2.1 CONVENTIONAL COOLANTS IN METAL CUTTING

In today’s competitive manufacturing environment, the enhancement of productivity with improved product quality and reduced cost, as well as the maximization of the profit decides the sustainability of a manufacturing organisation. The major problems in achieving high productivity and quality are caused by the high cutting temperature developed during machining, at high cutting velocity and feed rates, particularly when the work material is difficult to machine. In general, the condition of the cutting tools plays a significant role in achieving consistent quality, and also in controlling the overall cost of manufacturing.

The above objectives can be achieved by reducing the high cutting temperature in the cutting zone. Such high temperature adversely affects the tool life, dimensional accuracy and surface integrity of the product. Increased cutting force, excessive tool wear, poor surface finish, poor dimensional stability, etc. are temperature-dependent side effects; they are also interdependent and are the major concerns in the metal cutting industry (Boothroyd 1985). The high cutting temperature can be reduced and sustainable high productivity with acceptable product quality achieved by optimum selection of the machining parameters, and proper cutting fluid application, and by using heat resistant tools. In industries, the high cutting temperature and its detrimental effects are generally tried to be controlled, by applying soluble oil as a conventional coolant. These fluids act both as
coolants to reduce the tool temperature, and also as lubricant (Suresh et al 2009). According to Klocke and Eisenblatter (1997), the flood type cutting fluid is generally adopted to reduce the cutting temperature, and lubricate the sliding surface during machining.

2.2 TYPES OF CONVENTIONAL COOLING APPROACHES

All the machining processes produce heat and friction, which will potentially damage the cutting tools as well as the surface finish of the product. To reduce the friction, transfer the heat and remove the chips away from the cutting zone, normally, cutting fluids are used. Heat generation in machining involves two important processes; firstly the generation of heat during the plastic deformation of the work material by the tool, and secondly, friction during the movement of the chips between the workpiece and the cutting tool.

It is very important to apply the cutting fluids to reduce the friction, and remove the heat as rapidly as possible. There are different types of machining environments practised by the industries nowadays. They are;

1. Dry machining
2. Flood/Wet cooling
3. Minimal Quantities Lubricant
4. High pressure cooling
5. Chilled air cooling
2.2.1 Dry Machining

Dry cutting is practiced by certain industries, where coolant is not used for the metal cutting processes. It is ecologically desirable. The advantages of dry machining include: non-pollution of the atmosphere (or water); no residue on the swarf, which will be reflected in reduced disposal and cleaning costs; no danger to health; no injuries to the skin and allergy free. Moreover, it offers cost reduction in machining (Sreejith and Ngoi 2000). The elimination of the use of cutting fluids, if possible, can be a significant incentive. The costs connected with the use of cutting fluids are estimated to be many times more than the labour and overhead costs (Sreejith and Ngoi 2000). Hence, the implementation of dry machining will reduce the manufacturing costs.

Many metal-cutting processes have been developed and improved based on the availability of the coolants. It is well known that coolants improve the tool life and tool performance to a greater extent. In dry machining, there will be more friction and adhesion between the tool and the work piece, since they will be subjected to high temperatures. This will result in increased tool wear, and hence, reduction in tool life. Higher machining temperatures will produce ribbon-like chips, and this will affect the form and dimensional accuracy of the machined surface (Paul et al 2001). However, dry cutting also has some positive effects, such as reduction in thermal shock, and hence, improved tool life in an interrupted-cutting environment.

2.2.2 Application of Flood/Wet Cooling

This cooling technique is the most widely used in the machining industry. It provides the machining operation with a good level of lubrication,
cooling and chip removal. Generally, soluble oil is used in the cutting zone by flooding. The functions of cutting fluids are (DE Chiffre 1988):

1. Increased tool life
2. Improved surface finish
3. Improved tolerance
4. Reduction in the cutting force
5. Reduction in the vibration

The lubricant also facilitates the breaking of the chips, and can play an important role in the prevention and reduction of corrosion (Da Silvia and Wallbank 1998). Klocke and Eisenblatter (1997) have stated that despite the high cost of coolants, the most common cooling method in machining still consists of flooding the cutting area with a large quantity of the coolant. The application of a copious amount of cutting fluid during intermittent cutting could increase the large fluctuation of the cutting temperature. This can lead to thermal shock and initiate thermal cracks in the cutting edge, and eventually cause tool failure due to edge fracture (Shaw 2005, Elbestawi et al 1997, Vieira et al 2001). Therefore, some alternative methods have been reported to control the thermal shock, and thereby improve tool life during the milling process.

2.2.3 Application of Minimal Quantities/Mist Coolant Lubricant

The application of a minimum quantity of lubrication consists of a mixture of compressed air and oil droplets to the chip – tool interface; this is called a mist coolant. Most of the researchers evaluated the performance of minimum quantity lubrication applications in the milling process and found to significantly improve the tool life and surface finish compared to the

Rahman et al (2001) used minimum quantity lubrication (MQL) in milling applications of ASSAB 718 HH steel and found that the cutting force was reduced for MQL as compared with dry cutting and flood coolant cutting conditions, especially at low cutting speed of 75 m/min.

Researchers also investigated MQL applications in turning process. Dhar et al (2006) investigated the effect minimum quantity lubricant on cutting temperature, tool wear and product quality in turning AISI 4340 steel. It was shown that the MQL performance was better than dry cutting as it reduced the cutting temperature and improved surface finish and dimensional accuracy.

A study was conducted by Machado and Wallbank (1997) to evaluate the effect of extremely low lubricant volumes in machining. Small quantities of lubricant (200-300ml/hr) in a fast flowing air stream with a pressure of 2 bar were used in turning of medium carbon steel AISI 1040. Results were compared to the traditional flood cooling method as a benchmark with 5.2 l/min. The findings reveal that surface finish, chip thickness and force variation are all affected beneficially by the equivalent. Cutting force and feed force were found reduced when the lubricant was applied under low cutting speed and high feed rate.

In another study by Varadarajan (2002), a hard turning with minimal fluid application has been carried out to compare the machining performance with dry and wet turning. A specially formulated cutting fluid was applied with a high velocity, thin-pulsed jet at the immediate cutting zones at an extremely low rate of 2 ml/min. It was observed that cutting force
was lower during minimal application when compared to dry and conventional wet turning. Penetration of the cutting fluid with Epoxy additives into the interface can reduce the frictional contribution to cutting force, which in turn lower the cutting temperature, shortening of tool-chip contact length and increase of shear angle during minimal application bring forth better surface integrity and improved tool life. The overall performance during minimal cutting fluid application was found to be superior to that during dry turning and conventional wet turning on the basis of cutting force, tool life, surface finish, cutting temperature and tool-chip contact length. As the minimal rate of application is as low as 2 ml/min a major portion of the fluid is evaporated. The remnants carried away by the work and chips are too low to cause contamination of the shop environment. Applying a mist coolant also poses serious health hazards including eye irritation; Breathing of the mist may also cause serious respiratory problems and air pollution (Yuvan et al 2001).

2.2.4 Application of High Pressure Cooling

Kovacevic et al (1995) have experimentally investigated the effect of high pressure water jet cooling/lubrication in milling of titanium alloy. It was found that surface quality and tool life were improved.

Senthilkumar et al (2002) performed experimental investigation on ASSAB -718 steel during end milling operation using uncoated tungsten carbide insert and a Ti-Al-CN coated insert at a speed of 150 m/min with feed rate of 0.05 mm/tooth and depth of cut 0.35 mm shows that the effectiveness of high pressure coolant in terms of improved surface finish, reduced tool wear and cutting forces, and control of chip shape. The tool wear with high pressure coolant is significantly better than that with dry cut and conventional coolant. Hence, this reduces the friction at the tool – work interface and increases the surface finish. Due to the use of high pressure coolant, the removal of the heat from the cutting zone, the cyclic thermal shock does not take place, and hence a lower cutting force likely to occur.

However, the cooling with high pressure coolant does not meet industry standards. When the coolant pressure was increased from 15 to 20.3 MPa, the tool life decreased rapidly due to excessive notch wear reported by Ezugwu et al (2005).

2.2.5 Application of Chilled Air Cooling

In the cold compressed air environment, a Vortex air gun with a nozzle is used to direct cold air generated by the air gun to the tool – chip interface. With the applications of chilled air cooling during machining, the tool life and surface finish are improved.

Rahman et al (2003) studied the performance of chilled air cooling in end milling on ASSAB 718 mould steel and found that the improved tool
life and surface finish, and reduced cutting forces were observed as compared with dry and conventional coolant cutting.

Su et al (2006) studied the effect of dry, flood coolant, nitrogen oil mist, compressed cold nitrogen gas (0°C and -10° C), and compressed cold nitrogen gas and oil mist cutting conditions on tool life during high speed end milling of Ti-6Al-4V. It was found that the tool life under compressed cold nitrogen gas and oil mist cooling conditions have increased 2.69 times compared to dry cutting and 1.93 times over nitrogen oil mist. It was also reported that the tool life was less when using a flood coolant because of the effect of mechanical and thermal impact, which causes thermal cracks on the cutting edge.

Su et al (2007) conducted an experimental investigation on tool wear, surface finish, and chip shape on high speed milling of AISI D2 cold work tool steel under dry cutting, minimal quantity lubrication, air cooling, and air cooling with minimal quantity lubrication conditions. It was observed that the application of air cooling with minimal quantity lubrication techniques resulted longer tool life compared to dry and minimum quantity lubrication.

Yalcin et al (2009) performed end milling on AISI 1050 steel under dry, fluid and air cooling cutting conditions. The experimental results showed that the surface roughness values for air cooling are lower than that of dry milling, and higher compared to those under fluid cooling. It was also reported that the flank wear in air cooling was closer to that in fluid cooling, and higher in dry milling compared to the fluid and cool air cooling systems.

Lincoln et al (2008) carried out end milling of AISI H13 and AISI D2 steels with TiAlN coated and PCBN tools, under dry, compressed,
and cold air cooling systems. The results indicated that the cold air cooling systems provided better results compared with dry and compressed air cooling conditions. It was noted that the cutting temperature was higher in the machining of AISI D2 steel compared to AISI H13 steel.

Kim (2001) conducted an experiment in measuring the cutting temperature of ball-end milling of hardened steel, for different cooling condition by using a K-type thermocouple, implanted in a hole of the work piece. The cutting temperatures were about 790 °C, 350 °C, 540 °C, and 450°C in dry, wet and compressed chilled air at –9 °C and –35°C respectively. The cutting environment for compressed chilled air at –9°C provided the best tool life among all the cooling conditions. In the case of the wet condition, due to the cooling characteristics of the cutting fluid, the tool suffers serious thermal fatigue, and the tool wear rapidly increases compared to dry condition.

2.3 PROBLEMS IN CONVENTIONAL COOLING

The traditional cutting fluids pose serious health and environmental hazards. People exposed to cutting fluids may have skin contact with these fluids, inhale mists or vapor, or even swallow the mist particles of these fluids. Due to their toxicity, they may cause health problems like dermatitis, problems in the respiratory and digestive systems, and even cancer. Improper disposal of these cutting fluids may even cause serious environmental problems, such as water pollution and soil contamination. Strict regulations and their enforcement against using cutting fluids has therefore, been tightened. Thus, the waste disposal and post handling of the cutting fluids and other related costs have increased substantially, with tougher environmental laws. Companies and organizations are being forced to implement strategies to reduce the usage of cutting fluids in their machining operations (Klocke and Eisenblatter 1997).
Kramar et al (2010) have reported that conventional cooling is not efficient enough to prevent extreme thermal loading in the cutting zone. Nandy et al (2009) stated that conventional cooling methods fail to conduct effectively the heat generated in the cutting zone, which is responsible for the shorter tool life.

Shaw et al (1951), Merchant (1958) and Cassin and Boothroyed (1965) have reported that the conventionally applied coolants, even with extreme pressure additives, fail to provide the desirable control of the cutting temperature, as they cannot penetrate into the chip – tool interface predominantly, due to the plastic contact between the tool and chip, especially at high cutting speed.

Choudhury and El-Baradie (1998) and Rahman et al (1997) reported that conventional cooling systems solve the problem partially, but create plenty of technical and environmental problems, such as, the requirement of additional systems for storage, pumping, filtering, recycling and cooling; water and soil pollution on disposal; health problems to the operators when they come into direct contact with the cutting fluids; and environmental problems when the cutting fluids dissociate as they come into contact with the hot surface at high temperatures.

Tsai and Hocheng (1998) and Krabacher and Merchant (1951) have reported that the cost of cutting-fluid-disposal is becoming higher, as the environmental regulations are becoming tougher. Sokovic and Mijanovic (2001) stated that on the shop floor, the operators may be affected by the bad effects of the cutting fluids, such as skin and breathing problems.
Due to the problems in the conventional cooling system, it is necessary to use an environmentally acceptable coolant in the manufacturing industries. For this purpose, liquid nitrogen as a cryogenic coolant has been explored since 1950s in the metal cutting industry (Yakup and Muammer 2008).

2.4 CRYOGENIC MACHINING

The application of cryogenic coolants in machining began in the year 1950s. Cryogenic machining was first investigated around the year 1953 by E.W. Bartley, who used sub-zero cooled CO$_2$ as the coolant (Chattopadhyay et al 1985). Hollis (1961) has studied the effect of cryogenic cooling on the wear process of carbide tipped tools during the machining of titanium. Liquid carbon dioxide was supplied to the base of the carbide through a capillary tube carried in the tool shank, so as to provide a low ambient temperature, and increased temperature gradient through the cross-section of the tip. It was observed that the proximity of the low temperature heat sink retarded crater wear, as the welding and plucking action was significantly reduced.

Researchers at Grumman Aircraft Engineering Corporation reported safe and successful tool-life improvement when using LN$_2$ to cool high-speed steel end mills (Machinery 1965). The cryogenic approach is different, in that the temperature at the cutting zone is reduced to a very low range (Cassin and Boothroyed 1965). It has been reported that the temperature dependent wear is also reduced significantly in cryogenic machining.

Uehara and Kumagai (1968) made an initial effort towards studying fundamentally the effects of cryo-machining. A series of machining experiments have performed on different types of workpiece using LN$_2$ as a coolant. Decrease in size of build up edges was observed resulting in
improved surface roughness. Experiments showed that the cutting performance during cryogenic machining exhibits complicated tendencies that depend upon the combinations of cutting and cooling conditions and also the type of workpiece and tool used.

Uehara and Kumagai (1969a) have reported that cryogenic cooling notably reduced the cutting force and temperature, and improved tool life and surface integrity in continuous as well as interrupted machining.

Jainbajranglal and Chatopadhyay (1984) supplied the LN$_2$ onto the tool-workpiece interface by nozzles. The effect of LN$_2$ on turning and grinding of low carbon steels were compared with conventional soluble oil. During cryogenic turning the improved surface finish and tool life was observed compared to the conventional turning. Reduction in cutting forces was observed due to partial transformation of shear deformation of the chip into brittle fracture and reduction in stagnation tendency of chip material and formation of built up edge. During cryogenic grinding substantial decrease in both temperature and force were observed and provides smoother machined surfaces free from micro cracks when compared with conventional grinding. Machining of carbon steel using LN$_2$ decreases the cutting forces and tool wear and improves surface integrity.

Li et al (1989) have studied the cryogenic ultra-precision machining of ferrous metals with natural diamond tools. It was reported that when the ferrous metals were machined with natural diamond a tool under cryogenic cooling conditions, tool wear was controlled effectively, which means that the possibility of the diffusion and adhesion was reduced.

Evans (1991) investigated the effect of cryogenic cooling on tool wear mechanisms like adhesion and formation of build up edges, abrasion,
micro chipping, fracture and fatigue and tribo-thermal and tribo-chemical wears in the turning of ferrous materials. Specially designed cooling system has been developed that cools the tool shank clamped onto the special purpose tool holder designed to minimize the heat flux from the tool with the rear of the tool shank immersed in LN\(_2\) reservoir. A special chuck was also designed through which LN\(_2\) was supplied using stationary supply tube that hits the front face of the reservoir thereby throwing out the coolant centrifugally without stopping the spindle while the chuck is in operation. The results showed decreased tool wear and better surface finish.

Paul and Chattopadhyay (1995, 1996a, 1996b) have investigated the effect of cryogenic cooling by LN\(_2\) jet in the grinding of different steels like mild, high carbon, cold die, hot die and high speed steels. The results that were obtained through experiments with respect to forces, specific energy, grinding zone temperature, and surface residual stress using cryogenic coolant and compared it with dry grinding and with conventional emulsion cooling. Cryogenic cooling is superior with other coolants in controlling the temperature, residual stresses and grinding forces. With Cryo cooling significant reduction in grinding zone temperature has been observed particularly for ductile material leading to better surface characteristics of ground surface and less wheel loading and wheel wear.

Hong and Zhao (1999) studied the main functions of cryogenic cooling in the metal cutting process. It was reported that liquid nitrogen as a coolant removed the heat effectively from the cutting zone, lowering the cutting forces and modifying the frictional characteristics at the chip – tool interfaces.

Ghosh et al (2003) investigated the effect of cryogenic cooling on the machining of 52100 bearing steel, A2 tool steel and WC-Co rolls with
Alumina ceramic, PCBN and PCD tools. Significant tool life improvements in the cryogenic machining of such hard ferrous materials were attributed to more efficient heat removal from the cutting insert, and a reduction in the thermal softening of the cutting tools at a higher temperature.

2.5 STUDY OF DIFFERENT CRYOGENIC COOLING APPROACHES IN METAL CUTTING

2.5.1 Liquid Nitrogen Circulation System

Wang et al (1996a) made an effort to maintain the tool temperatures at a lower range by circulating liquid nitrogen using copper tubes, as shown in Figure 2.1.

Figure 2.1 Liquid nitrogen circulation system developed by Wang et al (1996a)

Wang et al (1996a) conducted experiments on machining advanced ceramic composite like reaction bonded silicon nitride ‘Si3N4’ (RBSN) with a LN$_2$ cooled Poly Crystalline Boron Nitride tool (PCBN). A liquid nitrogen circulation system was designed to keep the tool temperatures at a lower range. The surface roughness of the workpiece machined with liquid nitrogen cooling was much better than the surface roughness of the workpiece machined without liquid nitrogen cooling.
Wang and Rajurkar (1997) investigated the effect of cryogenic cooling on tool wear mechanism in the turning reaction bonded silicon nitride with CBN cutting tool inserts. It was found that the tool life was increased due to cooling by liquid nitrogen.

Wang and Rajurkar (2000) worked on the cryogenic machining of hard-to-cut materials. The cryogenic cooling system provides better cooling effect on the type of insert used, compared to those used in conventional coolants. Therefore the temperature effect in the cutting zone was minimized by maintaining the higher hot strength and hot hardness of the tool and reducing the tool wear. There was an increase in the tool life up to five folds when LN$_2$ coolant was used rather than the conventional coolant. The surface roughness of all the materials machined with liquid nitrogen cooling was found to be much better than the materials machined without liquid nitrogen for the same length of cutting.

Wang et al (2002) studied the influence of cryogenic cooling on cutting forces, tool life and workpiece surface finish during machining of tantalum. The results showed that, cryogenic machining provided better surface finish, longer tool life, and lower cutting forces compared with conventional machining. The reduction of tool wear in cryogenic cooling enhanced machining suggested an excellent machinability as compared to conventional machining. There was a sharp increase in temperature in the cutting zone making the tool – workpiece area red hot and the formation of built up edges when the LN$_2$ coolant was not used. It was also shown that the cryogenic cooling – enhanced machining is an efficient technique for machining tantalum, when a carbide tool insert is used.
2.5.2 Cryogenic Chip Cooling System

In this method of cryogenic cooling, the liquid nitrogen was supplied to the chip and tool rake face, instead of flooding the whole cutting zone, in order to improve the chip braking when the chip is cryogenically cooled. Figure 2.2 shows the schematic diagram of the liquid nitrogen jet that covers the chip and the tool rake face.

Hong et al (1999) investigated the effect of cryogenic cooling on the machining of low carbon steel AISI 1008 ductile material, and reported a significant improvement in chip breaking. The cooling setup was designed such that the cryogen is impinged to the chip faces instead of flooding the whole cutting zone, which optimizes the coolant consumption to a large extent.

Hong and Ding (2001a) developed a safe approach of the micro-manipulation of cutting temperatures in machining AISI / SAE 1008 low carbon steel. It was reported that in chip breaking, the micro-temperature manipulation by cryogenically cooling the chip, is an improvement over
pre-cooling the workpiece, especially at a higher cutting speed. Furthermore, the chip cooling approach reduced the negative side effect of increased shear strength in the shear zone, which occurs during workpiece pre-cooling.

2.5.3 Cryogenic Dual-Nozzle Cooling System

Researchers attempted in the past to introduce suitable cryogenic cooling approaches, which is economical and practical enough to replace conventional machining, that provide minimum wastage of the cryogenic coolant. This can only be done by locating the nozzle at a suitable position that allows a proper amount of the coolant to be impinged on the desired position at work – tool interfaces. In this method, the nozzle system supplies liquid nitrogen through a well controlled and focused jets to the tool rake face, the flank face, or simultaneously to both.

Hong (2001) developed a new economical and practical approach to cryogenic machining technique for machining of low and high carbon steels, and titanium alloys. The design implementation of the cryogenic dual-nozzle cooling system is shown in Figure 2.3. In this method, the micro nozzle jetting to the cutting point locally minimizes the LN$_2$ consumption.

This approach minimizes the amount of liquid nitrogen consumption to levels at which nitrogen costs less than the conventional cutting fluid. It was reported that cryogenic cooling reduces tool wear, and increases tool life up to five times, thereby allowing for high-speed cutting, improving productivity and reducing the overall production cost. In addition, this approach reduces the frictional forces, improves chip breaking, eliminates the build-up edge, and improves surface quality.
Figure 2.3 The design implementation of the cryogenic dual-nozzle system (a) Both the primary and auxiliary nozzles are used (b) Only the primary nozzle is used (Hong et al 2001)
Hong et al (2001) found the most effective cryogenic cooling approach that yields the longest tool life while maintaining the minimum usage of LN₂. It is also suggested that the cutting tools shall be cooled but not the workpiece material. In order to get optimal cooling the cutting fluid must be applied directly to, and only to, the tip of the cutting tool where the material is being cut and heat is being generated maintaining the flow rate proportional to the heat generated. A micro nozzle is located between the tool face and chip breaker which can be a new economical commercial cutting tool assembly and designed with convenience. During the machining the LN₂ absorbs the heat, evaporates quickly, and forms a fluid cushion between the chip and tool face that functions as lubricant thus reducing the coefficient of friction and secondary deformation.

Hong et al (2001a) have studied the effect of cryogenic cooling on friction and cutting forces in the turning of the Ti-6Al-4V alloy. The experimental results of the cutting force measurements indicated that the cold strengthening of the titanium material increased the cutting force in cryogenic machining, lower the friction reducing the feed force. It was reported that the friction coefficient on the chip – tool interface was considerably reduced in cryogenic machining. Increased shear angle and decreased thickness of the secondary deformation zone in cryogenic cooling was also reported.

Hong and Ding (2001) introduced an innovative and economical method of cryogenic cooling that directs the LN₂ through micro jets to the flank, the rake or both, near the cutting edge in the machining of the Ti-6Al-4V alloy. A small amount of liquid nitrogen applied locally to the cutting edge is superior to emulsion cutting, in lowering the cutting temperature. Liquid nitrogen applied in close proximity to the tool cutting
edge, can significantly reduce the tool temperature, depending on the target location. They also studied the influence of various cryogenic cooling approaches in the turning of the Ti-6Al-4V alloy.

The application of liquid nitrogen to a chamber between the tool insert and shim to freeze the tool back face, is shown in Figure 2.4. In cryogenic workpiece pre-cooling, freezing the workpiece ahead of the tool cutting edge, prior to and during the cutting cycle, is illustrated in Figure 2.5. The dual – nozzle system for localized liquid nitrogen supply to the rake and flank surfaces is shown in Figure 2.6.

The Cutting temperature under cryogenic machining was compared with those under conventional dry cutting and emulsion coolant machining. The results show the order of effectiveness of the cooling approaches to be from worst to best were dry cutting, cryogenic tool back cooling, emulsion cooling, pre - cooling the workpiece, cryogenic flank cooling, cryogenic rake cooling and simultaneous rake and flank cooling. It was also reported that the cooling effect of the LN$_2$ is maximized, when it is injected as close as possible to the cutting edge so that heat generation zone can be effectively cooled.
Figure 2.4 Cryogenic cooling on the tool back side (Hong and Ding 2001)

Figure 2.5 Cryogenic workpiece pre-cooling (Hong and Ding 2001)

Figure 2.6 Cryogenic dual-nozzle cooling (Hong and Ding 2001)
Hong et al (2002) measured the normal and frictional forces by directly simulating the pure frictional behaviour of the tool – chip interface in cryogenic cutting. A specially designed LN$_2$ nozzle was used to apply high pressure LN$_2$ jets through an obstruction type chip breaker by well controlled jets to the tool – chip interface, intended to achieve both cooling and lubrication effects with economical LN$_2$ consumption. Proper application of LN$_2$ to the contacting surfaces can reduce frictional coefficients by lowering the interface temperature and modifying the contact pattern that changes sticking contact to purely sliding contact leading to a reduced effective shear strength. It also enhances the hardness of the tool face during cutting by maintaining the surface integrity of the harder part, minimizing tendencies of increasing friction. The lubrication effect of LN$_2$ can be achieved by combination of various temperature dependent effects and micro scale hydrostatic effects.

2.5.4 Cryogenic Main and Auxiliary Cutting Edge Cooling System

In this cryogenic cooling method, the two liquid nitrogen jets from specially designed nozzles were applied almost along the main and auxiliary cutting edges.

Dhar et al (2000) investigated the effects of cryogenic cooling by LN$_2$ jets on machinability characteristics in turning of plain carbon steels C-40 by carbide inserts under different cutting speeds and feeds. The liquid nitrogen jets were supplied at the cutting zone along the main and auxiliary cutting edge at a pressure of 2 bar. The cryogenic cooling reduces the cutting forces, tool wear, and dimensional deviation and improves the chip formation and surface finish; it provides the benefits mainly through reduction in cutting temperature and favourable change in chip – tool interaction. The benefit of cryogenic cooling is significantly influenced by the tool geometry, tool and
work material characteristics, and the levels of the machining processes parameters.

Paul et al (2001) studied the role of cryogenic cooling by LN$_2$ jet on tool wear and surface finish in plain turning of AISI 1060 steel at different speed and feed combinations for two different cutting inserts. The effectiveness of cryogenic cooling was compared with those under dry and conventional cooling. The results showed that dry machining steel cause maximum tool wear and surface roughness while wet machining didn’t show any appreciable improvement. But cryogenic machining using LN$_2$ provided reduced tool wear, improved tool life and surface finish. The beneficial effects of cooling may also contribute to effective lubrication, retention of tool hardness and favorable chip – tool and work – tool interaction.

Dhar et al (2002) studied cryogenic machining of two types of steels AISI-1040 and AISI-4320 using carbide inserts and reported that the cooling by LN$_2$ jets can substantially reduces the cutting forces during machining without affecting the working environment. It also provides benefits mainly by reducing the cutting temperature, which helps in improving the chip – tool interaction and maintains sharpness of the cutting edges. In machining steels by carbide inserts cryogenic cooling is expected to be more beneficial in finish turning of high strength steels, which are usually done at low feed and cutting velocities.

Dhar et al (2002a) have studied the role of cryogenic cooling by a liquid nitrogen jet in the average chip – tool interface temperature, tool wear, dimensional accuracy and surface finish in the turning of the AISI 4140 steel. Cryogenic cooling enabled a substantial reduction in the cutting zone temperature, and favorable chip-tool and work-tool interactions. Cryogenic cooling provided a reduction in flank wear, and an improvement in tool life.
was reported over dry machining. It was also reported that the surface finish and dimensional accuracy significantly improved under cryogenic cooling.

Dhar et al (2002b) have carried out experimental investigations on the role of cryogenic cooling by liquid nitrogen jet on tool wear and product quality in the plain turning of AISI 1040 and E 4340C steels at industrial speed – feed combinations, by two types of carbide inserts of different geometry. The encouraging results include a significant reduction in the tool wear rate, dimensional inaccuracy and surface roughness by cryogenic cooling application, mainly because of favourable cutting zone temperature and a change in chip – tool and work – tool interactions.

Dhar and Kamruzzaman (2007) studied the effect of cryogenic cooling on the cutting temperature, tool wear, surface roughness and dimensional deviation in the turning of AISI 4037 steel at industrial speed – feed combinations by coated carbide insert, and compared the effectiveness of cryogenic cooling with dry and wet machining. The results indicated substantial benefit in the cryogenic cooling on tool life, surface finish and dimensional deviation. This may be attributed mainly due to the reduction in the cutting zone temperature and the favorable change in the chip-tool interaction. Further, it was reported that machining with soluble oil cooling failed to provide any significant improvement in tool life; rather the surface finish deteriorated.

2.5.5 Modified Cutting Tool Insert System

In this cryogenic cooling method, the standard cutting tool insert was modified to supply liquid nitrogen at the cutting zone.
Dhananchezian and Kumar (2011) investigated the effect of cryogenic cooling with a modified cutting tool inserts on cutting temperature, cutting force, workpiece surface finish and tool wear during the machining of Ti-6Al-4V alloy. The results have been compared with conventional wet machining. A substantial benefit of cryogenic cooling on tool life and surface finish was reported. It was also reported that the application of liquid nitrogen reduces cutting force due to effectively control the cutting temperature, maintaining the strength and hardness of the tool material, reduction in tool wear and less adhesion between tool – chip and tool – work interfaces.

Dhananchezian and Kumar (2011a) have studied the role of cryogenic cooling on cutting temperature, cutting force, workpiece surface finish and tool wear in the turning of AISI 304 stainless steel with a modified PVD TiAlN coated carbide tool inserts. The effectiveness of cryogenic cooling was compared with conventional cooling. The results showed that cryogenic cooling using LN₂ provided reduced cutting temperature, cutting force, surface roughness and tool wear compared with conventional cooling. The beneficial effects of cryogenic cooling can be contributed that the effective lubrication, retention of tool hardness and control of temperature dependent wear mechanisms.

2.5.6 Hybrid Machining System

The hybrid machining approach combines traditional turning with cryogenically enhanced machining and plasma enhanced machining.

Wang et al (2003) worked on the hybrid machining of the Inconel 718. It is reported that the hybrid machining of the Inconel 718 using WG-300 ceramic tool inserts, produced better surface finish, longer tool life, and lower cutting forces compared with conventional machining.
2.5.7 Cryogenic Rake and Flank Surface Cooling System

In this cryogenic cooling method, liquid nitrogen jets were impinged on the tool rake and flank surfaces, using a specially designed nozzle.

Venugopal et al (2007) studied the effect of cryogenic cooling on the growth and nature of tool wear in the turning of the Ti-6Al-4V alloy bars with microcrystalline uncoated carbide inserts. The influence of cryogenic cooling with liquid nitrogen jets enabled a substantial reduction in the tool wear, both on the crater and flank surfaces in the turning of the Ti-6Al-4V alloy. It was also reported that there was a substantial improvement in tool life by a reduction in adhesion – dissolution – diffusion tool wear through the desirable control of machining temperature at the cutting zone.

Venugopal et al (2007a) have investigated the tool wear and tool life of uncoated carbide cutting tool inserts in the machining of the Ti-6Al-4V alloy under dry, wet and cryogenic cooling environments. The rates of growth of all the tool wear parameters, namely, the average flank wear, maximum flank wear, average nose wear and edge depression, were less in cryogenic cooling. A substantial improvement in tool life was obtained under cryogenic cooling as compared to dry and wet machining.

2.6 RECENT STUDIES ON CRYOGENIC COOLING

Hong (2006) investigated the lubrication mechanism of liquid nitrogen in the cutting process. It was found that the injection of liquid nitrogen into the contact zone created a lubricating film. The test results showed that the liquid nitrogen jet was very effective in reducing friction. Liquid nitrogen injection forms a physical barrier or hydrodynamic effect between two bodies which is always effective in reducing the friction force.
Stanford et al (2008) carried out an experimental investigation in the turning of BS 970-080A15 (En 32b) plain carbon mild steel under various cutting environments. The following cutting environments were evaluated: i) Flood coolant ii) Compressed air blast iii) Dry cutting iv) Ambient temperature nitrogen gas environment v) Cold nitrogen gas and vi) Liquid nitrogen gas environment. The results indicated that uncoated tooling used in nitrogen cutting environments whilst cutting En 32b plain carbon mild steel, can provide a 55% reduction in the crater wear and 30% reduction in the flank wear over other environments.

Kumar and Choudhury (2008) studied the effect of cryogenic cooling on tool wear and the high frequency dynamic cutting forces generated during the high speed machining of stainless steel. Liquid nitrogen was supplied to the tool tip using a specially designed nozzle. It was found from the experimental results that cryogenic cooling was effective in bringing down the cutting temperatures which accounted for the substantial reduction of the flank wear. The cutting force in cryogenic machining was observed to be less than that of dry cutting, but the reduction in the cutting force is less than anticipated. About 37.89% reduction in the flank wear has been observed with cryogenic machining over dry cutting. Cryogenic machining is a possible answer for high speed eco-friendly machining.

Yakup and Muammer (2008) reviewed the use of liquid nitrogen as a coolant and investigated in detail the terms of application methods in material removal operations, and their effects on cutting tool and workpiece material properties, cutting temperature, tool wear and tool life, surface roughness and dimensional deviation, friction and cutting forces. It was reported that cryogenic cooling has resulted as one of the most favourable method for metal cutting operations due to its capability of producing considerable improvement in tool life and surface finish through the reduction in tool wear by a desirable control of machining temperature at the cutting zone.
2.7 SUMMARY

The review of the literature suggests that cryogenic cooling provides several benefits in machining. Based on the existing literature studies, it has been concluded that cryogenic cooling is a different approach, in which the temperature at the cutting zone is reduced substantially to a very low range (Mirghani et al 2007). It was also concluded from recent works that, cryogenic cooling is a possible answer for high speed eco-friendly machining (Kumar and Choudhury 2008). Cryogenic cooling is an environment-friendly clean technology for achieving the desirable control of cutting temperature and enhancement of tool life.

A recent work dealt with the experimental investigation of cryogenic cooling by liquid nitrogen in the machining of tool steels. The substantial benefits of cryogenic cooling on cutting temperature, cutting force, surface roughness, tool wear, chip shape and chip morphology were reported. However, more work is needed to explore the potential advantage of cryogenic cooling. In the existing cryogenic cooling methods, many researchers have attempted to supply the liquid nitrogen on the workpiece pre-cooling, tool back cooling, main and auxiliary cutting edges and tool rake and flank face. It has been seen that a lot of research has been done in the past, to improve the machinability of the difficult-to-cut materials, using the cryogenic cooling technique. Machining processes, like turning and grinding has been widely investigated under cryogenic machining conditions compared to that of milling. In the present study, the milling of the AISI D2, AISI D3, AISI H13 and AISI P20 steels using cryogenic cooling LN₂ as coolant has been investigated, for different cutting speeds and feed rates to evaluate the machining performance.