and is the principle power component. The cutting power in KW can be expressed from

$$\text{Power} = \frac{P_z . V_c}{60 \times 76 \times 1.31} \ldots\ldots \quad [4.33]$$

where V_c = cutting velocity m/min and P_z= cutting force, kg

The effect of the cutting velocity on the main cutting force is considered nearly linear and the relation is inversely related from the nature of the data of the cutting velocity and the effect on the main cutting force and feed force from the concept of Granovsky [**2005**]**.** So the relation between the cutting velocity and the effect of it on the main cutting force and on the feed force are determined by using the regression analysis in the following table.

Table 4.1 Regression analysis between the cutting velocity and the effect of cutting velocity on main cutting force

	Vc	Kc	Vc×Kc	Vc^2
	20	0.890	17.8	400
	40	0.975	39.0	1600
	50	1.000	50.0	2500
	60	0.970	58.2	3600
	80	0.910	72.8	6400
	100	0.870	87.0	10000
	120	0.860	104.0	14400
	140	0.855	120.0	15600
	160	0.810	129.6	25600
	200	0.800	160.0	40000
	240	0.795	190.8	57600
Sum	950.00	8.020	805.2	147700
Average	105.56	0.890	89.47	16411.11
b = -0.0009		Velocity effect, Kc=.98-.0009Vc		
a = 0.98				

This relation indicates the decreasing effect of the main cutting force with increasing the cutting velocity. Though the value of K_c is increasing up to a certain limit and then decreasing with increasing the cutting velocity, so a question may arise of the applicability of this relation on the main cutting force. As it is HSM, so the inverse relation between Vc and K_c will reflect approximately the acceptable nature of the value

Another very important factor is the exponent of feed rate which is also linear in nature and inversely related with the increment of feed rate. So this is also determined by the regression analysis.

Table 4.2 Regression analysis between the feed rate and the exponent

	So	n	So.n	So^2
	0.10	0.75	0.075	0.01
	0.12	0.73	0.0876	0.0144
	0.14	0.71	0.0994	0.0196
	0.16	0.69	0.1104	0.0256
	0.18	0.67	0.1206	0.0324
	0.20	0.65	0.13	0.04
	0.22	0.62	0.1364	0.0484
	0.24	0.60	0.144	0.0576
Sum	1.36	5.42	0.9034	0.248
Average	0.17	0.6775		0.055111
	Slop=-1.0714	n=.8596-1.0714So		
	Constant=.8596			

Similarly the relation of nose radius and the effect of that on the main cutting force are determined. Other effects have been used directly depending on the various combination of cutting velocity, feed rate and the depth of cut.

Taking into account the effect of the various cutting variables, the first order equation according to the discussion is as follow

$$\ln P_z = \ln C + \ln 1o + \ln K_y + \ln K_\varnothing + \ln(0.9852 - 0.0009 \times V_c) + \ln(0.747 + 0.1052 \times r) + \ln K_{hf} + \ln K_{cf} + \ln K_m + m_1 . \ln BHN + p . \ln t + n . \ln S_o \ldots\ldots \quad [4.34]$$

The coefficient of the coded values of cutting speed, feed rate and depth of cut in terms of $\ln V_c$, $\ln S_o$ and ln t is derived by first order regression analysis. Since all the three parameters are under the same logarithmic scale, the factor with highest value of coefficient possesses the most dominating effect over the response. From the Eq. (4.34) the non-linear model of the cutting force can be expressed as the following equation:

$$P_z = C \times K_y \times K_\varphi \times (0.9852 - 0.0009 \times V_c) \times (0.747 + 0.1052 \times r) \times K_{hf} \times K_{cf} \times K_m \times (BHN)^{m_1} \times t^p \times S_o{}^n \times 10 \ldots\ldots \quad [4.35]$$

where

K_y = Coefficient, the effect of rake angle for x, z direction

K_φ = Coefficient, the effect of principle cutting edge for x, z direction

K_{hf} = Coefficient, the effect of tool wear for x, z direction

K_{cf} = Coefficient, the effect of cutting fluid used for x, z direction

K_m = Material transfer coefficient for x, z direction

BHN = Brinnel Hardness Number for workpiece material

m_1 = Exponent of BHN

t = Depth of cut, mm

P = Exponent of t

S_o = Feed rate, mm/rev

n = Exponent of S_o

As for the single work-tool combination the values of $C, K_y, K_\varphi, K_{hf}, K_{cf}, K_m$, BHN are constant. So assuming $K = 10 \times C \times K_y \times K_\varphi \times K_{hf} \times K_{cf} \times K_m \times (BHN)^{m_1}$

$$P_z = K(0.9852 - 0.0009V_c)(0.747 + 0.1052 \times r)t^p {S_o}^n \ldots\ldots\ldots\ldots\ldots \qquad [4.36]$$

Again for single work-tool combination the values of $C, K_y, K_\varphi, K_{hf}, K_{cf}, K_m$, BHN, K_r are constant for feed force. Assuming

$$K' = 10 \times C \times K_y \times K_\varphi \times K_{hf} \times K_{cf} \times K_m \times K_r \times (BHN)^{m_1}$$

From the regression analysis the relation between S_o and q is $n = 0.8 - 0.2S_o$

The feed force (P_x) can be modeled considering the different effects as follows

$$P_x = K'(0.88 - 0.0014V_c)t^p {S_o}^n \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \qquad [4.37]$$

4.3 Experimental Model Validation of Cutting Force

In order to validate the model, the cutting force obtained during turning 42 CrMo4 steel at different V_c-S_o-t combinations has been compared with the predicted value. Following tables show the combination of V_c-S_o-t for different test conditions.

In Fig.4.11 and Fig.4.12 predicted values from two models of main cutting force and feed force respectively have been compared with the experimental values. From both figures, the model can predict the trend of the experimental data but, between the two predictive models the model for main cutting forces accurately giving the data near to actual data.

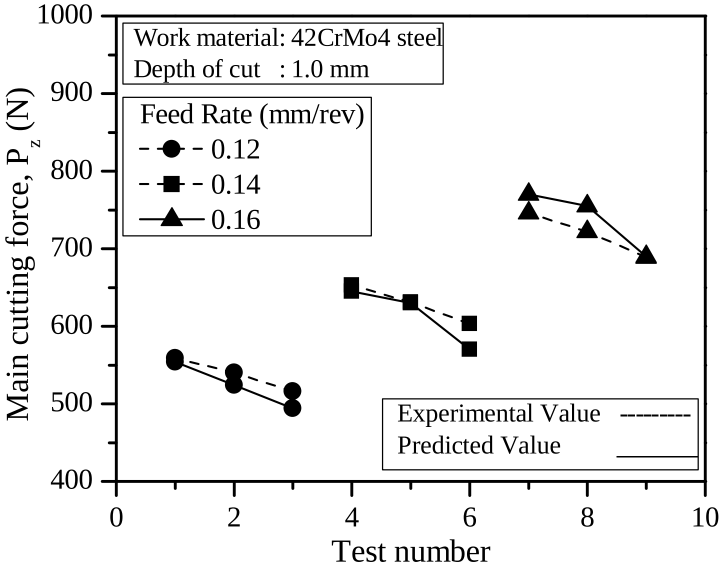


Fig.4.11 Comparison of measured and predicted main cutting force for different combinations of cutting velocity and feed rate under cryogenic condition.

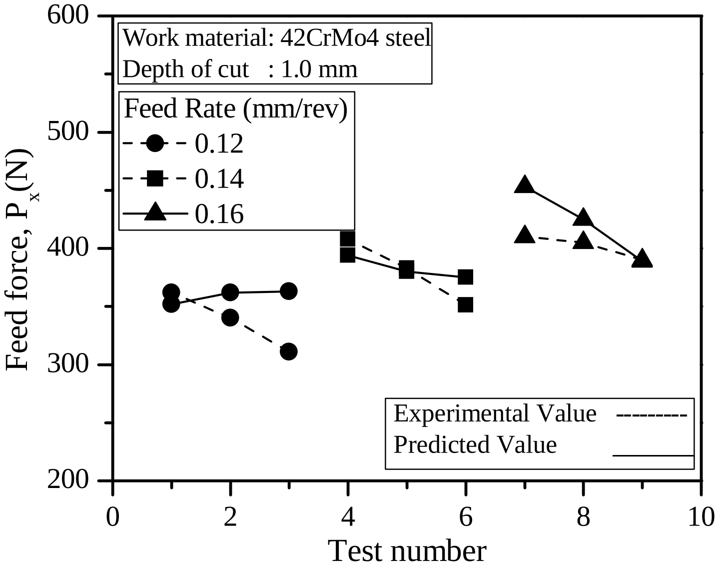


Fig.4.12 Comparison of measured and predicted feed force for different combinations of cutting velocity and feed rate under cryogenic condition.

Chapter-5

Discussion on Results

5.1 Cutting Temperature

From the data calculated from the model, with the increase in V_c, S_o and t generally cutting zone temperature increases due to increased energy input and it could be expected that cryogenic condition would be more effective at higher values of V_c, S_o and t. The average chip-tool interface temperature (θi) has been plotted against cutting speed for different work-tool combinations, feed rates and environments undertaken. Fig.2.5 is showing how and to what extent θ_i has decreased due to cryogenic condition application under the different experimental conditions. With the increase in V_c, S_o and t, θ_i increased as usual, even under cryogenic cooling condition cutting temperature shows the similar trend. Under cryogenic cooling condition cutting temperature reduced for all the cases but in different degree.

Under low speed-feed condition and apparently the temperature is decreased drastically and a small reduction is observed under high speed-feed condition. Even such apparently small reduction in the cutting temperature is expected to have some favorable influence on other machinability indices. With the increase in cutting velocity, plastic contact is increased and made the jet less effective to enter into the interface. Due to this, temperature reduction rate is lower under high speed-feed condition.

The effect of cryogenic cooling condition on machining performance is always dominant over machining under dry condition due to internal mechanics of liquid nitrogen flow jet. As liquid nitrogen jet is pressurized enough to gain huge velocity, it is able to penetrate in the chip-tool interface zone thus reducing chip-tool contact length resulting lower values of frictional co-efficient due to less sliding contact. It can be stated undoubtedly that cutting temperature is greatly influenced by the changes of cutting process parameters and environment. Changing any of the variables among cutting speed, feed, depth of cut, coolant pressure and flow rate of coolant the variation of cutting temperature is observed at the chip tool interface.

The difference of colours and shape of the chip when turning under both dry and cryogenic cooling conditions can be correlated with the cutting zone temperature.

Average cutting temperature is the ultimate outcome of heat generated at shear plane, chip-tool interface and work-tool interface. For a particular speed, feed condition, heat generation at shear plane and at the chip tool interface are expected to be constant. For as the time progresses, due to the development of wear land at the tool flank face, cutting temperature may shift upward.

There are several analytical methods to predict the mean temperature. In turning, nearly all of energy dissipated in plastic deformation is converted into heat that in turn raises the temperature in the cutting zone. In the analytical studies, empirical correlations have been used to determine heat generation and cutting zone temperature. Fig.4.9 and Table 5.1 shows the comparison of measured and predicted average chip-tool interface temperature for different tests when turning 42CrMo4 steel by SNMG insert under cryogenic condition. In the model the tool is considered as sharp with no rubbing heat source. But in real case, tool cannot remain sharp during cutting. The predictive values show a good agreement with the measured value with some deviation.

For the high speed the predicted temperature is sometimes smaller and sometimes larger than the experimental value and the difference between them is less than any other cutting condition. The deviation may be attributed mainly to the assumption that the entire cutting energy is converted into heat but in actual case a small fraction of cutting energy remains frozen in the chip as residual strain and its percentage is different for different V_c-S_o-t combinations. Experimental and predicted data of the average chip-tool interface temperature are almost same then it can be concluded that the model is authentic enough to be used for other machining condition for predicting the average chip-tool interface temperature.

Table 5.1 Percentage error of chip tool interface temperature under dry and cryogenic cooling condition

V_c (m/min)	S_o (mm/rev)	Environment					
		Dry			Cryogenic cooling		
		Predicted temperature (^{o}C)	Actual temperature (^{o}C)	% error	Predicted temperature (^{o}C)	Actual temperature (^{o}C)	% error
78	0.12	420	459	8.40	396	431	8.08
112		512	485	5.64	486	471	3.20
156		580	540	7.43	560	529	5.97
78	0.14	427	471	9.20	412	445	7.20
112		508	506	0.52	503	494	1.06
156		602	555	8.50	576	548	5.11
78	0.16	433	485	10.0	412	459	10.0
112		526	529	0.61	498	517	3.50
156		608	569	7.00	569	558	2.11

Cutting temperature can be measured by the tool-work thermocouple technique. Cutting temperature can also be predicted almost accurately from the modeling equation but these methods are limited to measure or predict only the average cutting temperature.

5.2 Cutting Forces

The component which decides the power consumption is the main cutting force component and that is P_z. For machining conventional materials producing continuous chips the main cutting force is a function of S_o, t, V_c, α and φ. From Fig.2.6 it shows that the cutting force component, P_z has gradually decreased with the increase in V_c almost in the same way the value of ξ decreased. Therefore, it can be concluded that the main reasons behind decrease in cutting forces with the increase in V_c are that which cause decrease in ξ with increase in V_c.

Also it is noted in Fig.2.4 that ξ decreased all along with the increase in S_o (i.e. uncut chip thickness). It is interesting and important to note that though apparently and the magnitude of P_z should increase proportionally with the increase in feed, S_o but actually the rate of increase of P_z with that of S_o has been much less as can be seen in Fig. 2.6. This can be attributed mainly to decrease in ξ with the increase in S_o for increase in average effective rake angle of the tool with the increase in uncut chip thickness. Ultimately, it can be clearly stated that, cutting force is greatly influenced by the behaviour of chip reduction coefficient, cutting speed, feed, depth of cut, effective rake angle, average cutting strain, and percentage elongation due to thermal softening.

Fig.2.6 also shows that the cutting force reduces with the application of liquid nitrogen. This can be explained by the fact that cryogenic coolant deliberately reduce the generation of cutting temperature as well as the lubrication property reduces the friction co-efficient that works between the flank surface of the cutting tool and work piece material resulting less cutting force compared to dry machining.

The check of the normality assumptions of the data is conducted; it can be seen in Fig.4.11 [for first order equation] that all the points on the normal plot come to close to forming a straight line. This implies that the data are fairly normal and there is a no deviation from the normality. Notice that the residuals are falling on a straight line, which means that the errors are normally distributed

Table 5.2 Percentage error of P_z under dry and cryogenic cooling condition

V_c (m/min)	S_o (mm/rev)	Environment					
		Dry			Cryogenic cooling		
		Predicted P_z (N)	Actual P_z (N)	% error	Predicted P_z (N)	Actual P_z (N)	% error
78	0.12	577	576	0.16	559	554	1.01
112		557	552	1.02	540	524	3.22
156		532	544	2.08	516	494	4.60
78	0.14	673	680	0.95	653	645	1.29
112		650	662	1.66	631	630	0.23
156		621	604	2.95	603	570	5.80
78	0.16	770	802	3.97	746	770	2.98
112		744	780	4.57	722	755	4.37
156		711	724	1.79	689	690	0.05

Table 5.3 Percentage error of P_x under dry and cryogenic cooling condition

V_c (m/min)	S_o (mm/rev)	Environment					
		Dry			Cryogenic cooling		
		Predicted P_x (N)	Actual P_x (N)	% error	Predicted P_x (N)	Actual P_x (N)	% error
78	0.12	450	400	12.50	362	352	3.1
112		439	403	8.93	340	362	5.9
156		420	402	4.48	311	363	14.0
78	0.14	462	431	7.19	408	394	3.8
112		445	433	2.77	383	380	0.98
156		430	420	2.38	351	375	6.4
78	0.16	475	460	3.26	453	410	10.0
112		451	468	3.63	425	405	5.1
156		438	445	1.57	389	390	0.17

Chapter-6

Conclusions

6.1 Conclusions

The aim of the present research work is to develop analytical models of cutting temperature and cutting force while turning 42CrMo4 steel by uncoated carbide insert (SNMG 120408-26TTS) under cryogenic condition. Modeling of the cutting temperature has been done by analytical approach. On the other hand, main cutting force has been studied and analyzed to correlate with cutting process variables such as cutting speed, feed rate and depth of cut. Experimental value of chip reduction coefficient, cutting temperature and cutting force are taken for validity test of cutting temperature and cutting force as well as for deriving some input variables for the predictive model. Based on the research work the following conclusions can be drawn:

i) At the first step, chip shape and colour for 42CrMo4 steel is studied. When machined under cryogenic cooling condition the color and shape of the chip indicates the amount of reduction of temperature due cryogenic condition enabled favourable chip-tool interaction and elimination of even trace of built-up edge formation.

ii) In the second step, chip reduction co-efficient ξ has a proportional relation with the cutting force theoretically. So, the lower value of chip reduction co-efficient is better. Controlling coolant pressure and flow rate of liquid nitrogen jet, effective lubrication can be carried out resulting more reduced friction at the interface zone and thus lower values of ξ can be obtained as desired. The model shows that with decreasing the value of ξ the cutting temperature will decrease.

iii) Cutting temperature is found to be proportional with cutting speed, feed rate and depth of cut. Application of liquid nitrogen reduces this high cutting temperature when compared to dry cutting. The reduction is between 1.5 and 6.5 % for the average chip-tool interface temperature for different V_c-S_o-t combinations. For as the time progresses, due to the development of wear land at the tool flank face, cutting temperature may shift upward, while speed, feed, depth of cut, pressure and flow rate of liquid nitrogen jet are constant. But this transient character is found to be not significant to a considerable extent. Approximately 7% variation has been observed in cutting temperature values from the analytical model.

iv) The trends of cutting forces can be increasing or decreasing with the increase of cutting process parameters. This behaviour solely depends on the range of cutting process variables that are considered as experimental condition of a particular research. From the modelled equation, main cutting force and feed force found to decrease with the increase of speed, and cutting forces increases with the increase of feed and depth of cut. With the application of liquid nitrogen, the reductions of forces have a significant amount.

v) From the analytical model in cryogenic cooling condition, the cutting temperature can be predicted accurately within error level of 10%.

vi) From the first order model, main cutting force can be predicted with maximum error of 5% and feed force can be predicted with maximum error of 14% in the cryogenic cooling condition.

6.2 Scope for Future Work

i) Three variables such cutting velocity, feed rate and the depth of cut are considered for the experimental part, for getting the response parameter. This research work can be extended by increasing the variable. The new variable may be the cryogenic condition parameter such as pressure and flow rate of the jet.

ii) In this research, analytical modelling of cutting temperature has been developed for a particular tool work combination. Another modification of the analytical model can be the model with wear out tool. In that method a rubbing heat source (tertiary) need to be considered at the surface of the zone, where the clearance face of the tool rubs the newly machined surface deformation can occur.

iii) The parameter of the liquid nitrogen jet such flow rate of LN_2 and the outlet pressure of the jet have significant effect on cutting temperature and cutting force. In the present work these factors are not studied. So, these factors can be studied experimentally in future by doing the experiment with different pressure and flow rate of LN_2. Then the predictive equation for the cutting force and temperature can be derived with the cutting variables and the cryogenic variables.

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