CHAPTER 1

INTRODUCTION

1.1 METAL CUTTING

Material removal is the principal operation carried out by a majority of the manufacturing industries. It is the process of removing the unwanted material, using a sharp cutting tool from the given workpiece, so as to obtain the required shape on the product. Machining of materials is adopted to get higher surface finish, close tolerances, and complex geometric shapes, which are otherwise difficult to obtain. Among all the manufacturing processes available, metal removal is perhaps the most expensive one. This is because, from the raw material, quite a substantial amount of material is removed in the form of chips. Also, a lot of energy is expended in the process of material removal. So, the choice of material removal as an option for manufacturing should be considered only when no other manufacturing process suits the purpose. However, all the components invariably undergo a material removal operation at one point or the other. The metal cutting process is unique and difficult to analyse, due to:

1. Prior work hardening that greatly affects the process.

2. Different materials behave differently during machining.

3. Strain and the strain rate level are high.

4. The cutting process is sensitive to any variation in the tool geometry, and the process is mostly bounded by the cutting tool.
5. The process is sensitive to variation in tool geometry, tool material, cutting temperature, environment (cutting fluid), and other process dynamics, like chatter and vibration.

Turning is a basic metal cutting process using a single point tool that removes unwanted material to produce a family of cylindrical end products. Turning is typically carried out on a basic machine tool, called the lathe. Workpieces in various shapes such as straight, conical, curved and grooved, can be produced from the turning operation. Different categories of metals have different optimum set of angles in the cutting tool, which have been developed through the years. The bits of waste material produced from the turning operation are known as chips or swarf or turnings.

1.2 IMPORTANCE OF METAL CUTTING

It is mandatory for any engineering industry to carry out metal cutting operations in some form or the other. Modern machining industries always aim at higher production rates to obtain high profit. To accomplish this target, industries aim at higher material removal rate. Further, the metal cutting process is complex, due to a variety of input variables in machining; machine tool chosen to perform the process, properties of the workpiece, selected cutting parameters (speed, feed and depth of cut), cutting tool geometry and material and the type of tool holding devices. Some of the essential factors that influence metal cutting operations are the cutting tool materials and cutting fluids. New cutting inserts are developed by the manufacturers for obtaining better performance on the product produced. Machining industries started concentrating on the selection of a proper cutting fluid, as it is the prime factor which controls the cutting temperature of any machining process. The increase in the cutting temperatures is directly related with the tool life, and surface finish of the product. Care must be taken in the selection of suitable cutting fluids, so as produce lower cutting temperatures,
less cutting forces, better surface finish and dimensional accuracy of the finished part.

1.3 BASIC MECHANICS OF METAL CUTTING

During the machining operation metal ahead of the tool rake face gets compressed, first elastically and then plastically. This zone is traditionally called the shear zone, in view of the fact, that the material in the final form is removed by shear from the parent metal. The actual separation of the metal starts as a yielding or fracture, depending on the cutting conditions, starting from the cutting tool tip. Then, the deformed metal, called chip, flows over the tool (rake) face. If the friction between the tool rake face and the underside of the chip (deformed material) is considerable, then the chip gets further deformed, which is termed as secondary deformation. The chip, after sliding over the tool rake face, is lifted away from the tool, and the resultant curvature of the chip is termed as the chip curl. The type of chip produced during metal cutting, depends on the material being machined and the cutting conditions used. High strength materials require larger forces than low strength materials, causing increased friction, heat generation and operating temperature. Work hardness prior to machining is an important factor in machining, as it controls the onset of shear. The onset of shear is delayed by increased hardness, and hence, the shear plane angle increases leading to shear strain. During this process, based on the process parameters chosen, three different types of chips are formed:

a. Discontinuous  
b. Continuous  
c. Continuous with Built-Up Edge (BUE)

Discontinuous types of chips are produced, mainly when the machining operation is carried out on a brittle material like cast iron.
The material ahead of the cutting edge gets compressed, and fractures as the stress concentration increases. Some of the other factors which influence the formation of discontinuous chips are: a small rake angle, coarse machining feed, and low cutting speeds. The formation of discontinuous chips results in a poor surface finish of the machined surface.

Continuous chips are those produced like a metal ribbon during the cutting process that flows up the chip-tool zone. Such chips are considered to be ideal for efficient cutting action. Conditions that favour the continuous type of chips are: a ductile workpiece, fine feeds, high cutting speeds, sharp cutting tools with large rake angles, and proper coolants.

Continuous chips with a built-up edge are the same as the previous type, except for the factor that when machining is carried out continuously, small particles of the metal start adhering and welding to the face of the cutting tool. As the material starts to weld to the cutting tool continuously, it affects the cutting action of the tool. This kind of chips are generally formed in softer non-ferrous metals and low carbon steels. Problems which are encountered during the machining operation because of the formation of a built-up edge are: welded edges break off and remain on the workpiece surface, drastically affecting the tool life and also resulting in a poor surface finish.

Hagiwara et al (2008) have reported that the chip shape and size are the major factors in chip breakability. The form of chips produced in metal cutting is an important aspect to be considered for economical and precise machining. Long and unbroken chips usually create a hindrance to machining. The form of chips produced in metal cutting is shown in Table 1.1.
Table 1.1 Chip form classification (ISO 3685)

<table>
<thead>
<tr>
<th>Cutting</th>
<th>Favourable</th>
<th>Unfavourable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Straight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Ribbon Chips</td>
<td>1.2 Short</td>
<td>1.1 Long/1.3 Snarled</td>
</tr>
<tr>
<td>Mainly up curling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Tubular Chips</td>
<td>2.2 Short</td>
<td>2.1 Long</td>
</tr>
<tr>
<td>Mainly side curling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Spiral Chips</td>
<td>3.1 Flat/3.2 Conical</td>
<td></td>
</tr>
<tr>
<td>Up and side curling</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Washer type Chips</td>
<td>4.2 Short</td>
<td>4.1 Long</td>
</tr>
<tr>
<td>5 Conical helical Chips</td>
<td>5.2 Short</td>
<td>5.1 Long</td>
</tr>
<tr>
<td>6 Arc Chips</td>
<td>6.2 Loose/6.1 Coni</td>
<td></td>
</tr>
<tr>
<td>7 Natural Broken Chips</td>
<td>7 Elemental</td>
<td>8 Needle</td>
</tr>
</tbody>
</table>

1.4 ORTHOGONAL CUTTING AND OBLIQUE CUTTING

Orthogonal cutting is the process wherein the cutting edge of the tool is kept perpendicular to the direction of the motion (velocity vector), and the chip flows along the orthogonal plane. It is considered to be a two dimensional cutting as it has only two force components. Oblique cutting is the process where the cutting edge is kept inclined to the velocity vector, and
in such a case the chip tends to deviate away from the orthogonal plane. Hence, oblique cutting (three dimensional) arises with a third force component, in addition to the two force components mentioned earlier, which are perpendicular to each other. Figures 1.1 and 1.2, show orthogonal and oblique cutting.

Figure 1.1 Orthogonal Cutting

Figure 1.2 Oblique Cutting
1.5 THERMAL ASPECTS OF METAL CUTTING

During metal cutting, the power input to the process gets largely converted to heat, elevating the temperature of the chips, the workpiece and the tool. The high temperatures generated in the region of the tool cutting edge have a controlling influence on the rate of wear of the cutting tool, and on the friction between the chip and the tool. During the machining process, the workpiece material initially gets deformed elastically and then plastically. When the material gets deformed elastically the energy is stored in the material in the form of strain energy and produces a negligible amount of heat. However, during plastic deformation the entire energy is converted to heat. Increased cutting temperatures have greater influence on tool life, chip formation, accuracy of the product and machining conditions (Klocke and Eisenblatter 1997). The mean temperature in turning on a lathe is found to be proportional to the cutting speed and feed (Kalpakjian and Schmid 2011).

\[ \text{Mean temperature } \propto V^a f^b \]  \hspace{1cm} (1.1)

Where, \( a \) and \( b \) are constants that depend on tool and workpiece materials

- \( V \) - Cutting speed
- \( f \) - Feed of the tool

The major sources of heat during machining are:

(i) The shear zone, where plastic deformation causes major source of heat, which is predominantly retained in the chip.

(ii) Tool/chip interface contact zone where significant plastic deformation takes place in the chip and considerable heat is generated due to sliding friction.

(iii) The heat on the flank surface of the tool, where the machined surface rubs against the tool.
In general, heat is generated in three distinct regions (Figure 1.3), these are:

1. **Primary deformation zone or shear zone (along the shear plane):** In this zone the energy needed for the shear of the chip is the source of heat.

2. **Secondary deformation zone (chip and tool interface):** Here, the energy needed to overcome friction is the source of heat. Some amount of plastic deformation also takes place in this region.

3. **Tertiary deformation zone (tool-workpiece interface):** Here, the energy needed to overcome the frictional rubbing of the flank face of the tool with the workpiece surface is the source of heat.

![Figure 1.3 Zones of heat generation in metal cutting](image)

**Figure 1.3 Zones of heat generation in metal cutting**
It can be noted that each of these three zones leads to the rise of temperature at the tool-chip interface, and it is found that the maximum temperature occurs slightly away from the tool tip. This temperature plays a major role in the formation of a crater on the tool face, and leads to a failure of the tool by softening and thermal stresses. The various factors which lead to a rise in the tool temperature are cutting speed, feed, properties of the work and tool materials, and cutting environments. These machining variables also affect the size of the shear zone and chip tool contact length, and thereby, the area over which the heat is distributed. The shorter length of contact of the chip with the tool results in a severe temperature rise (Rajput 2008).

1.6 FACTORS INFLUENCING THE CUTTING TEMPERATURE

Some of the important factors affecting the cutting temperature are:

1.6.1 Workpiece and the Tool Material

Materials with higher thermal conductivity produce lower temperatures, than tools with lower conductivity. The mechanical properties of the workpiece material, particularly the tensile strength and hardness, have a considerable influence on the cutting temperature. In general, the cutting temperature increases drastically if the work material is tough to be machined.

1.6.2 Tool Geometry

The influence of the tool geometry on the cutting temperature is not significant, as the increase or decrease in the rake angle has only a marginal influence on the rise in the cutting temperature. Comparatively, a negative rake angle increases the cutting temperature as the amount of input energy is more. But the cutting temperature increases considerably with the increase in the approach angle. An increase in the tool nose radius also increases the cutting temperature as the contact surface is increased.
1.6.3 Cutting Conditions

The basic cutting conditions such as speed, feed and depth of cut used for machining purposes also influence the cutting temperature. An increase in the cutting speed affects the cutting temperature predominantly. Change of feed has a little effect, and depth of cut has the least effect on the cutting temperature.

1.6.4 Cutting Fluid

The cutting fluid dissipates the heat produced in metal cutting. It helps to avoid the heat accumulation and temperature build-up on the cutting edge of the tool. At high cutting speeds the cutting fluid has a negligible effect on the tool-chip interface temperature (Mazurkiewicz et al 1989). The fluid is carried away by the outward flowing chip more rapidly, than it could be forced between the tool and the chip.

1.7 FORCES IN METAL CUTTING

In metal cutting, especially the turning operation, the following three principal forces will act on the tool tip.

1. **Main cutting force** ($F_z$): It acts downward on the tool tip allowing the deflection of the workpiece upward. It supplies the energy required for the cutting operation.

2. **Feed force** ($F_y$): It acts in the longitudinal direction. It is also called the feed force, because it is in the feed direction of the tool. This force tends to push the tool away from the chuck.

3. **Radial force** ($F_x$): It acts in the radial direction and tends to push the tool away from the workpiece.
1.8 EFFECT OF THE CUTTING TEMPERATURE AND CUTTING FORCES IN METAL CUTTING

The major factors which influence the metal cutting operation are the cutting temperature, cutting forces, and the friction existing between the workpiece material (chip) and the tool face. Due to the increase in the cutting temperature, cutting forces and the friction between the chip and the tool face, the hardness of the tool decreases, thereby damaging the tool. A worn out tool always results in an unsatisfactory performance. Unsatisfactory performance includes poor dimensional accuracy, poor surface finish and increased power requirements. A worn out tool also increases the total tool cost involved in any production process. Hence, care must be taken in reducing the cutting temperature, cutting force and the friction existing at the chip-tool interface.

1.9 CONVENTIONAL COOLING

The cutting fluid acts primarily as a coolant and lubricant for reducing the frictional effects at the tool-chip interface, and the work and flank region. Further, cutting fluid helps in curving of the chip and provides frictional force reduction where tool surface rubs against work. The reduction in the temperature helps in retaining the tool hardness, thereby extending the tool life. Faster heat dissipation from the cutting zone reduces thermal distortion of the tool and ensures better dimensional control. The cutting fluid provides lubrication between the chip and the tool face. An effective lubricant can modify the geometry of chip formation, yielding thinner, low deformed cooler chips, thereby reducing the possibility of BUE, and promoting surface finish. Most machining industries adopt a conventional cooling process, where flood cooling by soluble oil is employed. It is found to be ineffective in removing the heat, especially at high cutting velocity and feed, as the fast moving chip does not allow the cutting fluid to enter the chip-tool interface area effectively. To overcome this problem a high pressure soluble jet of fluid
is used. This can reduce the cutting temperature in the cutting zone to a certain extent, and also improve the tool life by reducing the wear. The usage of conventional coolants is not so effective and moreover, it imposes major environmental problems, due to the chemical breakdown of the cutting fluid at elevated temperatures, thereby contaminating the water and soil during huge disposal. It also imposes a high cost for the setup of a coolant system, as it has to be stored, pumped, filtered and recycled when it is used. It can have adverse effects on the parts of the machine tool and workpiece, causing corrosion, which may lead to its failure. In addition to these factors, the following points have to be observed in the selection of cutting fluids for environmentally clean manufacturing.

1. The constituents of the cutting fluid must not have negative effects on the health of the production worker or on the environment.

2. During their use, cutting fluids should not produce contaminants.

3. Multifunctional oils which can be used for hydraulic systems, for slide way lubrication, and as coolants and lubricants in machining, with minimum vaporization characteristics, have to be developed.

4. The zone of cutting should not necessarily be flooded, but rather cooling and lubrication should take place in a defined manner thereby minimizing the volume of fluid necessary.

5. Through adequate care and maintenance of the cutting fluids, the amount of water required for emulsions can be reduced leading to cost savings (Byrne and Scholta 1993).
1.10 CRYOGENIC COOLING

Cryogenics involves the study and use of materials at very low temperatures, generally, below -150°C. Cryogenic gases have a wide variety of applications in diverse fields such as health, electronics, manufacturing, automotive and aerospace industry, particularly for cooling purposes. Gases such as helium, hydrogen, nitrogen, oxygen, neon, carbon dioxide are some of the cryogens available. Most cryogens are generally colourless, odourless, tasteless, non-toxic and non flammable. Carbon-dioxide, a cryogenic fluid is an effective and eco-friendly coolant with extreme low temperature which also shows better surface finish dimensional accuracy when compared to other conventional coolants. It is a slightly toxic, odourless, colourless gas with a slightly pungent, acid taste. Carbon-dioxide has a melting point of -78°C, and boiling point of -56°C and density of 1.977 kg/m³. Liquid nitrogen is the most commonly used cryogen with molecular weight as 28.01. It condenses at -196°C and freezes at -210°C; it is the most abundant gas, forming about four-fifths (78.03%) by volume of the atmosphere.

Cryogenic machining is the process, where cryogenic fluids are applied as coolants for reducing the cutting temperature in the metal cutting process. Carbon dioxide was used as a cryogenic coolant from the early days (Bartley 1953). It was reported that when liquid nitrogen is used as a coolant, it is environmentally safe and requires no disposal facilities (Kalyan Kumar and Choudhury 2008). The application of cryogenic liquid nitrogen is more economical in metal cutting as the liquid nitrogen jet can be precisely controlled so that the coolant flow can be restricted exactly on the cutting area. Cryogenic cooling provides improved tool life, lesser cutting force, better surface finish, efficient chip breaking and chip handling, better dimensional accuracy, higher productivity and lower production cost (Wang and Rajurkar 2000, Paul et al 2001, Dhar et al 2002).
1.11 NEED FOR THE PRESENT STUDY

High production machining particularly of high strength and heat resistant materials, is associated with the generation of a large amount of heat and cutting temperature. Such high temperature rise causes dimensional deviation in the workpiece and premature failure of the cutting tools. It also impairs the surface integrity of the product by inducing tensile residual stresses, and surface and subsurface micro-cracks in addition to rapid oxidation and corrosion (Leskovar and Grum 1986 and Tonshoff and Brinkomeier 1986). Generally, these problems are controlled by using flood cooling by a conventional coolant. Conventional cooling methods are not only ineffective, but also spoil the working environment by producing harmful gases and smoke.

Starting from Bartley, many researchers had used cryogenic carbon dioxide for carrying out the machining process, and have reported that better tool life, reduced cutting temperature, better surface finish and reduced cutting forces were obtained (Bartley 1953, Hollis 1961, De Chiffre et al 2007, Cakir et al 2004 and Liu et al 2007). Cryogenic machining was carried out earlier in machining steels (Chattopadhyay et al 1985, Paul et al 2001 and Dhar et al 2002), by using liquid nitrogen as the cutting fluid. A difficult-to-machine material, such as titanium, was also machined by using liquid nitrogen as the coolant, and its effects in terms of cutting temperature, cutting force, surface finish, tool wear were studied (Wang and Rajurkar 2000, Hong and Ding 2001 and Hong et al 2001). Cryogenic machining was also carried out by modifying the tool holders or adopting a different method for supplying the cryogenic coolant to the cutting zone (Hong et al 2001 and Yakup Yildiz 2008). A review of the above literature suggests that by cryogenic machining the life of the cutting tool gets enhanced with better surface finish, reduced cutting temperature and cutting forces.
1.12 **SCOPE OF THE PRESENT STUDY**

In the present research work, a cryogenic cooling setup for delivering cryogenic CO\textsubscript{2} and LN\textsubscript{2} coolants was prepared for carrying out the turning operation. Cutting environments such as CO\textsubscript{2}, LN\textsubscript{2}, wet and dry were used for turning three different work-tool combinations (AISI 1045 steel with multi-coated carbide insert and AISI 316 stainless steel and Titanium alloy (Ti-6Al-4V) with PVD coated carbide insert) under 3 different speeds, 4 different feeds, and a constant depth of cut (1mm). The machining performance of CO\textsubscript{2} and LN\textsubscript{2} cooling was analyzed for all the work-tool combinations to evaluate the cutting temperature, cutting force, surface roughness, chip thickness, chip form, chip morphology, shear angle and tool wear.

1.13 **OBJECTIVES OF THE RESEARCH WORK**

The present work investigates the effect of cryogenic carbon dioxide and liquid nitrogen coolants in machining AISI 1045 steel, AISI 316 stainless steel, and Titanium alloy, using a carbide cutting tool under different machining parameters, and compares the effectiveness of cryogenic cooling with that of dry and wet machining conditions. The major objectives of this work are:

1. To develop a cryogenic cooling system for supplying cryogenic CO\textsubscript{2} and LN\textsubscript{2} coolants for the turning process.

2. To evaluate the performance of cryogenic CO\textsubscript{2} and LN\textsubscript{2} on the cutting temperature, cutting force, surface roughness, chip thickness, chip form, chip morphology, and shear angle in turning AISI 1045 steel, by using multi-coated carbide inserts,
and to compare it with dry and wet machining processes under similar cutting conditions.

3. To investigate the effect of cryogenic coolants on the cutting temperature, cutting force, surface roughness, chip thickness, chip form, chip morphology, and shear angle in turning AISI 316 stainless steel, and Titanium alloy material, with PVD coated carbide inserts.

4. To perform wear tests, and to analyze crater and flank wear in machining AISI 1045 steel, using multi coated carbide inserts, AISI 316 stainless steel and Titanium alloy using PVD coated carbide inserts under cryogenic CO\(_2\) and LN\(_2\) cooling conditions, and to compare it with wet and dry machining under similar cutting conditions.

1.14 METHODOLOGY

In this research work, machining experiments were carried out with three different work-tool combinations, under cryogenic carbon dioxide, cryogenic liquid nitrogen, wet and dry machining conditions. The methodology adopted for machining AISI 1045 steel, AISI 316 stainless steel and Titanium alloy is shown in Figure 1.4.
Figure 1.4  Methodology for turning AISI 1045 steel, AISI 316 stainless steel and Titanium alloy (Ti-6Al-4V) under different machining environments

1.15 OUTLINE OF THE THESIS

This research work deals with the development of a cryogenic cooling setup for supplying cryogenic CO$_2$ and LN$_2$ coolants to the machining zone during the metal cutting process. This thesis consists of two major parts;
the first part deals with the development of a cryogenic cooling setup for supplying the cryogenic coolants, and the latter one deal with the performance evaluation of cryogenic CO$_2$ and cryogenic LN$_2$ coolants in machining AISI 1045 steel, AISI 316 stainless steel and Titanium alloy, under different speed-feed and tool-work combinations. The performance of cryogenic CO$_2$ coolant is compared with the performance of cryogenic LN$_2$, and wet and dry machining. Chapter 1 of the thesis deals with the introduction and the necessity of the research work, Chapter 2 presents the literature review of the previous research work carried out in the field of cryogenic machining, and Chapter 3 states the experimental parameters considered to carry out the machining operation. In Chapter 4, the performance of the cryogenic coolants in machining different workpiece materials under different machining environments is discussed in detail, and finally, in Chapter 5 the conclusion of the research work carried out and the scope for further research study is given.

**Chapter 1:** It deals with the basics of the metal cutting process along with the necessity of a cutting coolant in the machining process. The effects of the rise in the cutting temperature, and cutting forces are also discussed. The functions of any cutting coolant, its types along with the need for carrying out the research work, with its scope and objectives are given here. Finally, the methodology adopted for carrying out the experimental work is schematically represented at the end of the chapter.

**Chapter 2:** This section discusses the previous research work carried out by various researchers in the field of cryogenic machining, its merits and demerits, and the methods adopted for cooling the cutting zone. Various types of cooling methods, functions of the cutting fluids/lubricants, problems encountered in the use of conventional coolants, and the types of cryogenic cooling approaches are also discussed in detail.
Chapter 3: This part of the thesis discusses the experimental methods and machining conditions used for the turning of the workpiece materials such as AISI 1045 steel, AISI 316 stainless steel and Titanium alloy, using different tungsten carbide cutting inserts. The details about the chemical composition of each workpiece and the geometry of the cutting insert are given here. This chapter also deals with the construction and development of a cryogenic cooling setup used for supplying the cryogenic CO\textsubscript{2} and cryogenic LN\textsubscript{2} coolants.

Chapter 4: This part includes all the results of the turning experiments carried out under different machining environments (dry, wet, cryogenic CO\textsubscript{2} and cryogenic LN\textsubscript{2}). The experimental results include the cutting temperature, cutting forces, chip thickness, chip form, chip morphology, surface roughness, shear angle and tool wear. A comparison of these factors in each machining condition is analyzed and discussed here. Tool wear is analyzed by observing the insert samples under the Scanning Electron Microscope (SEM), and same has been given here.

Chapter 5: This final chapter summarizes the results obtained from the experimental work. The conclusions drawn from the research work carried out are mentioned in this chapter. Suggestions for carrying out further research work are also highlighted at the end of this chapter.