Effect of Applying Conventional Cutting Fluid and Liquid Nitrogen on Grindability of Different Steels

A Project Thesis

By

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Submitted to the Department of Industrial & Production Engineering, Bangladesh University of Engineering & Technology, Dhaka, in partial fulfillment of the requirements for the degree of **Master of Industrial & Production Engineering**.

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September, 2004

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Declaration

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

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Acknowledgements

The author is deeply indebted to Dr. Nikhil Ranjan Dhar, Associate Professor of the Department of Industrial and Production Engineering, Bangladesh University of Engineering and Technology (BUET), Dhaka for his continuous help and encouragement throughout the progress of the project work

The author also expressed his gratitude to Dr. M. Ahsan Akhtar Hasin, Associate Professor of Industrial and Production Engineering Department, BUET for his support and kind interest in this project work. The author is grateful to Dr. A K. M. Masud, Assistant Professor of Industrial and Production Engineering Department, BUET.

The author is highly thankful to Dr. Md. Fazlul Karim, Principal, Bangladesh College of Leather Technology (BCLT) and Dr. P. Bala of the same for giving permission to use Scanning Electron Microscope to carry out the research work.

The author has great pleasure in expressing his indebtness to Vice-Chancellor, DUET, Gazipur and Head of the Department of Mechanical Engineering of the same university for their permission, help and encouragement. The help extended by the British Oxygen Company (BOC), Bangladesh for supplying a liquid cylinder with liquid nitrogen to carry out the work is also sincerely acknowledged.

The author is deeply indebted to Sumaiya Islam, Research Assistant, IPE Department, BUET for her help at various stages of the work A special word of thanks is due to all staff members of Machine Tools Laboratory for their helps in conducting the experimental work

Finally, the author offers his sincore thanks to all those who either directly or indirectly helped him in various ways to complete this project thesis, especially to his wife for her very painstaking work to spend her time alone and continuous support of patienco.

September, 2004 Author

Abstract

Strained environment is a global problem. In metal industries the use of coolant has become more problematic in terms of both employee health and environmental pollution. It is said that the use of coolant forms approximately 8-16 % of the total production cost.

The traditional methods that use coolants are now obviously becoming obsolete. Hence, it is clear that using a dry cutting system has great implications for resource preservation and waste reduction. For this purpose, a new cooling system is designed for dry cutting. This research work presents an eco-friandly cooling innovation and the benefit gained by using this method. In order to compare the performance of using this system, grinding experiments were carried out on dry and flood cutting environment in different infeed condition

The present work investigates the role of cryogenic cooling by liquid nitrogen jet on chip formation, grinding zone temperature and surface roughness in grinding steels. The experimental results indicate significant reduction in cutting temperature on application of cryogen, which enables favorable chip formation. It was also noted that cryogenic grinding provide relatively more surface roughness for less plastic deformation and rubbing, shearing and fracturing modes of chip formation and retention of the grit's sharpness. Therefore, it appears that cryogenic cooling, if properly employed, not only provides environment friendliness but can also improve the grindability characteristics.

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Chapter-1

Introduction

1.1 Introduction

Grinding is a widely used conventional process employed mainly for finishing surfaces of wide range of materials, such as metals, carbides, ceramics, rocks etc with high dimensional and form accuracy and a good surface finish. Often grinding is also done for stock removal and semi finishing in the industries.

In grinding, material is generally removed by shearing and ploughing in the form of micro sized chips by the abrasive grits The grits are distributed and held in position on the wheel by a non-metallic or metallic bond.

The advantages of grinding over conventional machining processes are;

i. high dimensional and form accuracy

ii. good surface finish

iii. not much restricted by the hardness of the work material.

The major applications of grinding are;

i. finishing of flat and cylindrical surfaces

ii. finishing and sharpening of the cutting tools

iii. form grinding and contour grinding of cold and hot working dies

iv. form grinding of threads and gears

v. stock removal

The grinding process can be broadly classified as;

i. surface grinding-by the periphery and the face of the wheels

ii. cylindrical grinding-internal and external; straight, taper and form

iii. center less grinding-internal and external; straight and form

iv. special purpose grinding-cams, threads, bearing, cutting tools etc.

Grinding process is characterized mainly by high specific energy requirement due to large negative rake and high cutting speed, which results in very high temperature. Such high temperature often leads to several problems like;

i. a large heat affected zone

ii. change in hardness and micro structure of the work piece

iii. development of un-tempered and over tempered martensitic layer in heat treatable ferrous alloys

iv. burning and its consequences

v. developments of high tensile residual stresses and micro cracks.

The tensile residual stresses, if present in the ground sample, results in reduction in both the static and dynamic strength and corrosion resistance, and leads to distortion just after machining and in service life. The tensile residual stress also induces surface and sub surface micro cracks specially in case of brittle materials.

Another distinct problem in grinding ductile and sticky materials is wheel loading mainly due to accumulation of chip particles in the inter grit spaces. This reduces the grinding efficiency and hence requires frequent redressing of the wheel. Thus, wheel loading also cuts down the total useful life of the wheel. Besides that wheel loading also causes rise in forces, temperature and vibrations, poor surface finish, redeposition, poor surface integrity etc.

It appears that the high temperature in grinding zone is the main problem and hence methods were tried out over the years to tackle this problem. Application of proper grinding fluids at times, reduced the above problems to some extent through cooling and lubrication of the grinding zone. The commonly used fluids are neat oil, soluble oil, semi synthetic and synthetic fluids with or without additives and inorganic salts. The application procedures of these fluids are generally by flood cooling or in the form of jet or even mist. Interrupted grinding technique by using grooved wheels or Dalmatian wheels, continuous cleaning or dressing by ultrasonic, use of CBN wheels, electrochemical grinding have also been investigated and tried out to reduce the grinding temperature.

Ample research has been done in various directions and is still going on aiming improvement in overall grinding efficiency through controlling the aforesaid problems.

1.2 Survey of the Previous Work

1.2.1 Mechanism of Chip Formation and Chip Characteristics

The study of grinding chip is required to understand the mechanism of chip formation and those of material removal. Early investigators [**Dall 1939, Ernst 1950 and Tarasovs 1950**] identified the mechanism of chip formation in grinding to be mainly shearing, like that in other conventional machining processes, by studying the shapes of the chips under optical microscope.

Wetton [**1969**], while analyzing the composition of the grinding debris, found not only grinding chips but also fractured and pulled out grit and bond materials, which latter necessitated careful interpretation of optical and scanning electron microscope.

Cashion et al [**1974**], while studying Mossbauer spectrum from fine grinding chips, observed that the chips are mainly formed by shearing process Doyle and Aghan [**1975**] supported the same observations while examining the grinding chips under transmission microscope. They also obtained clear lamella or segments, which clearly indicated the mechanism of chip formation to be shearing Malkin [**1979**] also opined that the major mode of material removal in grinding is shearing. Doyle and Dean [1980], classified different types of chips obtained in grinding as;

i. chips of no particular shape

ii. spherical chips and

iii. lamellar chips.

Debris having no shapes is generally produced by rubbing of the wear flats of the grits with the work surface and by ploughing, and these kinds of chips are associated with poor surface finish and redeposition of chips on the ground surface. Spherical chips are generated by surface oxidation of other kinds of chips. Lamellar chips are generally produced by shear as in conventional metal cutting action.

Sakuma and Tado [1982] reported that the mode of chip formation changes with the change in the hardness and the heat treatment cycle of the work material and the wheel speed. They obtained leafy lamellar chips at low wheel speed, which became longer with the increase in wheel speed. With further increase in wheel speed follow spherical chips were obtained

Ramanath et al [1987] opined that the spherical chips can form either by exothermic reaction of the chips with the oxygen present in the vicinity or due to sharp bending of the very thin platelets. These platelets are generally formed because of elastic rubbing of the wear flats of the grits on the work piece. They suggested that high count of spherical chips indicate severe rubbing of the wheel with the work piece.

Pai et al [1989], while grinding ductile materials, reported that long lamellar filament type chips, blocky particles and spherical chips were obtained. The length of the filament type chips and number of spherical chips were found to decrease on taking harder materials and/ or using sharper wheels.

Abundance of spherical chips within the grinding debris hints that even melting may takes place in grinding. But Outwater [1952] and Shaw [1990], suggested that as melting is a time-temperature phenomenon the material never stays at very high temperature for sufficient time to melt.

Kumandari [1971] and Moneim et al [1983] investigated the mechanism of grinding by simulating it by turning and shaping with highly negative rake tool and found that side flow occurs instead of chip formation when the tool is provided with very large negative rake.

König Schmalt [1978] observed lamellar chips for ductile materials and less number of lamellar chips for harder materials. Chattopadhyay et al [1990, 1991] similarly observed that mostly crushed type chips and lamellar chips are obtained while grinding harder and ductile materials respectively with brazed monolayer CBN and diamond wheels.

1.2.2 Grinding Temperature

Outwater and Shaw [**1952**] noted that grinding is associated with much high specific energy requirement which may be an order higher than that required in conventional machining processes. The obvious consequences of this high specific energy are very high grinding zone temperature. They analytically found the mean and maximum surface temperature using Jaegar model of semi-infinite body and insulated friction slider with uniform heat distribution.

Walter et al [**1975**] measured the temperature history by embedded thermo-couple technique and correlated the grinding temperature with the structural changes in the ground workpiece.

Dex Ruisseaux and Zerkle [**1970**] reported that the heat generated due to chip formation in grinding at the shear plane results in high temperature near the cutting edges of the grits and in the material. But this temperature is not of any importance as the material ahead of the grit is removed as chips. The quality of the ground surface would depend upon the surface and subsurface temperature and they analytically found the expressions for the same using Jeager's Model assuming uniform distribution of the heat source.

Malkin and Anderson [**1974**] in an experimental study arrived at the percentage of the total heat flowing into the work piece as,

$$R = \frac{U - 0.45U_{ch}}{U} X 100\% \qquad (1)$$

Where,

R = partitioning coefficient

U = specific energy

U_{ch} = specific energy of chip formation (13.8 J/mm^3)

Malkin [1974] realized that the temperature on the surface of the work piece is governed by two temperature fields, namely, the local temperature field below a particular grit and the average temperature due to distributed heat source action over the whole contact length. The analytical solution was obtained assuming the material properties at a particular elevated temperature.

Yamamoto et al [1977] noted that the average temperature at the work surface is dependent on the grinding wheel performance, work piece material characteristics and the grinding parameters.

Snoeys et at [1978] indicated that the estimation of temperature by analytical or numerical techniques would be influenced by the type of heat source distribution. However, they pointed out that the use of rectangular distribution would suffice the purpose of evaluating the temperature field The actual contact length greatly differs from the geometric contact length and they expressed the actual contact length as a function of the process parameters and geometric contact length.

Kops and Shaw [1982] identified the temperature at the grit, surface and subsurface of the work piece to be related to;

i. grinding wheel wear
ii. surface finish
iii. surface integrity and accuracy.

Skalli et al [1982] estimated temperature field and its history on the surface and subsurface of the work piece using finite element method. They considered the actual contact length to be twice the geometric contact length and the heat source to be uniformly distributed. The variation of thermal properties of the material with temperature was neglected.

In a similar work, Vansevenant [1987], however, assumed the heat source to be triangular in nature. The variation in the thermal properties of the work material with temperature was taken into account.

Recently Shaw [1990] proposed a simpler analytical approach to evaluate surface temperature in fine grinding and finally arrived at an expression of partitioning coefficient.

Levine [1991] has modified a few previously developed models to account for the fact that some of the grinding energy is generated at the shear plane and not entirely at the wear flats as has been assumed previously. The modification did not affect the results for alumina wheels, but the errors of the previous models were considerable for CBN wheels.

Rowe et al **[1991]** have also developed a thermal model for the grinding process at the grain zone. The only problem with the present model is in assigning the grain wear flat area.

Recently Wager and Wu **[1991]** studied the nature of temperature variation in up and down grinding. They noted that the temperature increases with the increase in infeed and work speed and the temperature difference between the up and down grinding follows the same pattern

1.2.3 Control of Grinding Temperature

Grinding is basically a mechanical process, characterized by high temperature, which is generally controlled by application of grinding fluid. Duwell et al **[1966]** postulated that the chemical reactions at the ground surface during grinding play a vital role due to high temperature and higher reactiveness of the freshly formed ground surface.

Malkin and Lenz **[1978]** suggested that the grinding fluids should be used to lubricate and thus reduce the specific energy requirement, as the normal grinding fluids are ineffective in controlling the high temperature

Snoey et al **[1978]** also supported the idea that in grinding, lubrication should be given more importance as long as normal fluids are used.

Nee [1979] studied the applicability of additives and solid lubricants in grinding tool steels with diamond wheels. Some of the additives, especially colloidal graphite, improved the wheel performance but solid lubricant failed to improve the tool performance.

Kops and Shaw [1982] observed that the chips adhering to the wheel act as additional heat source, which may lead to overheating of the wheel and hence more wheel wear.

Yasui and Tsukuda [1983] reported that though the application of grinding fluids brings down the temperature, but their film boiling temperature restricts their effectiveness.

Shaw [1985] suggested the following methods to control the grinding temperature:

i. lower wheel speed
ii. lower material removal rate
iii. use of coolants
iv. softer wheels
v. intermittent grinding.

Howes [1990] has reported that the lubricating and the cooling properties of the grinding fluids directly influence the surface integrity of the work piece. But the effectiveness of coolants are lost if the temperature exceeds the film boiling temperature of the fluids.

One of the most important factors preventing or restricting the grinding fluid from penetrating into the grinding zone has been the thin but stiff layer of air around the rotating wheel. The rotating wheel sucks the air through the facial pores and due to the centrifugal action this air comes out through the periphery forming a stiff airflow.

Akiyama et al [1984] and Aoyama and Inasaki [1984] studied the improvements in the grinding fluid action using painting and cardboard technique. The faces of the wheels are covered with silicon rubber paints, which prevent the wheels to draw in air from the surrounding. In card board technique a scrapper board made of soft card board is held against the wheel, which diverts the air strip away and facilitates the coolant delivery at the grinding zone.

Nakayama et al [1977], Snoeys et al [1978] and Shaw [1985] advocated the use of slotted wheels to control the temperature. Nakayama et al [1977] reported reduction in the forces and temperature by using grooved wheels due to intermittent cutting and better coolant delivery.

Shaw [1985] reported that disk wheels provided with through holes randomly distributed over their faces are found to perform with less temperature in face grinding mode. This was attributed to intermittent cooling of the work piece. Shaw reported the use of 'Dalmatian' wheel to control the temperature.

Aoyama and Inasaki [1984] adopted on line ultrasonic cleaning method to continuously dress the wheel and remove any loaded particle. This helped in maintaining the wheel sharpness and provided less temperature.

Graham and Whitson [1978] delivered the coolants through the pores of the wheels and observed benefits like reduction in the forces, temperature and surface cracking and improvement in wheel life.

Eda et al [1985] studied the effectiveness of the jet infusion technique of application of the grinding fluids. This technique brings out all the potentials of the grinding fluids.

Pecher and Malkin [1984] reported that grinding with CBN wheels is almost free from thermal damages because of retention of its grit sharpness and chemical stability. Shaw [1990], Levine [1991] and Rowe [1991] suggested that the partitioning coefficient is also very small in case of CBN wheels, which further reduces the thermal damages.

1.2.4 Adverse Effects of Conventional Cutting Fluid Applications

Traditionally, the manufacture of a product had been attempted to be done as quickly and inexpensively as possible. Now that more environmental regulations are being put in place, manufacturers are forced to re-evaluate their manufacturing processes and reduce or eliminate their waste streams.

The waste streams present in machining include cutting fluid flow, chip flow, and cutting tool usage.

The application of cutting fluid may not always reduce the cutting tool wear as is commonly believed. Rather some conditions like machining steels by carbide tools, the use of coolant may increase tool wear. It has been experienced [**Shaw et al. 1951**] that there was more tool wear when cutting with coolant than cutting dry in case of machining AISI 1020 and AISI 4340 steels by M-2 high speed steel tool cutting. Seah et al. [**1995**] also reported that at the first stage of machining (first 40 seconds or so), tool wear was faster in wet cutting than in dry cutting. Later on, the wear rate stabilized and was somewhat the same for both dry and wet cutting.

During machining, the cutting tool generally undergoes [**Trent 1983**] both flank wear and crater wear. Flank wear generally causes an increase in the cutting forces, dimensional inaccuracy and vibration. Crater wear takes place on the rake face of the tool where the chip slides over the tool surface. Another experimental investigation was conducted [**Cozzens et al. 1995**] on single point boring. This was aimed to study the role of cutting fluid, tool and workpiece material, tool geometry and cutting conditions on machinability. The results indicated that the cutting fluid conditions had no significant effect on surface texture, forces and built-up edge. Since boring is a high-speed operation and lubrication is ineffective, no effect was seen on the forces. However, the cutting fluid was found to have a significant effect on surface integrity.

Proper selection and application of cutting fluid generally improves tool life. At low cutting speed almost four times longer tool life was obtained **[Satoshi et al. 1997]** by such cutting fluid. But surface finish did not improve significantly. Wearing of cutting tools not only causes loss of the cutting edges or tips of the inserts but loss of the entire insert after wear of all the corners. From an environmental perspective, therefore, the significant waste is not the portion of the tool worn away by the tool-work contact, but the remaining portion of the tool that is disposed after its useful life **[Sheng and Munoz 1993]**.

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

i. environmental pollution due to breakdown of the cutting fluids into harmful gases at high cutting temperature (Fig.1.1)
ii. biological hazards to the operators from the bacterial growth in the cutting fluids

iii. requirements of additional systems for pumping, local storage, filtration, temporary recycling, cooling and large space requirement

iv. disposal of the spent cutting fluids which also offer high risk of water pollution and soil contamination

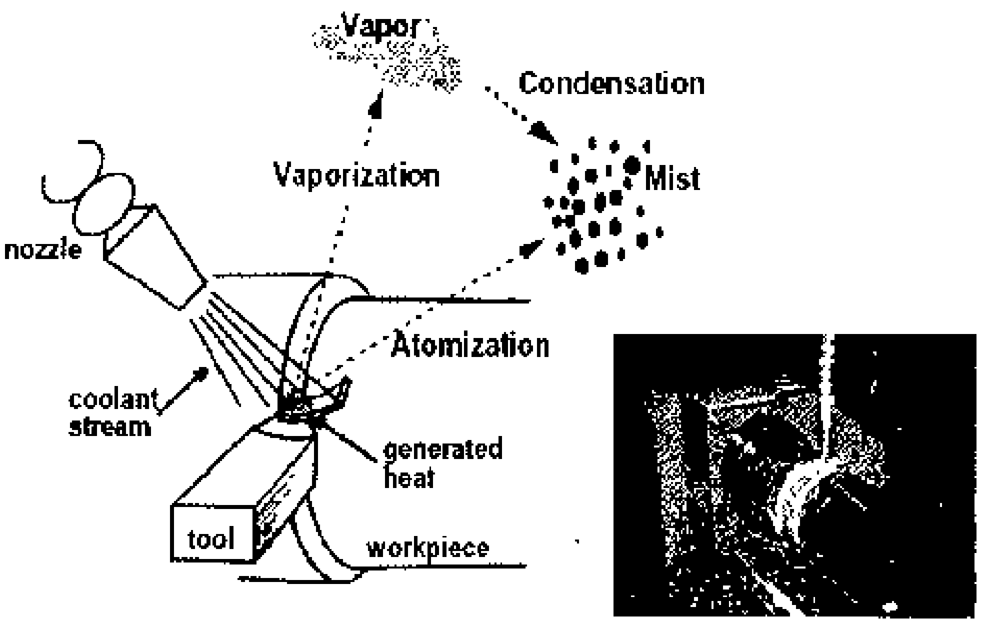


Fig. 1.1 Mist formation during machining with flood cooling

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

It has been estimated [**Bennett 1983**] that about one million workers are exposed to cutting fluids in the United States alone. Since cutting fluids are complex in composition, they may be more toxic than their constituents and may be irritant or allergenic. Also, both bacteria and fungi can effectively colonize the cutting fluids and serve as source of microbial toxins. Hence significant negative effects, in terms of environmental, health, and safety consequences, are associated with the use of cutting fluids. The effects of exposure to the fluids on health have been studied for over 50 years; beginning with the concern that cutting fluid (oil) is a potential etiologic factor for occupational skin cancer (Epidemiological studies indicate that long-term exposure to metalworking fluids can lead to increased incidence of several types of cancer). The International Agency for Research on Cancer has concluded that there is "sufficient evidence" that mineral oils used in the workplace is carcinogenic **[Peter et al.1996]**. Basically, workers are exposed to metal cutting fluids via three routes **[Bennett et al. 1985]**; skin exposure, aerial exposure and ingestion (Fig.1.2)

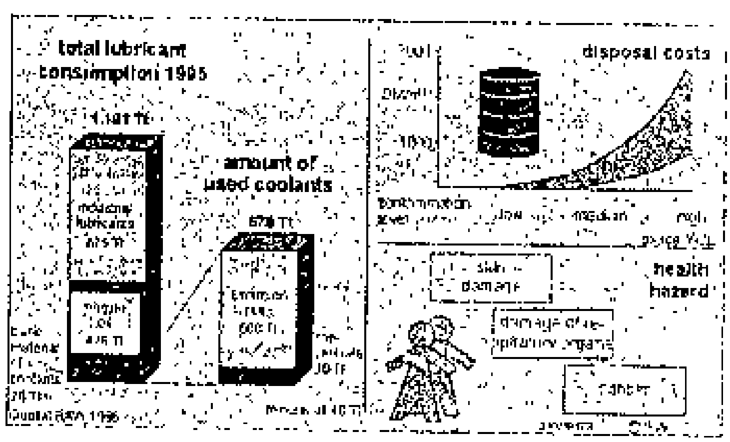


Fig. 1.2 Cost and health hazard of using cutting fluid

Skin exposure is the dominant route of exposure, and it is believed that about 80 percent of all occupational diseases are caused by skin contact with fluids **[Bennett et al.1985]**. Cutting fluids are important causes of occupational contact dermatitis, which may involve either irritant or allergic mechanisms. Water mixed fluids generally determine irritant contact dermatitis and allergic contact dermatitis when they are in touch with workers skin. Non-water-miscible fluids usually cause skin disorders such as foliculitis, oil acne, keratoses and carcinomas (Fig.1.3).

Iowa Waste Reduction Center [1996] reported that besides potential skin and eye contact, inhalation is also a way to occupational exposure. Mists are aerosols comprised of liquid particles (less than 20 μm). During machining process, a considerable amount of heat is generated for which the cutting fluid may attain a temperature sufficiently higher than the saturation temperature. The vapor is produced at the solid-liquid interface as a result of boiling. Vapor may be generated also at the liquid-air interface when the fluid vapor pressure is less than the saturation pressure, namely as evaporation phenomena. Vapor generated then may condense to form mist (Fig.1.1 and Fig.1.3). The non-aqueous components of the cutting fluid, such as the biocide additives, appear as fine aerosol that can enter the workroom air. Additionally, the cutting fluids impact with both stationary and rotating elements within the machine tool system, which leads to mechanical energy being transmitted to the fluid. Thus, the cutting fluid has higher surface energy and becomes less stable and disintegrates into drops (atomization). The spray from the fluid application also may generate mist. A total fluid loss of 5 to 20 percent may occur due to evaporation, atomization, splashing and drag out processes. Whether formed by atomization or evaporation/ condensation, small droplets may be suspended in the air for several hours even several days in the workers breathing zones. These drifting droplets tend evaporate further. Inhaled particles (with aerodynamic diameters less than 10 μm) deposit in the various regions of the respiratory system by the complex action of the different deposition mechanisms. The particulate below 2.5 μm aerodynamic diameter deposit primarily in the alveolar regions which is the most sensitive region of lung. The particulate in size ranges from 2.5 μm to 10-μm deposits primarily in the airways. The potential health effects of exposure to cutting fluid mists have been the subjects of epidemiological studies in the automotive industry. The mist droplets can cause throat, pancreas, rectum, and prostate cancers, as well as breathing problems and respiratory illnesses. One acute effect observed is mild and reversible narrowing of airways during exposure to cutting fluid mist **[Kennedy 1989]**.

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

Anti misting compounds, such as a polymetha-acrylate polymer, poly-isobutylene and poly-n-butane in concentrations of 0.2% as well as poly (1, 2-butene oxide) have been suggested for addition into cutting fluids **[Bennett**

et al. 1985]. But, consideration must be given to the effects of these chemicals upon humans. The most effective way to control mist exposure is to use mist collector to prevent mist from entering plant air [**Leith et al. 1996**]. Many collectors use several stages of filters in series for the purpose. Other collectors use centrifugal cells or electrostatic precipitators as intermediate stages. Any collector using a 95% Di-Octyl Phthalate (DOP) or High-Efficiency Particulate Air (HEPA) filter as a final collection stage has been tested as high efficiency when new. However, its efficiency will decrease with time. Moreover, the oil droplets may undergo partial or complete evaporation as they travel to collector [**Raynor et al. 1996**]. The generated organic vapors may return to the room and affect work health, and may re-condense on the cool surface causing safety and maintenance problems.

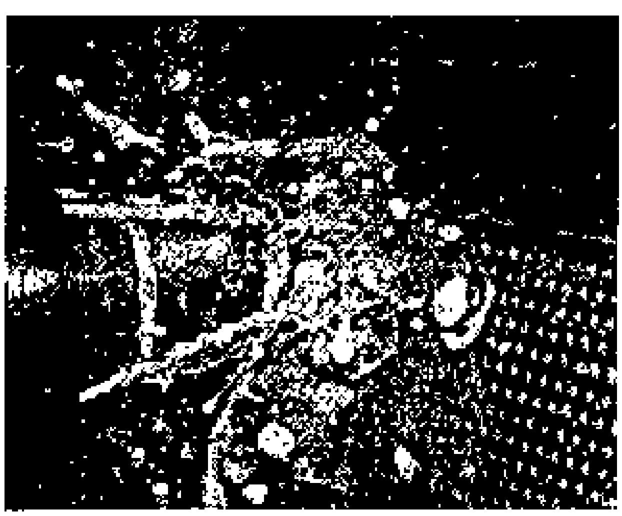


Fig.1.3 Mist formation during turning operation under flood cooling condition

Pollution free manufacturing is increasingly gaining interest due to recent development of pollution-prevention legislation, European initiatives on product take-back or recycling, which affect many export industries in the US, and a growing consumer, demand for green products and production processes. Concern for the environment, health and safety of the operators, as well as the requirements to enforce the environmental protection laws and occupational safety and health regulations are compelling the industry to consider a cryogenic machining process as one of the viable alternative instead of using conventional cutting fluids.

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

1.2.5 Characteristics of Ground Surface

Marshall and Shaw [**1952**] described burning as the appearance of the temper color on the ground surface due to high temperature. They observed burning to occur with loaded wheel.

Outwater and Shaw [**1952**] found that the redeposition of chips on the ground surface increases in absence of oxygen and this may render a material almost ungrindable. The oxygen, even if present in traces, would from a thin oxide layer on the nascent ground surface and that hinder further redeposition rendering the material grindable.

Welton [**1969**] noted that redeposition increases with the increase in infeed due to higher temperature. Bond materials were found to exist along with the redeposited chip particles on the ground surface.

Malkin and Cook [**1971**] observed a relation between burning and the forces. The normal and the tangential forces and their ratio suddenly increase at the onset of the burning.

Malkin [1974] reported that in grinding hardened steels, burning is associated with a hardened zone at the subsurface followed by a soft tempered zone just beneath it Burning would occur when the critical temperature for austenite formation has been reached on a sufficiently large portion of the grinding zone.

Field and Koster [1978] suggested that the ground surface should not contain undesirable surface defects such as micro cracks, surface hardening or softening, overheating or burning, untempered and /or over tempered martensites.

Malkin and Lenz [1978] described the burning to be characterized by the formation of oxide layers on the surface and transformation of austenitic structure. Burning is a critical average temperature phenomenon and the burning temperature is insensitive to normal grinding fluids.

Snoeys et al [1978] suggested that the surface characteristics can be expressed as change in the physical and/or chemical characteristics of the upper layers of work piece, fatigue life, stress corrosion, appearance of tensile stresses, surface and subsurface cracks etc.

Burning causes change in color and Shimamune and Ono [1983] attributed this to optical interference. The color depends on the thickness of the oxide film, which develops due to temperature over a certain limit

(500^0C). Howes [1990] noted that the redeposition of chips decreases substantially with the application of grinding fluid.

Prasad and Prasad [1991] studied the surface and the subsurface of abraded ferrous alloys by pin on disk method. For hardened steel, the abraded surfaces appear to be uniform and had a groovy structure, whereas in annealed specimens micropitting is observed. In annealed steel subsurface cracks, microstructural changes and grain refinement occurs, but negligible microstructural changes takes place for the hardened steels.

1.2.6 Summary of the Review

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

Metal cutting fluids changes the performance of machining operations because of their lubrication, cooling and chip flushing functions Typically, in the machining of hardened steel materials, no cutting fluid is applied in the interest of low cutting forces and low environmental impacts. Cryogenic cooling presents itself as a viable alternative for hard machining with respect to tool wear, heat disserfation and machined surface quality This research compares the mechanical performance of cryogenic ceoling by liquid nitrogen to cempletely dry and wet lubrication for the grinding of steel based on experimental measurement of chip formation mode, cutting temperature and surface finish.

1.3 Objectives of the Present Work

Literature survey reveals that application of cryogen as coolant may improve the machinability characteristics in high speed machining and grinding which are inherently characterized by high temperature, which is responsible for several detrimental effects. But it appear that research in this direction has not been done yet systematically and thoroughly to have clear understanding of the behavior and extent of benefits of cryogenic cooling in grinding different work materials including various steels.

The main object of the present work is to experimentally investigation of the mechanism of metal removal and grindability characteristics in surface grinding of several steels of common use at different infeed rates;

i. in dry condition
ii. under flood cooling with soluble oil
iii. under cryogenic cooling by liquid nitrogen jet

Mainly in respect of

i. chip formation modes
ii. actual grinding zone temperature and
iii. surface topography

The present research work provided the scopes of development and use of

i. a suitable nozzle for liquid nitrogen jet
ii. simple technique of measuring grinding zone temperature

Chapter-2

Development of Cryogenic Cooling System

2.1 Introduction

The high cutting temperature generated during machining not only reduces tool life but also impairs the product quality. The temperature becomes more intensive when cutting velocity and feed are increased for higher MRR and the work materials are relatively difficult to machine for their high strength, hardenability and lesser thermal conductivity. Cutting fluids are widely used to reduce the cutting temperature. But the major problems associated with the use of conventional methods and type of cutting fluids, which are mostly oil based, are:

i. ineffectiveness in desired cooling and lubrication

ii. health hazards due to generation of obnoxious gases and bacterial growth

iii. inconvenience due to uncleanliness of the working zone

iv. corrosion and contamination of the lubricating system of the machine tools

v. need of storage, additional floor space, pumping system, recycling and disposal
vi. environmental pollution and contamination of soil and water.

In this regard, it has already been observed through previous research that proper application of cryogenic cooling by agents like liquid nitrogen may play vital role in providing not only environment friendliness but also some techno-economical benefits.

For achieving substantial technological and economical benefits in addition to environment friendliness, the cryogenic cooling system needs to be properly designed considering the following important factors:

i. effective cooling by enabling liquid nitrogen jet reach as close to the actual hot zones as possible
ii. avoidance of bulk cooling of the tool and the job, which may cause unfavorable metallurgical changes
iii. minimum consumption of cryogen by pin-pointed impingement and only during chip formation

2.2 Liquid Nitrogen Delivery System Selected and Used for the Present Work

The liquid nitrogen needs to be drawn at high pressure from the dewar and impinged at high speed through the nozzle. Considering the conditions required for the present research work and uninterrupted supply of liquid nitrogen at consistent pressure around 10 bar over a reasonably long cut, a vacuum insulated and self pressurized stainless steel dewar of large capacity (180 litre) has been procured and used. The photographic view and the circuit of the Dewar are shown in Fig 2 1.

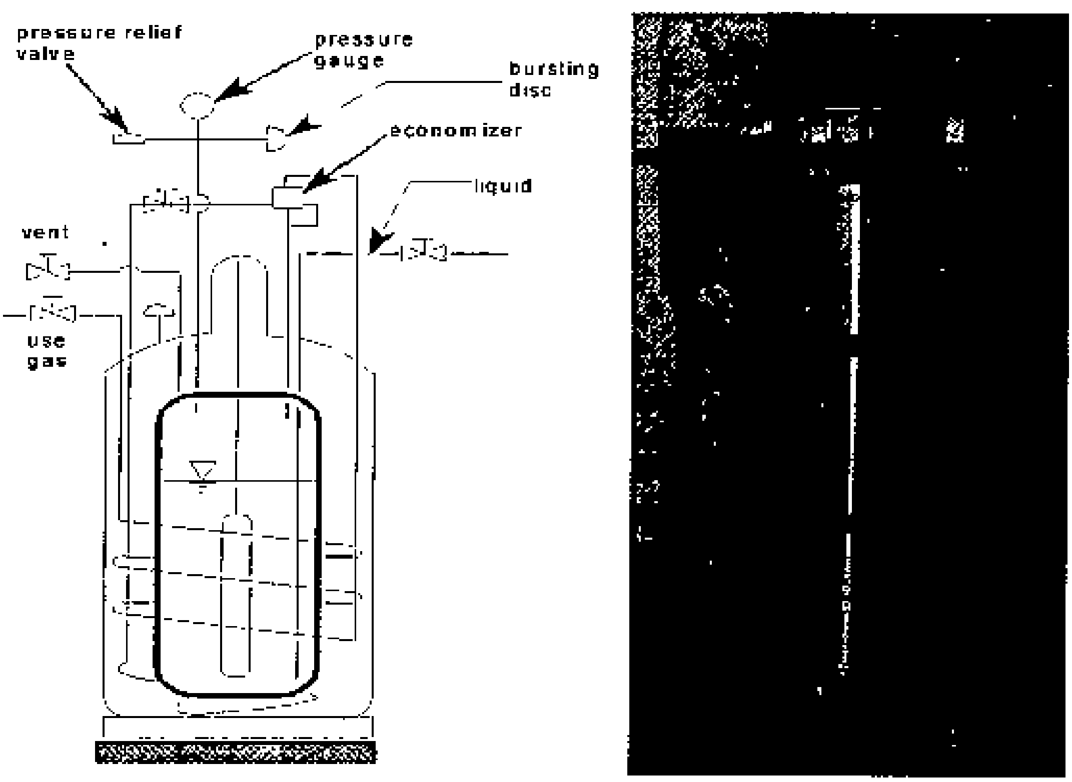


Fig.2.1 Dewar and its operating circuit

The liquid nitrogen is contained in the dewar and a pressure building circuit is used to ensure desired high driving pressure during the high withdrawal periods. This is accomplished by opening a hand valve that creates a path from the liquid at the bottom of the container, through the pressure building regulator, to the gas space in the top. When the pressure building valve is open and the container pressure is below the pressure building regulator setting, liquid taken from the inner container is vaporized in a heat exchanger which is inside the outer casing. The expanding gas is fed into the upper section of the container to build pressure. The resulting pressure will drive either the liquid or gas delivery system.

An economizer circuit withdraws gas preferentially from the headspace over the liquid in the container otherwise that gas would be lost to venting. Excess pressure in the head space of the container is relieved by allowing gas to flow from this area directly to the USE valve outlet while gas is being withdrawn from the container. The economizer is automatic and requires no operator attention.

The internal heat exchanger inside the vacuum space attached to the container's outer casing provides a means of introducing heat from outside the container's insulated jacket, to vaporize liquid as gaseous product.

Liquid product is added or withdrawn from the container through the connection controlled by the liquid valve. It has the CGA fitting that is required for liquid line connections. The valve is opened for fill or liquid withdrawal after connecting a transfer hose with compatible fittings to the Liquid line connection. Pressure building valve isolates the liquid in the bottom of the container to the Dual Pressure Building/Economizer Regulator. This valve must be opened to build pressure inside the container. The Vent valve controls a line into the head of the container. It is used during the fill process. The Vent valve acts as a fill point during a pump transfer, or to vent the headspace area while liquid is filling the inner container during a pressure fill through the Liquid valve.

The container contents a float type level sensor that indicates liquid content through magnetic coupling to a yellow indicator band. This gauge is an indication of approximate container contents only and should not be used for filling. These cylinders have a gas service relief valve and inner container-bursting disc with setting of 230 psig or 16 bars and 380 psig or 26 bars respectively. A 22 psig or 1.5 bar relief valve is provided for liquid delivery applications.

2.3 Design and Fabrication of the Nozzle

The nozzle has been designed so that the nozzle spray pattern, covering area and liquid nitrogen rate can be controlled. The nozzle developed and used and its setting along the tangential direction of the rotating grinding wheel are shown in Fig.2.2. The nozzle of 1.5 mm bore diameter was fixed to grinding wheel casing and is connected with insulated copper pipe to supply liquid nitrogen in the form of jet to the grinding zone. The expected result of this arrangement is effective cooling with economical liquid nitrogen dispensing. The construction and setting of the nozzle tips have been made primarily aiming:

i. less interference with the flowing chips
ii. high speed liquid nitrogen jet reaching quite close to the grinding zone and
iii. simple and low cost.

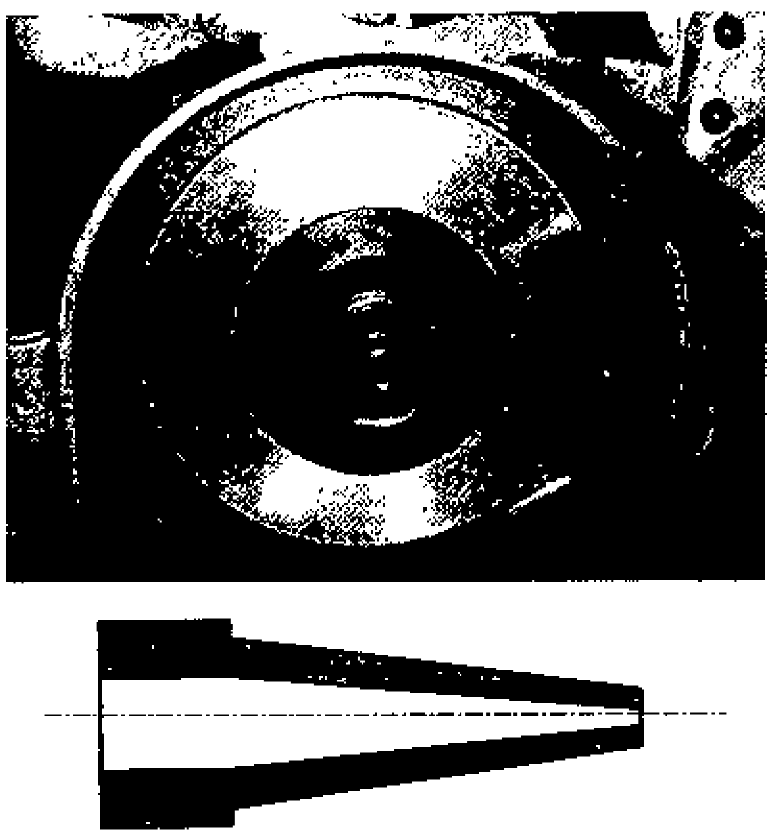


Fig. 2.2 Photographic and schematic view of the nozzle used for liquid nitrogen delivery at the cutting zone

Chapter-3

Experimental Investigations

3.1 Experimental Procedure and Conditions

The beneficial role of cryogenic cooling on environment friendliness has already been established. The aim of the present work is primarily to explore and evaluate the role of such cryogenic cooling on grindability characteristics of some commonly used steels mainly in terms of chip formation modes, cutting zone temperature and surface topography, which govern productivity, product quality and overall economy.

The present experiments were conducted in a surface grinder in plunge surface grinding mode. The grinding experiments have been carried out under dry, wet (soluble oil) and cryogenic cooling conditions. The conventional cooling system provided in the machine has been used for wet grinding tests. In the cryogenic grinding, liquid nitrogen jet is made to impinge the grinding zone from suitable distance and angle as shown in Fig.3.1.

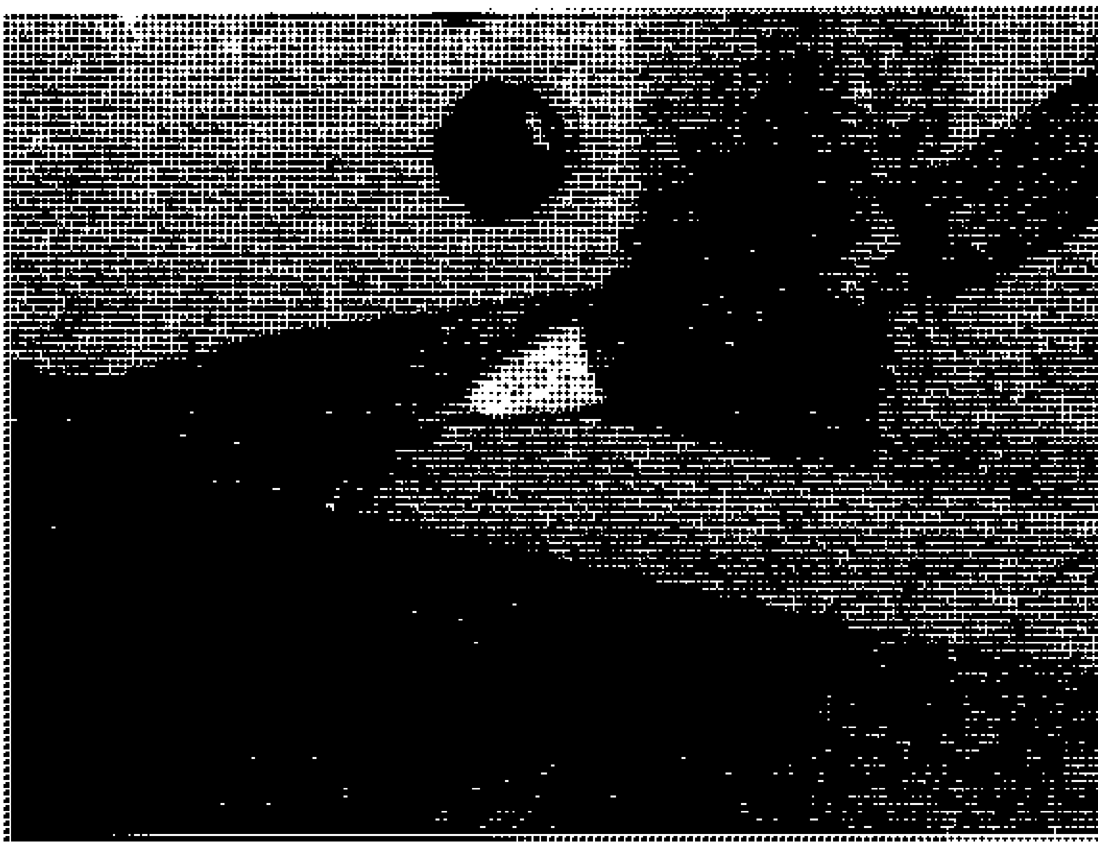


Fig.3.1 Photographic view of liquid nitrogen delivery nozzle injecting liquid nitrogen during grinding

The experimental set-up is schematically shown in Fig.3.2 and the photographic view of the same is shown in Fig.3.3. The present experimental conditions are given in Table-3.1.

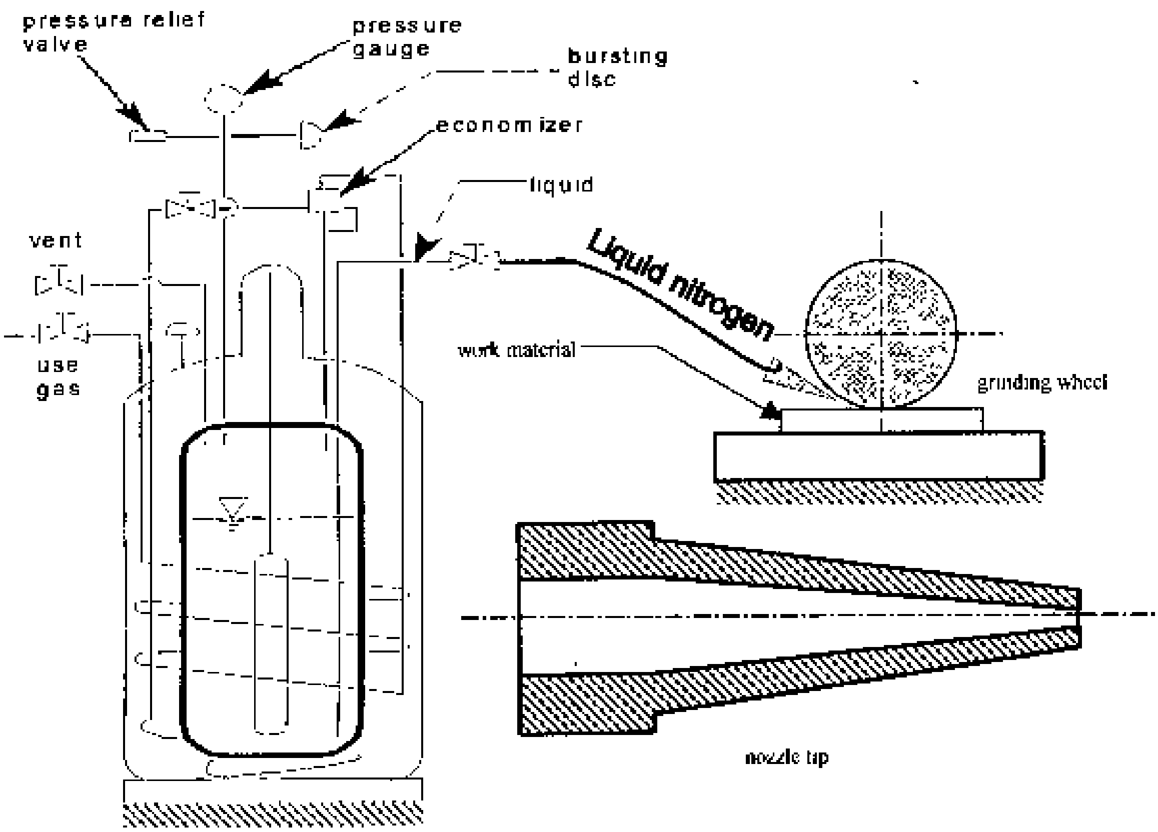


Fig.3.2 Schematic layout of the experimental set-up

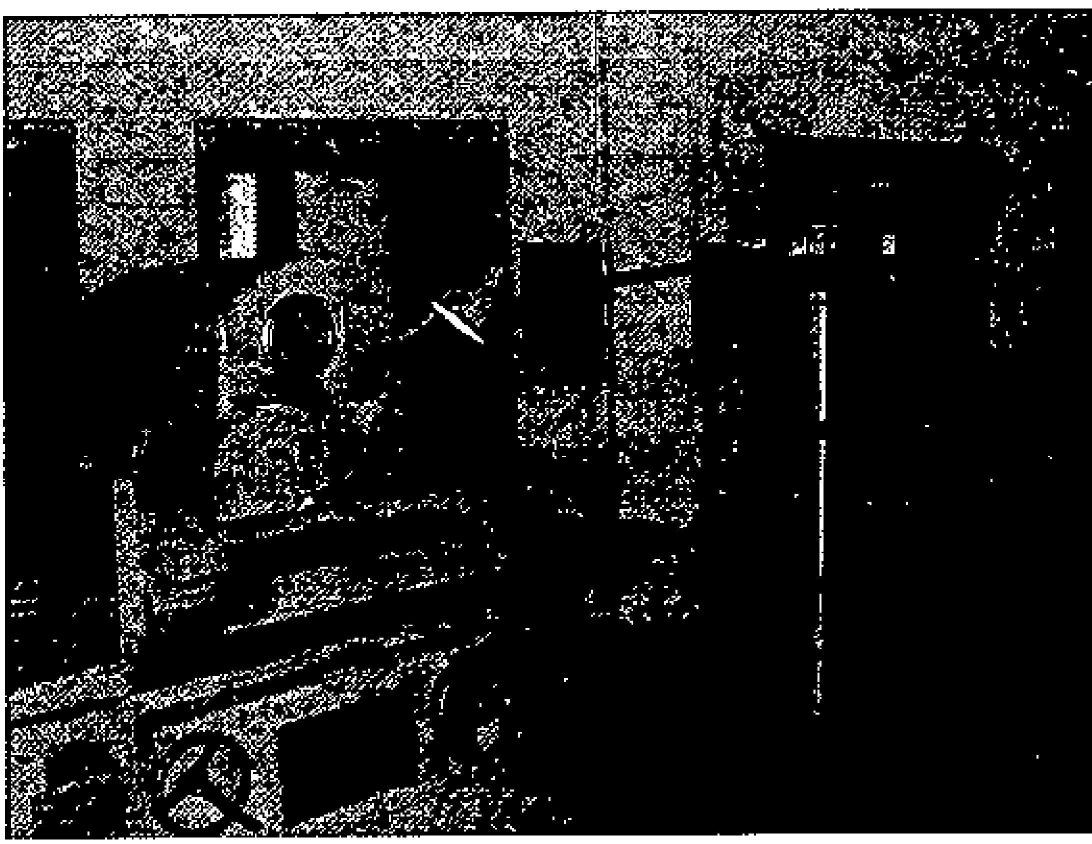


Fig.3.3 Photographic view of the experimental set-up

Table-3.1 Experimental conditions

Machine	Horizontal Spindle Surface Grinding Machine with Rectangular Table (model: M7120A), 2.8 kW
Workpiece	o 42CrMo4 Steel o 16MnCr5 Steel
Workpiece Size	100mm X 68mm X 16mm
Wheel	D126R100 B60-3 mm
Spindle speed	3000 rpm
Wheel speed	39.89 m/sec
Table speed	6 m/min
Infeed	10 μm, 20 μm, 30 μm and 40 μm
Environment	1. Dry condition 2. Flood cooling with soluble oil and 3. Cryogenic cooling

Machining ferrous metals by carbides is a major activity in the machining industries. Machining of steels involves more heat generation for their ductility and production of continuous chips having more intimate and wide chip-tool contact. Again, the cutting temperature increases further with the increase in strength and hardness of the steels for more specific energy requirement. Keeping these facts in view the commonly used steel like 42CrMo4 steel and 16MnCr5 steel have been undertaken for the present investigations. The compositions, strength, hardness and industrial use of this steel are given in Table 3.2.

Table-3.2 Characteristics of the used steel **[Rothman 1988 & Bagchi 1979].**

Work material	BHN	UTS (Kgf/mm^2)	Chemical composition (wt %)	Applications
42CrMo4	252	101	C=0.450%, Si=0.300%, Mn=0.75%, Cr=1.02%, Mo=0.30%, Ni=0.60%, P=0.035%, S=0.035%	• Axles shafts • Induction track pins • Crankshafts • Connecting rods • Gears
16MnCr5	201	111	C=0.17%, Si=0.30%, Mn=1.2%, Cr=1.02%, P=0.035%, S=0.035%)	• Heavy duty gears • Pinions • Camshafts • Clutch plates

The positioning of the nozzle tip with respect to the grinding wheel has been settled after a number of trials. The final arrangement made and used has been shown in Fig.3.1. The cryogenic cooling jet is directed in such a way that it reaches at the grinding wheel and workpiece interface.

3.2 Experimental Results

3.2.1 Microscopic study of the chips

The chips were collected for all the treatments by placing a glass slide coated with petroleum jelly on the spark stream during grinding. The collection of the chips were carried out only after the grinding has reached the steady state indicated by almost no vibration in the magnitude of the grinding forces with the number of passes. Those chips were thoroughly washed with acetone, dried and magnetically separated from the grinding wheel debries. Then the cleaned chips were mounted on small brass disk and observed under scanning electron microscope (HITACHI, S-2600N Scanning Electron Microscope, Japan) to study the morphological characteristics of the chips. The photographs of the chips obtained under the different environments and at different infeeds have been shown in Fig.3.4 to and Fig.3.11 respectively.

Environment	Infeed
	10 µm
Dry	
Wet	
CRYOGENIC COOLING	

500 µm

Fig.3.4 SEM photographs of grinding chips under dry, wet and cryogenic cooling conditions at 10 µm infeed while grinding 42CrMo4 Steel

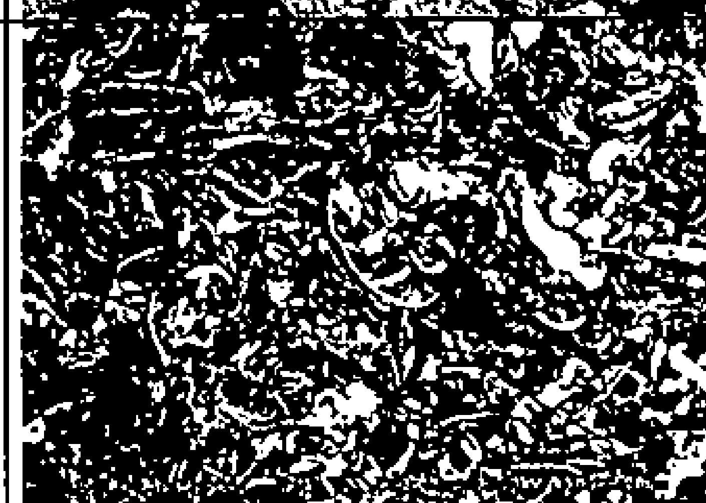
Environment	Infeed
	20 μm
Dry	
Wet	
CRYOGENIC COOLING	

Fig.3.5 SEM photographs of grinding chips under dry, wet and cryogenic cooling conditions at 20 μm infeed while grinding 42CrMo4 Steel

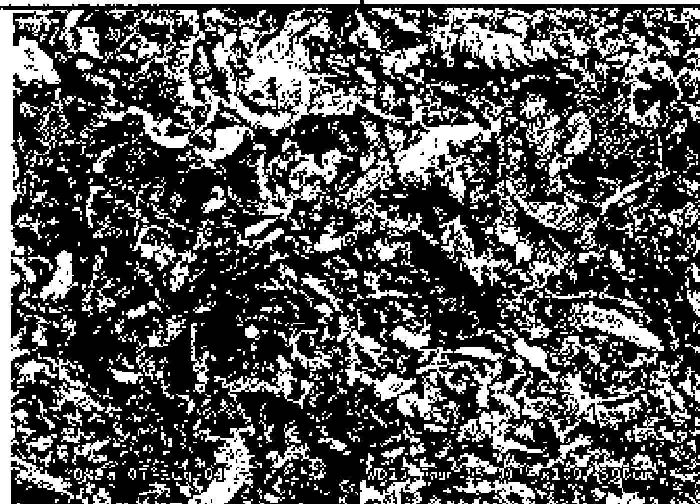
Environment	Infeed
	30 µm
Dry	
Wet	
CRYOGENIC COOLING	

Fig.3.6 SEM photographs of grinding chips under dry, wet and cryogenic cooling conditions at 30 µm infeed while grinding **42CrMo4 Steel**

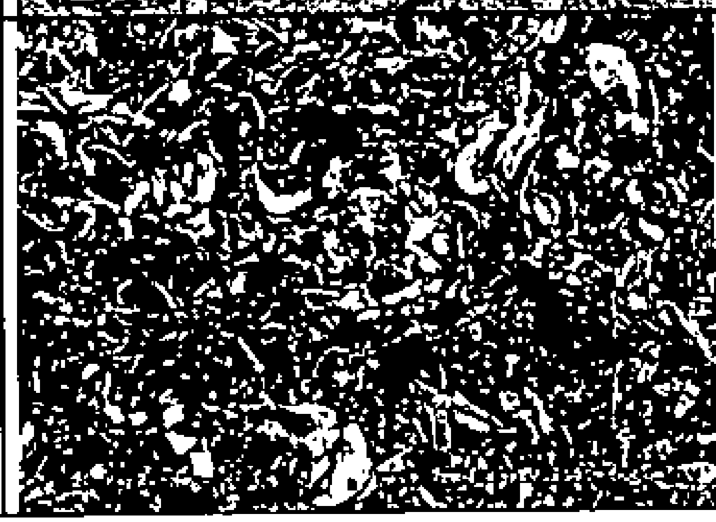
Environment	Infeed 40 μm
Dry	
Wet	
CRYOGENIC COOLING	

Fig.3.7 SEM photographs of grinding chips under dry, wet and cryogenic cooling conditions at 40 μm infeed while grinding 42CrMo4 Steel

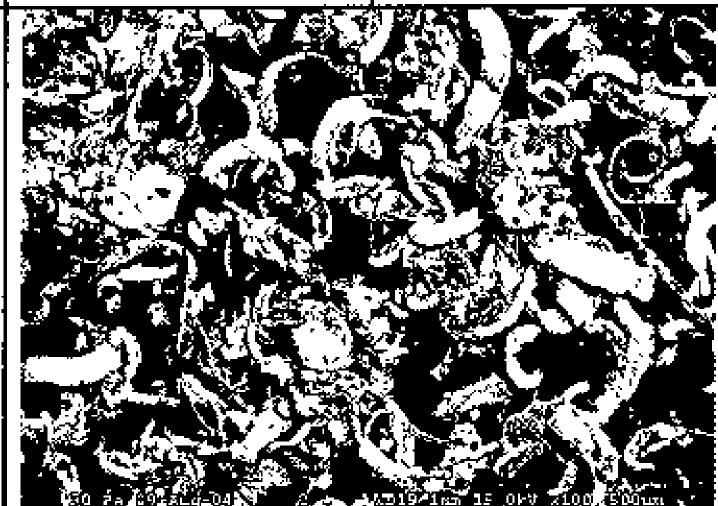
Environment	Infeed
	10 µm
Dry	
Wet	
CRYOGENIC COOLING	

Fig.3.8 SEM photographs of grinding chips under dry, wet and cryogenic cooling conditions at 10 µm infeed while grinding **16MnCr5 Steel**

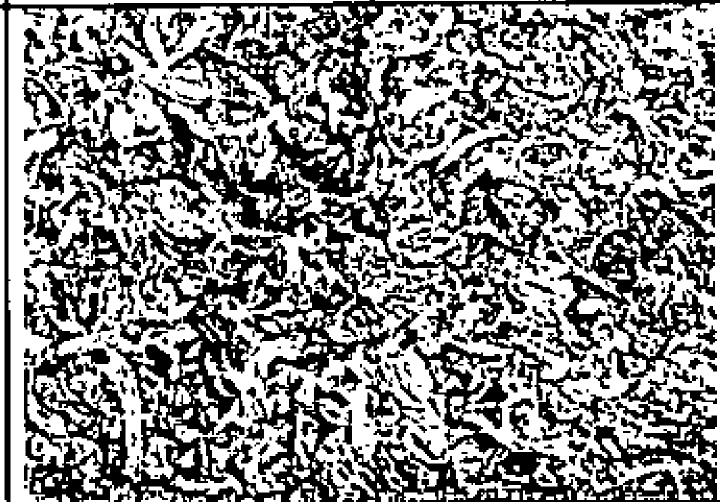
Environment	Infeed
	20 μm
Dry	
Wet	
CRYOGENIC COOLING	

Fig.3.9 SEM photographs of grinding chips under dry, wet and cryogenic cooling conditions at 20 μm infeed while grinding **16MnCr5 Steel**

Environment	Infeed
	30 µm
Dry	
Wet	
CRYOGENIC COOLING	

Fig.3.10 SEM photographs of grinding chips under dry, wet and cryogenic cooling conditions at 30 µm infeed while grinding 16MnCr5 Steel

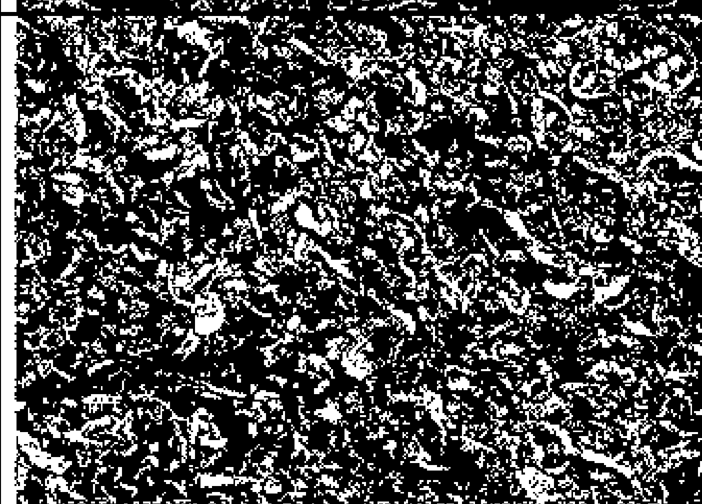
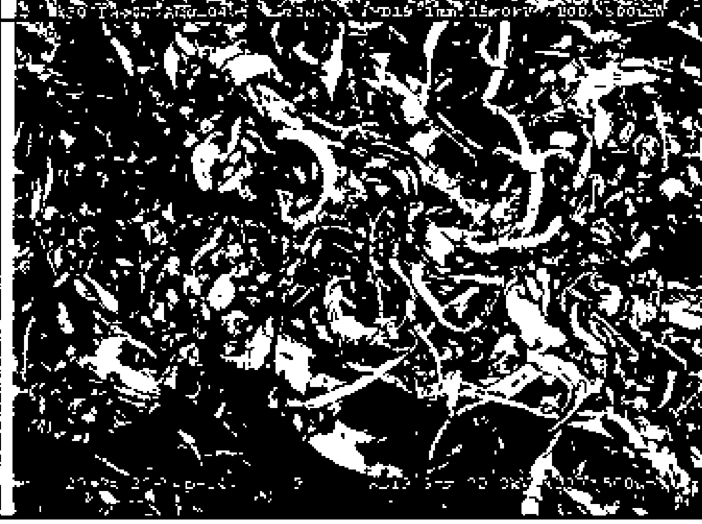
Environment	Infeed
	40 µm
Dry	
Wet	
CRYOGENIC COOLING	

Fig.3.11 SEM photographs of grinding chips under dry, wet and cryogenic cooling conditions at 40 µm infeed while grinding **16MnCr5 Steel**

3.2.2 Grinding temperature

The temperature of the grinding surface has been measured by simple technique by using a constantan wire fitted into a thin slit provided by wire cutting at the middle portion of the work specimens as indicated in Fig.3.12. The constantan wire has been properly secured and insulated in the slit. During grinding operation the wire tip contacted the work surface and formed the hot junction of the constantan-steel thermocouple pair. The voltage signals from the thermocouple were monitored using a suitable digital millivoltmeter (RISH Multi 15S, India). Fig.3.13 and Fig.3.14 show the vitiation of the grinding zone temperature observed in different environments at various infeeds.

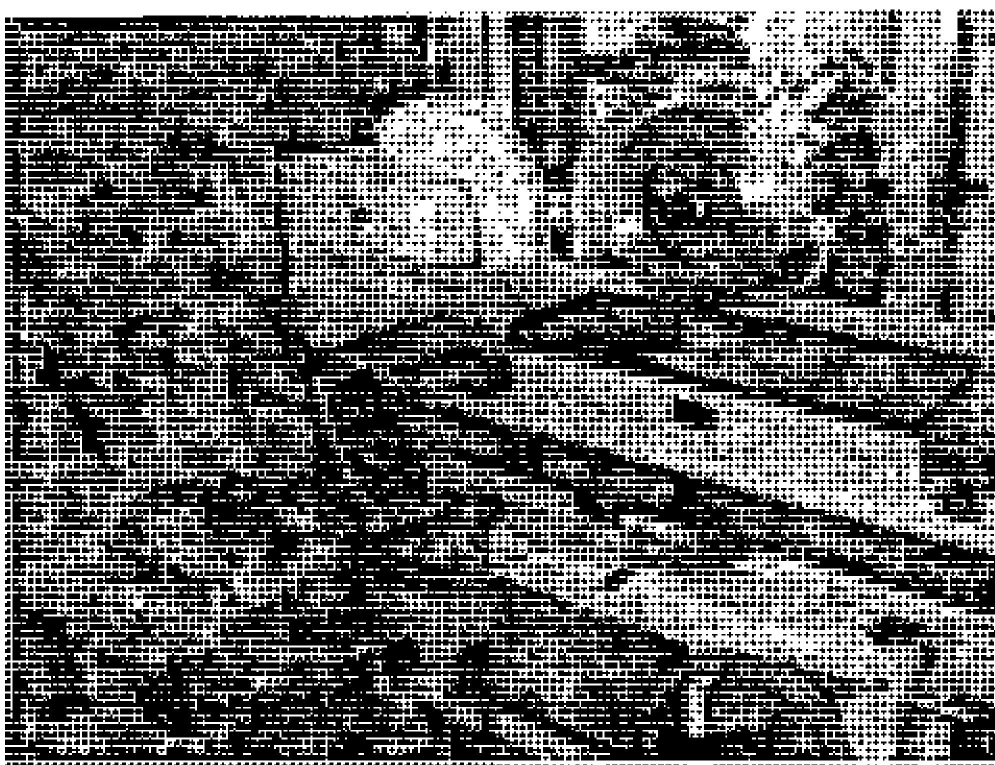


Fig.3.12 Methods of measuring the grinding zone temperature.

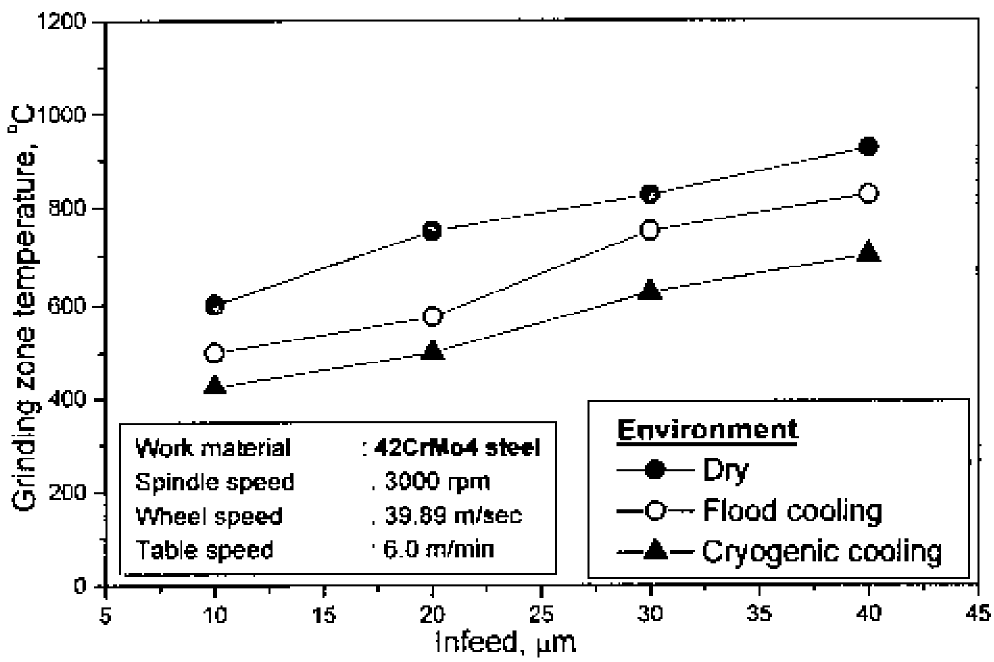


Fig.3.13 Variation in the grinding zone temperature with infeed under dry, wet and cryogenic cooling conditions while grinding **42CrMo4 Steel**.

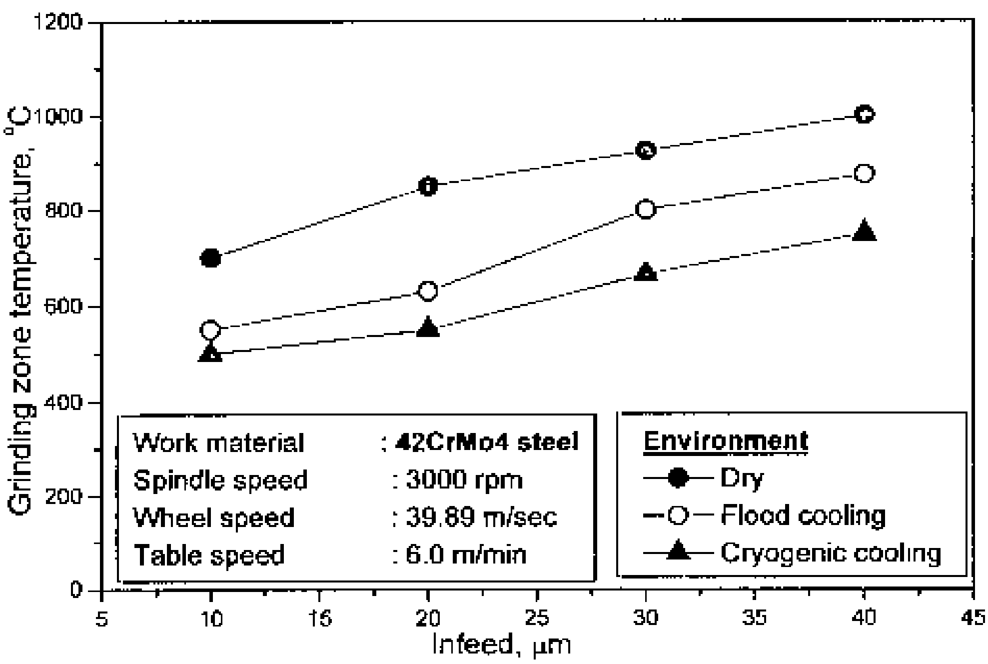


Fig.3.14 Variation in the grinding zone temperature with infeed under dry, wet and cryogenic cooling conditions while grinding **16MnCr5 Steel**.

3.2.3 Surface roughness

The grinding characteristics of any material for any given conditions of the wheel and the grinding process are judged also by the topography of the ground surface. The surface features include general textures, plastic deformation of the asperities, oxidations, and cracks etc. all of which are more or less governed by the high grinding temperature. The surface roughness of the ground specimens has been measured in transverse directions by a Talysurf (Surfronic 3+ roughness checker, Rank Taylor Hobson, UK) as shown in Fig.3.15. Fig.3.16 and Fig.3.17 show the variation in surface roughness observed in different environments at various infeeds.

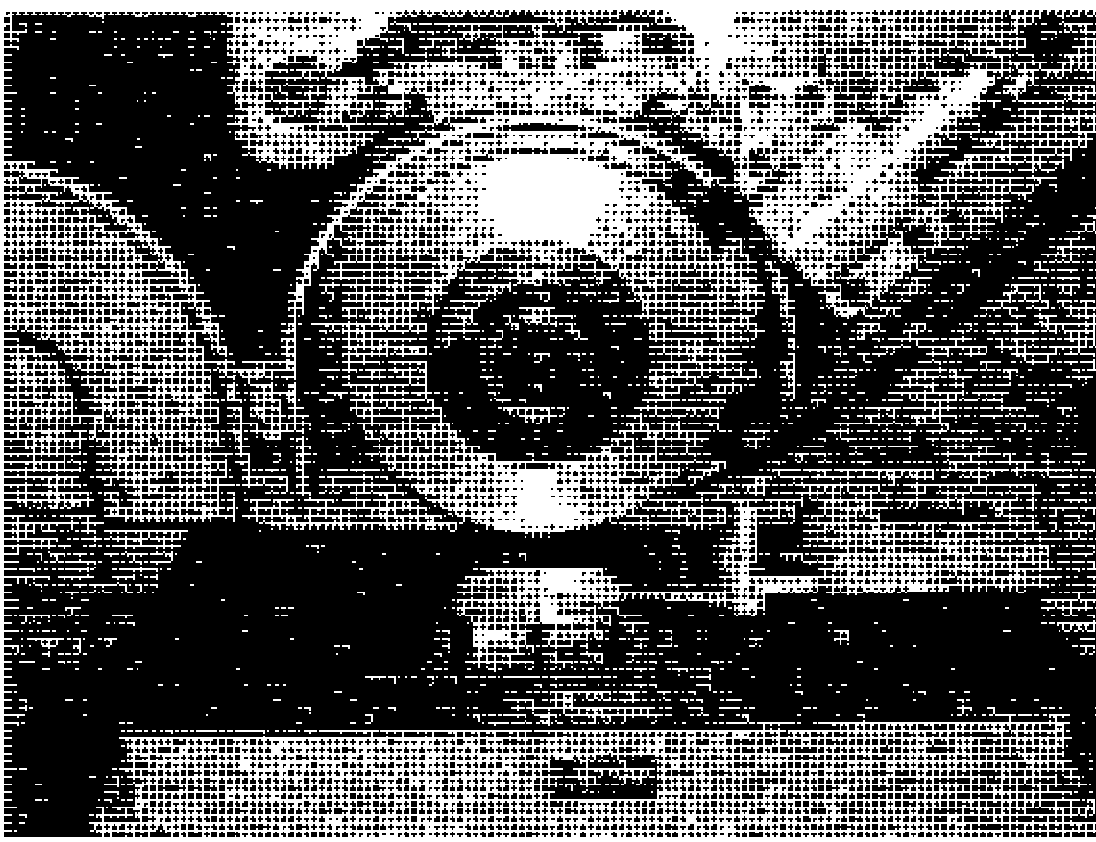


Fig.3.15 Photographic view of measuring surface roughness

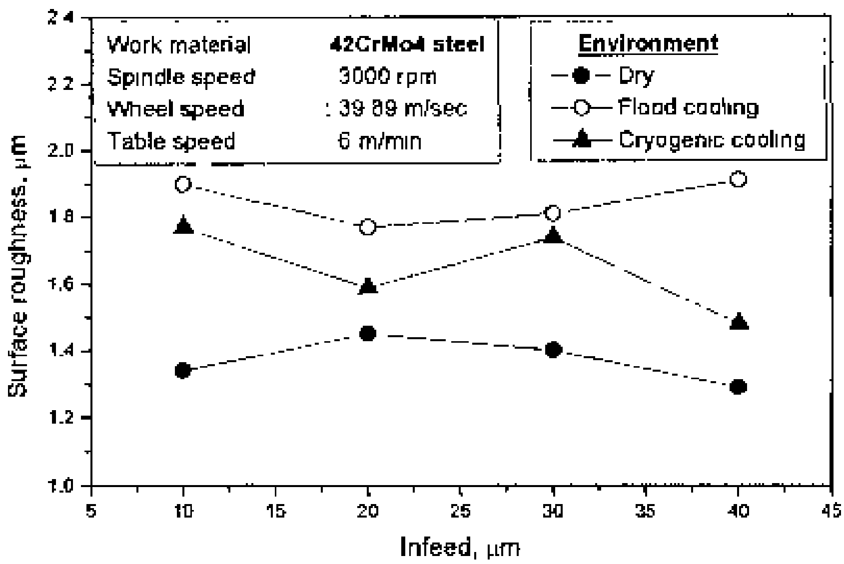


Fig.3.16 Variation in the surface roughness with infeed under dry, wet and cryogenic cooling conditions while grinding **42CrMo4 Steel**.

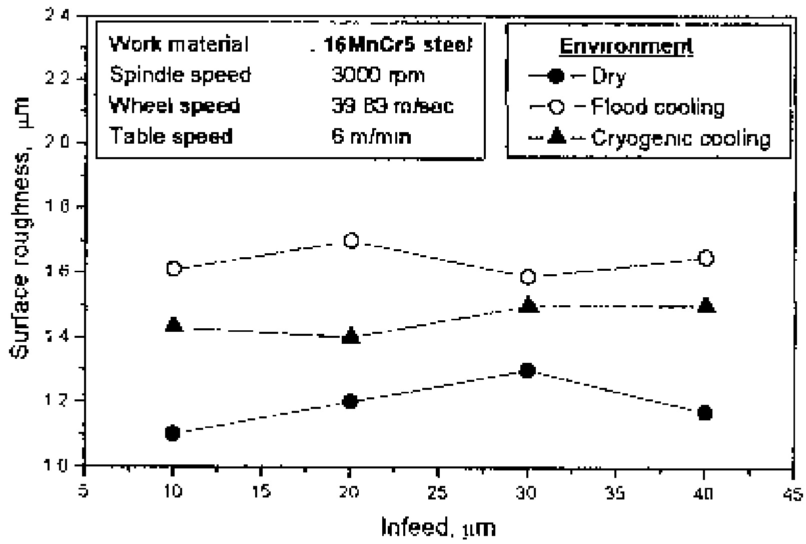


Fig.3.17 Variation in the surface roughness with infeed under dry, wet and cryogenic cooling conditions while grinding **16MnCr5 Steel**

Chapter-4

Discussion on Experimental Results

4.1 Grinding Chips

The study of grinding chip is required to understand the mechanism of chip formation and those of material removal. The chips produced during grinding 42CrMo4 steel at different infeeds have been shown in the figures from Fig.3.4 to Fig.3.7 respectively under the different environments. Dry grinding at both 10 μm and 20 μm infeeds provided different types of chips such as lamellar, spherical, irregular shaped and blocky particles. The clear lamellar structure of the chip indicates shearing to be one of the mechanisms of chip formation. Some small and medium size chips have taken up spherical shape possible due to excessive heating and exothermic oxidation. Higher grinding zone temperature and ductility of this steel specimens are expected to yield larger number of spherical chips. Wet grinding at both 10 μm and 20 μm infeeds also provided almost all types of chips indicating the mechanism of chip formation to be primarily by shearing, ploughing and rubbing. Chips produced under cryogenic cooling condition at both 10 μm and 20 μm infeeds are mainly shear long thin lamellar chips indicating the mechanism of chip formation to be predominantly by shearing.

At higher infeeds of 30 μm and 40 μm, dry grinding yielded almost similar types of chips suggesting similar mechanism of chip formation Under wet grinding at higher infeeds of 30 μm and 40 μm, the chips attained at their backsides smooth appearance with central ridges produced by the tip of the grits and lamellar top surfaces. The increased width of the chip depicts distinct ploughing. Cryogenic grinding on the other hand, provided small fragment crushed chips also along with long lamellar chips, which indicate that, the shearing and fracturing are the main mechanisms of the chip formation under such cryogenic cooling condition. By studying the chip characteristics, it is evident that in dry and wet grinding the mechanism of chip formation is primarily shearing, ploughing and rubbing. And cryogenic cooling substantially changed the mechanism of material removal to predominantly shearing and fracturing. However, no indication was obtained regarding the change in chip formation mechanism with the increase in infeed.

The chips obtained while grinding 16MnCr5 steel at different infeeds under different environments are shown in the figures from Fig.3.8 to Fig.3.11. In case of 16MnCr5 steel spherical chips have been almost absent under all the environments, though all other kinds of chips have been obtained particularly under dry and wet grinding. This indicates that here also the mechanism of chip formation is particularly shearing, ploughing and rubbing. However, the chip formation in cryogenic cooling sheared fracturing significantly. Fig.3.8 to Fig.3.11 reveal that cryogenic grinding yielded much lesser lamellar chips compared to dry and wet grinding and this has been more pronounced when infeed was raised to 40 μm, though as such no substantial variation in the type, length and shape of the chips could be found due to change in infeed. However, comparing figures from Fig.3.4 to Fig.3.7 with the photographs of chips of 16MnCr5 steel (Fig.3.8 to Fig.3.11), it appears that the size of the lamellar chips have decreased, which can be attributed to higher hardness of 42CrMo4 steel as compare to 16MnCr5 steel. Also the number of fractured chips has substantially increased in case of 42CrMo4 steel as compare to 16MnCr5 steel under cryogenic cooling. This indicates that under cryogenic grinding the mechanism of chip formation shifts further from shearing to fracturing with increase in the work hardness. The sixes of the lamellar chips under cryogenic cooling have also been observed to be smaller than those obtained under dry and wet grinding

4.2 Cutting Temperature

Grinding is associated with high temperature which is responsible for aggravating several problems like wheel loading, thermal damages of the ground surfaces, poor grindability etc. in the present work, the benefits expected out of cryogenic cooling over dry and wet conditions are also based mainly on the reduction in the grinding zone temperature. Therefore, to evaluate the major effects of cryogenic cooling in grinding different steels and to explore the main causes of such effects it is essential to determine the grinding temperature under various conditions. The magnitude and distribution of grinding temperature depends on many factors and their relations are quite complex for which it is difficult to evaluate the grinding temperature analytically. A simple technique by using a constantan wire fiffed into a thin slit provided by wire cutting at the middle portion of the work specimens was used to measure the grinding zone temperature

The experimental results shown in the Fig.3.13 and Fig.3.14 clearly indicate that the grinding zone temperature decreases due to cryogenic cooling condition. It is also noted that the cooling efficiency of the liquid nitrogen becomes higher at larger infeeds. Whereas, the ability of cooling by the soluble oil has been quite poor and decreased further with the increase in infeed possibly due to its inability to reach the grinding zone and film boiling at elevated temperature.

4.3 Surface Roughness

In respect of surface finish, Fig.3.16 and Fig.3.17show that cryogenic grinding has all along provided relatively higher surface roughness in compare to dry grinding but lower surface roughness in compare to wet grinding. It has already been stated that in cryogenic grinding by liquid nitrogen jet, efficient cooling and hence retained grit sharpness enable metal removal mainly by shearing, and partly by ploughing and fracturing, producing higher surface roughness in compare to dry grinding. Plastic deformation and oxidation occurring in dry grinding smoothens the surface irregularities. Hence, cryogenic grinding provided apparently higher surface roughness. The aspect of surface burning observed, which indicates that unlike dry and wet grinding, cryogenic grinding has expectedly always been free from burning. This can obviously be attributed to lower temperature, retained grit sharpness and less rubbing and ploughing in cryogenic grinding.

Chapter-5

Conclusions

Based on the experimental results the following conclusions can be drawn

- Cryogenic cooling provided significant improvements expectedly, though in varying degree, in respect of chip formation modes, surface characteristics throughout the infeed range undertaken mainly due to reduction in the grinding zone temperature. Flood cooling by soluble oil could not control the grinding temperature appreciably and its effectiveness decreased further with the increase in infeed.

- Cryogenic grinding shifted the chip formation modes from shearing, ploughing and severe rubbing resulting in long lamellar, leafy, spherical and irreguler shaped chips observed in dry as well as wet grinding to the more favorable modes like sharp shearing and minute fracturing due to retention of the sharpness of the grits, absence of wheel loading and lesser ductility of the steels under lower temperature. Such relative benefit of cryogenic cooling enhanced with the increase in infeed rate.

- Cryogenic cooling by liquid nitrogen provided relatively more surface roughness in comparison with dry grinding but lower in comparison with wet grinding for less plastic deformation and rubbing, shearing and fracturing modes of chip formation and retention of the grit's sharpness.

Chapter-6

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