

A Comparative Study of Air-Cooled Metal Machining with Dry Machining

A Project Thesis

By

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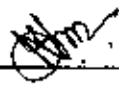
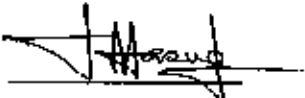
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Abstract

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 costs.

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 the new eco-friendly cooling innovation and the benefits gained by using this method. In order to compare the performance of using this system, cutting experiments were carried out. A series of tests were performed on a horizontal turning machine.

High production machining at high cutting velocity and feed generates large heat and high cutting temperature, which shortens the tool life and deteriorates the job quality. This problem becomes more acute when the jobs are difficult to machine and are to be used under dynamic loading. The conventional cutting fluids are not that effective in such high production machining particularly in continuous cutting of materials like 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 problem. Machining of soft, sticky and ductile materials yields long continuous chips and rapid tool wear due to inefficient action of the cutting fluids. In the present decade, with increased environmental awareness, the researchers are striving to develop environment friendly machining technology; one such technology is to use cooling air. The benefits of reduction in machining temperature are significant reduction in cutting force and feed force. The

benefits of cooling air are dependent on the process parameters and the tool geometry.

Compared to the dry machining, cooling air machining performed many superiors mainly due to substantial reduction in cutting zone temperature enabling favorable chip formation and chip-tool interaction. It also provides substantial reduction in tool wear, which enhanced the tool life, dimensional accuracy. Furthermore, it provides environment friendliness (maintaining neat, clean and dry working area, avoiding inconvenience and health hazards due to heat, smoke, fumes, gases etc. and preventing pollution of the surroundings) and improves the machinability characteristics.

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Chapter-1



Introduction

1.1 High Production Machining under Friendly Environment

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

The performance and service life of engineering component depends on their material, dimensional and forms accuracy and surface quality. Machining and grinding to attain the desired accuracy and surface integrity finish the preformed blanks.

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

But high production machining and grinding with high cutting velocity, feed and depth of cut is inherently associated with generation of large amount of heat and high cutting temperature. Such high cutting temperature not only

reduces dimensional accuracy and tool life but also impairs the surface integrity of the product.

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

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

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

Cutting fluid not only cools the tool and job but also provides lubrication and cleans the cutting zone and protects the nascent finished surface from

contamination by the harmful gases present in the atmosphere. But the conventional types and methods of application of cutting fluid have been found to become less effective. With the increase in cutting velocity and feed, the cutting fluid cannot properly enter the chip-tool interface to cool and lubricate due to bulk plastic contact of the chip with the tool rake surface. Besides that, often in high production machining the cutting fluid may cause premature failure of the cutting tool by fracturing due to close curling of the chips and thermal shocks. For which application of high cooling type water base cutting fluids are generally avoided in machining steels by brittle type cutting tools like carbides and ceramics. But what is of more serious concern is the pollution of the working environment caused by use of cutting fluid, particularly oil-based type.

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

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

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

1.2 Literature Review

Uptil now, ample research and investigations have been done in different parts of the world on machinability of different materials mainly in respect of chip morphology, cutting forces, cutting temperature, chip tool interaction, dimensional accuracy, surface integrity and wear and life of cutting tool with and without (dry machining) using cutting fluid. Environmental pollution arising out of conventional cutting fluid applications has been a serious concern of the modern machining industries. Research has also been initiated on control of such pollution by air-cooling and their technological effects particularly in temperature intensive machining and grinding. A brief review of some of the interesting and important contributions in the closely related areas is presented in this section.

1.2.1 On causes, effects and control of cutting temperature

Machining is inherently characterized by generation of heat and high cutting temperature. At such elevated temperature the cutting tool if not enough hot hard may lose their form stability quickly or wear out rapidly resulting in increased cutting forces, dimensional inaccuracy of the product and shorter tool life. The magnitude of this cutting temperature increases, though in different degree, with the increase of cutting velocity, feed and depth of cut, as a result, high production machining is constrained by rise in temperature. This problem increases further with the increase in strength and hardness of the work material.

It was observed [Jawahir and van Luttervelt 1993] that, in machining ductile metals producing long chips, the chip-tool contact length has a direct influence on the cutting temperature and thermo-chemical wear of cutting tools. The cutting temperature becomes maximum on the rake face of the tool at a certain distance from the cutting edge where cratering occurs. Such

high rake face temperature can also raise the temperature at the flank of the tool.

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

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

Trent [1983] also reported that in machining ductile metals, the chip contact length plays significant role on the chip and tool temperature which becomes maximum almost at the center of the chip-tool contact surface where then crater wear begins and grooves intensively.

Kosa et al [1989] suggested that in machining ductile metals, the heat and temperature developed due to plastic deformation and rubbing of the chips with tool may cause continuous built-up of welded debris which affects machining operation. Austenitic stainless steels are generally considered difficult-to-machine because of high work-hardening rate, toughness and ductility. Therefore, tools will be subjected to high frictional heat, and chips will have a tendency to stick and cause severe built-up edge formation

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

Reed et al. [1983] reported that the hardness, plastic modulus and the fracture toughness of the tool decline with increase in cutting temperature, which accelerates tool wear rate. Moreover, thermal stresses in the tool increase with the temperature resulting in more cracks in the tool and premature failure of the tool. The high cutting temperature also causes mechanical and chemical damage of the finished surface.

Vleugels et al. [1995] observed that the contact length between the tool and chip has a direct influence on the cutting temperatures and the amount of heat energy that is dissipated in the tool which enhances thermally activated chemical wear. Maximum temperature is found to develop on the rake face of the tool, at a certain distance from the cutting edge, where cratering occurs. The amount of energy dissipated through the rake face of the tool also raises the temperature at the flanks of the tool.

The high specific energy required in machining under high cutting velocity and unfavorable condition of machining results in very high temperature, which reduces the dimensional accuracy and tool life by plastic deformation and rapid wear of the cutting points [Chattopadhyay and Bhattacharya 1968, Chattopadhyay and Chattopadhyay 1982 and Singh et al. 1997]. On the other hand such high temperature, if not controlled, impairs the surface integrity of the machined component by severe plastic flow of work material, oxidation and by inducing large tensile residual stresses, micro cracks and subsurface cracks. This problem is further intensified while

machining for faster material removal in bulk and finishing very hard, strong and difficult-to-machine materials that are gradually adventing with vast and rapid developments in the modern areas like aerospace technology and nuclear science.

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

Usually profuse cooling [Alexander et al. 1998, Kurimoto and Barroe 1982 and Wrethin et al. 1992] controls the high cutting temperature. But such profuse cooling with conventional cutting fluids is not able to solve these problems fully even when employed in the form of jet or mist. With the advent of some modern machining process and harder materials and for demand for precision machining, the control of machining temperature by more effective and efficient cooling has become extremely essential.

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

and particularly at the chip-tool interface due to bulk or plastic contact at high cutting speed.

The cooling and lubricating effects by cutting fluid [Merchant 1958 and Kitagawa et al. 1997] influence each other and diminish with increase in cutting velocity. Since the cutting fluid does not enter the chip-tool interface during high speed machining, the cutting fluid action is limited to bulk heat removal only. Mazurkiewicz [1989] reported that a coolant applied at the cutting zone through a high pressure jet nozzle could reduce the contact length and coefficient of friction at chip-tool interface and thus could reduce cutting forces and increase tool life to some extent.

In machining ductile metals even with cutting fluid, the increase in cutting velocity reduces the ductility of the work material and causes production of long continuous chips, which raises the cutting temperature further [Nedess and Hintze 1989].

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

A cutting fluid may impart two more actions, namely the mechanical strength reducing action and the electro-chemical action. The mechanical strength reducing action (known as the Rebinder effect) seemed to be negligible when steel jobs are machined at moderate cutting speeds with carbide tools [Kurimoto and Barroe 1982]. The influence of the electric current flowing through the cutting zone on the rate of tool wear is also well known [Ellis

and Barrow 1969]. However, most commercial cutting fluids are non electro-conductive, and as such the situation with respect to current flow will not vary significantly from the dry cutting case. The electrochemical action is treated as a corrosion phenomenon in respect of tool wear.

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

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

A recent development **[Chandrasekaran et al. 1998]** in this context is the use of Co₂ snow as the coolant in machining. This is feasible if Co₂ in liquid form under pressure (60 bars) is fed to the cutting zone and diffused through a capillary jet. This results in a change of state and the formation of Co₂ snow (endothermic reaction resulting in a temperature of -79°C). Earlier investigations **[Thoors and Chandrasekaran 1994]** observed that Co₂ snow

could function as a good cutting fluid/coolant under certain circumstances, which are very much related to the tool-work combination and the actual mode of feeding the coolant to the cutting zone.

1.2.2 On adverse effects of conventional cutting fluid applications

1.2.2.1 Technological problems

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

The application of cutting fluid may not always reduce the cutting tool wear as is commonly believed. Rather some conditions like machining steels by carbide tools, the use of coolant may increase tool wear.

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

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

During 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].

1.2.2.2 Environmental problems

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

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

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

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

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 folliculitis, oil acne, keraloses and carcinomas.

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. 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/m³, and the United Autoworkers (UAW) has proposed a reduction in the standard to 0.5 mg/m³. The oil mist level in a plant ranged from 4.2 to 15.6 mg/m³ but fell to between 0.47 to 1.68 mg/m³ 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.

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 cooling air machining process as one of the viable alternative instead of using conventional cutting fluids.

1.2.2.3 Economical aspects

Cutting fluids are widely used in machining operations to obtain accuracy of part dimensions, longer tool life and in some cases better surface finish. The research literature identifies two primary functions of cutting fluids in machining operations: lubrication to reduce process friction and cooling to remove process generated heat. A secondary function of the cutting fluid is to transport the chips from the cutting zone. Cutting fluid systems are used in industry to deliver fluid to the cutting process, 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.

1.2.3 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 like 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.

Cooling air is a promising new technology in high production machining and grinding, which economically addresses the current processes' environmental and health concerns. In this unique process cooling air is impinged through a nozzle precisely at the narrow cutting zone. Chilling the cutting tool by cooling air enhances tool hardness and life. Cooling the chip makes it brittle and aids its removal. Since atmospheric air is an abundant source, there is no unfavorable environmental or health impact or coolant disposal cost, and the chips may be reused.

1.3 Objectives of the Present Work

It is revealed from the aforesaid literature survey that cooling air can substantially control the cutting temperature, which is the cause of several problems restraining productivity, quality and hence machining economy.

problems restraining productivity, quality and hence machining economy. The growing demands for high MRR, mainly the high cutting temperature restrains precision and effective machining of exotic materials. Thorough investigation is essential to explore the potential benefits of air-cooling machining in such cases. But enough work has not been done systematically yet in this direction.

The main objective of the present work is to make a thorough and systematic experimental investigation on the role of cooling-air on the major machinability characteristics and overall benefits in respects of

- i. mechanism of machining
- ii. cutting temperature and
- iii. dimensional deviation

in machining commercial steel (AISI 1040 steel) by the industrially used carbide tools at different speeds, feeds and depth of cut combinations.

The scopes of the present work are design and development of

- i. an air-cooling chamber
- ii. a suitable nozzle for air-cooling jet
- iii. an air-cooling machining set up
- iv. temperature measuring technique

Chapter-2

Development of Air 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:

- ineffectiveness in desired cooling and lubrication
- health hazards due to generation of obnoxious gases and bacterial growth
- inconvenience due to uncleanness of the working zone
- corrosion and contamination of the lubricating system of the machine tools
- need of storage, additional floor space, pumping system, recycling and disposal
- environmental pollution and contamination of soil and water.

In this regard, it has already been observed through previous research that proper application of cooling air 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 cooling air system needs to be properly designed considering the following important factors:

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

2.2 Cooling Air Delivery System

Cooling air needs to be drawn at high pressure from the air-cooling unit and impinged at high speed through the nozzle. Considering the conditions required for the present research work and uninterrupted supply of cooling air at consistent pressure around 6 bar over a reasonably long cut, a refrigeration unit with a belt type compressor has been used. The schematic view of the refrigeration circuit is shown in Fig 2.1.

Compressed air from a belt type compressor (6 bars) passes through the refrigerator, which cools the compressed air at a certain temperature and then passes through the flexible pipe (diameter 10 mm) and finally impinges through the nozzle at the cutting zone. During suction of air the outlet valve of the cooling air unit should be closed and the intake valve is open. Air should deliver to the cooling chamber until the pressure indicator indicates 6 bars. Above 6 bars the compressor should be stopped automatically otherwise the high pressure may causes damage to the cooling chamber. At this certain pressure the cooling chamber was run around five minutes to

cool the compressed air. Then the outlet valve is open to pass out the cooling air through the flexible pipe and impinges at the cutting zone through the nozzle.

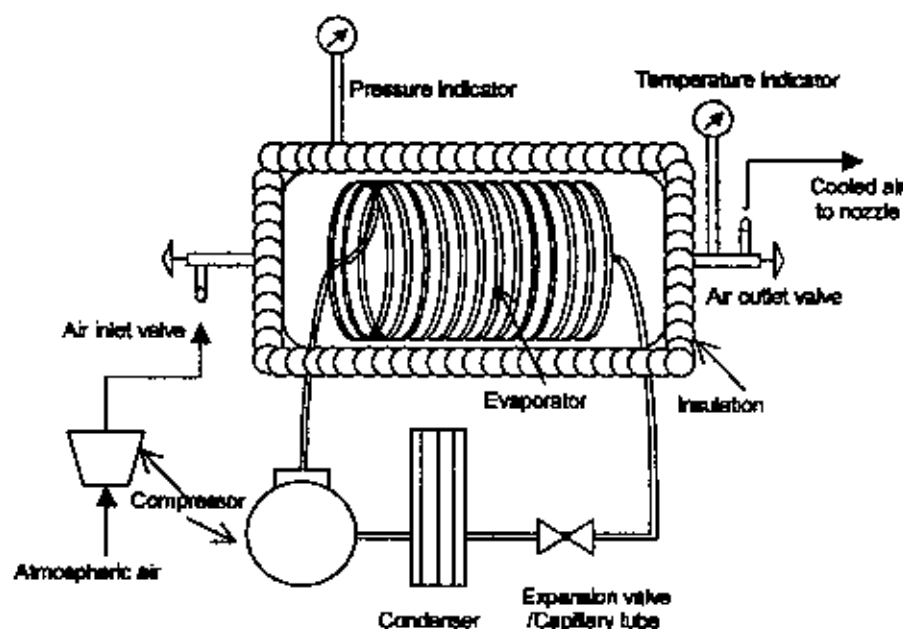


Fig. 2.1 Schematic view of air cooling unit

2.3 Design and Development of the Cooling Air Delivery Nozzle

The nozzle has been designed so that the nozzle spray pattern, covering area and cooling airflow rate can be controlled. The nozzle developed and used and its setting along the tool holder are schematically shown in Fig.2.2. The nozzle with tip of 2.0 mm bore diameter was fixed to the tool post and is connected with flexible pipe connecting end to supply cooling air in the form of jets to the cutting zone. The expected result of this arrangement is effective cooling with economical cooling air dispensing. The construction and setting of the nozzle tips have been made primarily aiming:

- less interference with the flowing chips
- high speed cooled air jet reaching quite close to the chip-tool and work-tool contact zones
- simple and low cost.

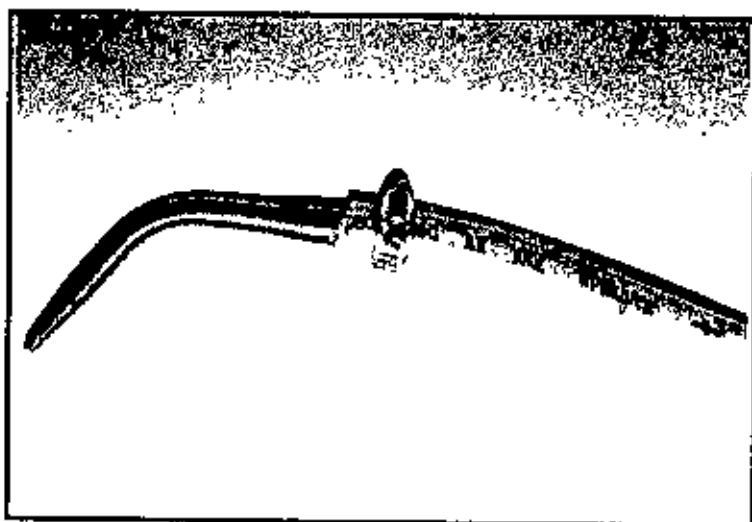


Fig. 2.2 Schematic view of the nozzle used for cooling air delivery at the cutting zone

Chapter-3

Experimental Investigations

3.1 Experimental Procedure and Conditions

The beneficial role of cooling air on environment friendliness has already been established. The aim of the present work is primarily to explore and evaluate the role of such cooling air on machinability characteristics of some commonly used tool-work combinations mainly in terms of cutting temperature and chip-forms, which govern productivity, product quality and overall economy.

The machining tests have been carried out by straight turning of steel in a lathe (4 hp: BMTF, Bangladesh) by standard uncoated carbide insert at different cutting velocities (V_c) and feeds (S_o) under both dry and cooling air condition.

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 AISI-1040 steel has been undertaken for the present investigations. The

compositions, strength, hardness and industrial use of this steel are given in Table 3.1.

Table-3.1 Characteristics of the used steel [Rothman 1988 & Bagchi 1979].

Work material	BHN	UTS (Kgf/mm ²)	Chemical composition (wt %)	Applications
AISI 1040 steel	180	63	C - 0.410, Mn - 0.700, P - 0.040, S - 0.050	• Shafts & crank shafts • Automobile axles • Spindles • Lightly stressed gears

Machining industries generally use sintered carbide tools, both uncoated and coated for machining steels. High performance tools like ceramics toughened and strengthened by stabilized zirconia [Mondal et al. 1992] metals [Tuan and Brook 1990 and Wang et al.1993] and SiC whiskers [Li and Low 1994] and CBN [Narutaki and Yamane 1979] are also used now-a-days by the modern industries. But such tools are not only expensive but also require very rugged and powerful machine tools, which common industries cannot always afford. Diamond tools [Hinterman and Chattopadhyay 1993] are excellent performing for exotic materials excepting ferrous metals which graphitise diamond.

Considering common interest and time constraint only uncoated carbide inserts of grade P30 have been used for the present work. Wide scope will remain for further study on air-cooling effect in machining steels by coated carbides and exotic materials by high performance ceramics, CBN and diamond.

Effectiveness of cooling and the related benefits depend on how closely the cooling air jet can reach the chip-tool and the work-tool interfaces where, apart from the primary shear zone, heat is generated. The tool geometry is reasonably expected to play significant role on such cooling effectiveness. Keeping this view tool configuration (Drillco) namely SNMM-120408 has

been undertaken for the present investigation. The inserts were clamped in a PSBNR-2525 M12 (Drillco) type tool holder.

The positioning of the nozzle lip with respect to the cutting insert has been settled after a number of trials. The final arrangement made and used has been shown in Fig.3.1. The cooling air jet is directed along the main cutting edge to reach at the principal flank and partially under the flowing chips through the in-built groove parallel to the cutting edges. The photographic view of the experimental set-up is shown in Fig.3.2.

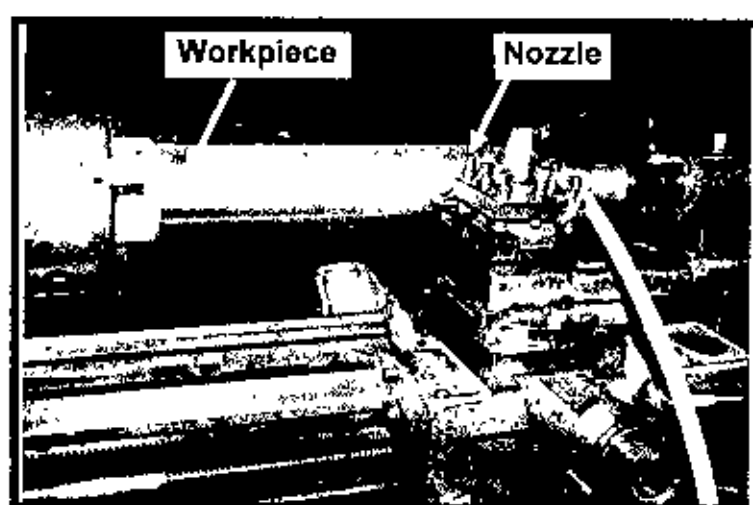


Fig. 3.1 Photographic view of cooling air delivery nozzle injecting cooling air during machining

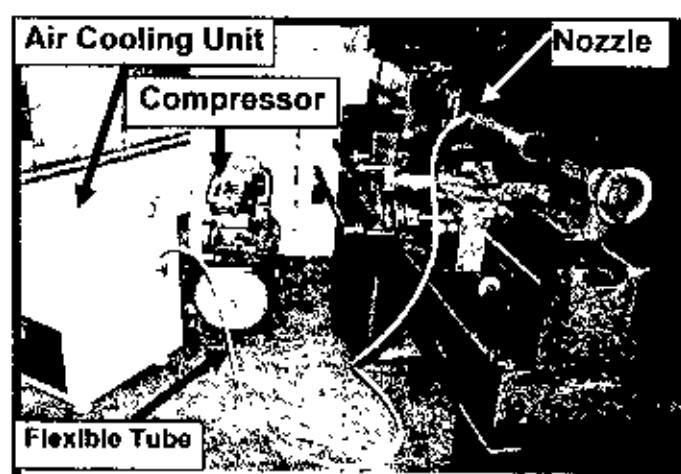


Fig. 3.2 Photographic view of the experimental set-up for turning steel with cooling air condition

The machining responses that have been studied and evaluated for assessing the machinability characteristics of the steel specimen under both dry and air cooling conditions are indicated in Table 3.2. It has already been reported [Dhar et al 2002, Paul et al. 2000 and Seah et al. 1995] that use of conventional cutting fluids (wet machining) does not serve the desired purpose in machining steels by carbides, rather reduces tool life and often may cause premature failure of the insert by brittle fracture. The conditions under which the machining tests have been carried out are briefly given in Table 3.3.

Table-3.2 Machining responses investigated

Investigation on	Environment	
	Dry	Cooling air
Temperature calibration	✓	X
Cutting temperature	✓	✓
Chip morphology	✓	✓
Dimensional deviation	✓	✓

Table-3.3 Experimental conditions

Machine tool	BMTF Lathe, Bangladesh, 4 hp
Work specimen	AISI 1040 steel (size: $\phi 110 \times 620$ mm)
Cutting tool	Carbide, TTS (P-30 ISO specification), Drillco
 SNMM 120408	
Tool holder	PSBNR 2525 M12 (ISO specification), Drillco
Geometry	-8,-8,6,8,15,75, 0.8 (mm)
Process parameters	
Cutting velocity, V_c	63, 80, 90 and 128 m/min
Feed rate, S_o	0.10, 0.13, 0.16 and 0.20 mm/rev
Depth of cut, t	1.0 mm
Environment	Dry and cooling air

A number of cutting velocity and feed have been taken over relatively wider ranges keeping in view the industrial recommendations for the tool-work materials undertaken and evaluation of role of variation in V_c and S_o on effectiveness of cooling air.

Keeping in view less significant role of depth of cut (t) on cutting temperature, saving of work material and avoidance of dominating effect of nose radius on cutting temperature, the depth of cut was kept fixed to only 1.0 mm, which would adequately serve the present purpose.

The machining responses have been monitored and studied using sophisticated and reliable equipment and techniques as far as possible.

Cutting temperature can be measured using direct and indirect techniques [Venkatesh 1987]. Direct methods include the use of

- temperature sensitive powders [Narutaki and Yamane 1979]
- infrared measurement [Prins 1971 and Abrao et al. 1996]
- the tool-work thermocouple techniques [Stephenson 1993, Gottwein 1925] and
- embedded thermocouple techniques [Matsumoto and Hsu 1987 and Kitagawa et al. 1997]

whereas indirect methods mainly include microstructural changes [Wright and Trent 1973] and microhardness changes [Wright and Trent 1973] in the tool materials due to high cutting temperature.

Tool-work thermocouple technique [Stephenson 1993, Gottwein 1925 and Herbert 1926] is simple but quite reliable for measurement average cutting temperature in machining with continuous chip formation like plain turning. But proper functioning of this technique need care about;

- parasitic emf generation by secondary junction
- proper calibration and
- electrical insulation of the tool and the job

In the present work the average cutting temperature has been measured by tool-work thermocouple technique as indicated in Fig.3.3 taking care of the aforesaid factors.

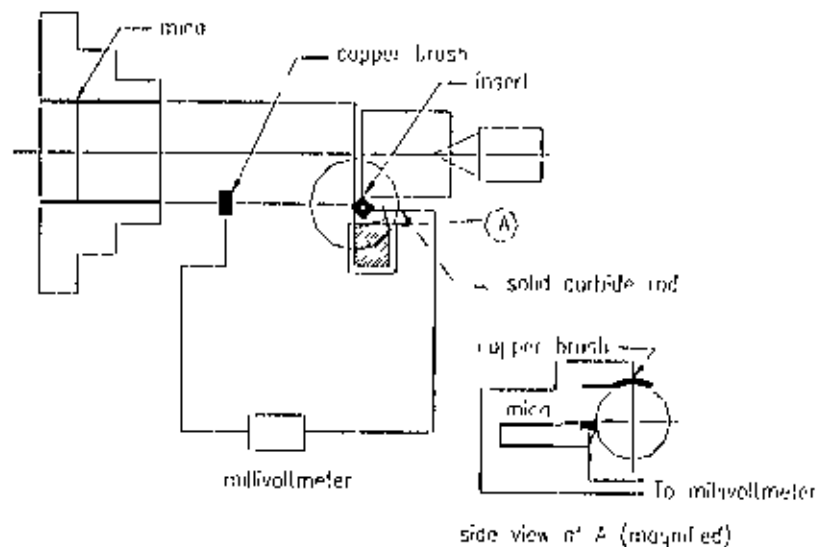


Fig. 3.3 Schematic view of the tool-work thermocouple loop

Tool-work thermocouple can be calibrated in several ways, which include:

- furnace calibration [Bus et al. 1971 and Byrne 196]
- resistance heating [AlvedId 1970]
- embedded silver bit technique [Barrow 193]
- induction heating [Braiden 1967]
- lead bath technique [Shaw 1984] and
- flame heating [Leshock and Shin 1997]

For the present investigation, the calibration of the work-tool thermocouple has been carried out by external flame heating. Fig.3.4 schematically shows the set-up. The work-tool thermocouple junction was constructed using a long continuous chip of the concerned work-material and a tungsten carbide insert to be used in actual cutting. To avoid generation of parasitic emf, a long carbide rod was used to extend the insert. A standard chromel-alumel

thermocouple is mounted at the site of tool-work (junction of chip and insert) junction. The oxy-acetylene torch simulated the heat generation phenomena in machining and raised the temperature at the chip-tool interface. Standard thermocouple directly monitored the junction temperature (measured by a Eurotherm Temperature Controller and Programmer, model. 818P, made in UK) when the emf generated by the hot junction of the chip-tool was monitored by a digital multimeter (model: DH 334, Philips). Fig.3.5 shows the photographic view tool-work thermocouple set up.

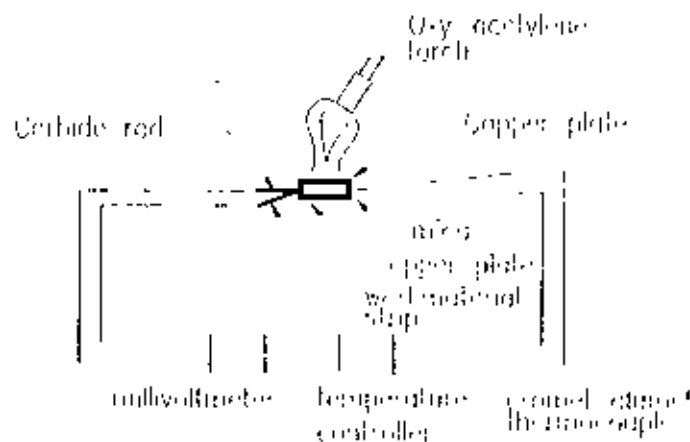


Fig 3.4 Scheme of calibration of present tool work thermocouple



Fig.3.5 Photographic view of the present tool-work thermocouple set up

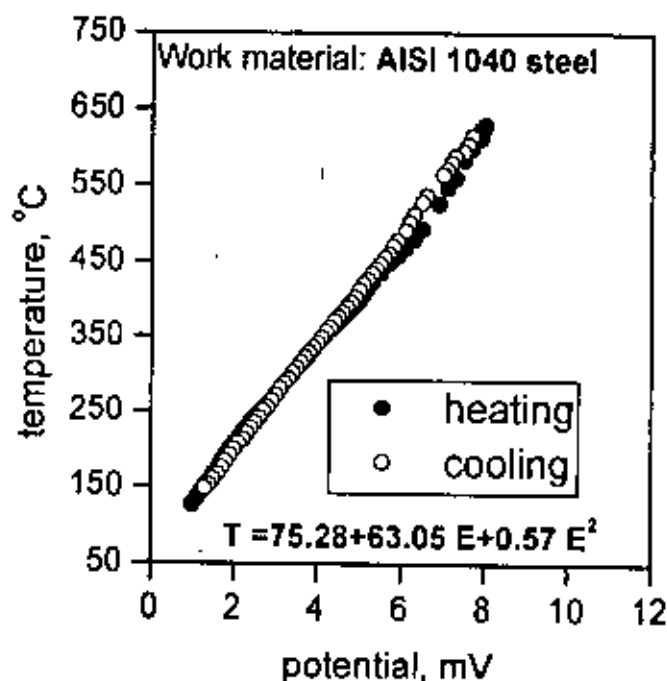


Fig. 3.6 Temperature calibration curve for carbide and AISI-1040 steel

Fig.3.6 shows the calibration curve obtained for the tool-work pair with tungsten carbide (P30 Grade, Drillco) as the tool material and the steel undertaken as the work material. In the present case, almost linear relationships between the temperature and emf have been obtained with multiple correlation coefficients around 0.994.

The form, colour and thickness of the chips also directly and indirectly indicate the nature of chip-tool interaction influenced by the machining environment. The chip samples were collected during both short run and long run machining for the work-tool and V_c - S_o combinations under dry and cooling air condition. The form and colour of all those chips were noted down. The thicknesses of the chips were repeatedly measured by a digital slide calliper to determine the value of chip reduction coefficient, ζ (ratio of chip thickness after and before cut), which is an important index of machinability.

Form-stability and service life of cutting tools plays a major role on productivity, product quality and overall economy in manufacturing by machining. Cutting tools generally fail, particularly while machining ductile metals like steels by hard as well as strong tools like sintered carbides, by gradual wear at their flanks and the rake surface. Often failure may occur only by plastic deformation or macro fracturing under stringent conditions due to excessive cutting temperature and pressure and thermal-cum-mechanical shocks.

The life of the tools, which ultimately fail by systematic gradual wear, is generally assessed at least for R&D work, by the average value of the principal flank wear (V_B), which aggravates cutting forces and temperature and may induce vibration with progress of machining. The pattern and extent of wear (V_S) of the auxiliary flank affects surface finish and dimensional accuracy of the machined parts. Growth of tool wear is sizeably influenced by the temperature and nature of interactions of the tool-work interfaces, which again depend upon the machining conditions for given tool-work pairs.

After machining the steel rod by the insert, at different V_c - S_o combinations under both dry and cooling air, the dimensional deviation on diameter in axial direction of the machined jobs was measured by a sensitive dial gauge which was firmly fitted on the saddle and travelled slowly parallel to the job axis.

3.2 Experimental Results

3.2.1 Cutting temperature

During machining any ductile materials, heat is generated at the (a) primary deformation zone due to shear and plastic deformation (b) chip-tool interface due to secondary deformation and sliding (c) work-tool interfaces due to rubbing. All such heat sources produce maximum temperature at the chip-tool interface, which substantially influence the chip formation mode, cutting forces and tool life. Therefore, attempts are made to reduce this detrimental cutting

temperature. Conventional cutting fluid application may, to some extent, cool the tool and the job in bulk but cannot cool and lubricate expectedly effectively at the chip-tool interface where the temperature is high. This is mainly because the flowing chips make mainly bulk contact with the tool rake surface and may be followed by elastic contact just before leaving the contact with the tool. Bulk contact does not allow the cutting fluid to penetrate in the interface. Elastic contact allows slight penetration of the cutting fluid only over a small region by capillary action. The cutting fluid action becomes more and more ineffective at the interface with the increase in V_c when the chip-tool contact becomes almost fully plastic or bulk.

However, it was observed that the cooling air jet in its present way of application enabled reduction of the average cutting temperature by about 5 to 10% depending upon the levels of the process parameters, V_c and S_0 and the types of the cutting inserts. Even such apparently small reduction in the cutting temperature is expected to have some favourable influence on other machinability indices.

The cutting temperature generally increases with the increase in V_c and S_0 , though in different degree, due to increased energy input and it could be expected that air cooling would be more effective at higher values of V_c and S_0 .

In the present work, the average chip-tool interface temperature could be effectively measured under dry and cooling air machining very reliably throughout the experimental domain. However, the distribution of temperature within the tool, work and chip cannot be determined effectively using experimental techniques. The evaluated role of cooling air on average chip-tool interface temperature in turning the steel by the uncoated insert at different V_c and S_0 under dry and cooling air conditions have been shown in Fig.3.7.

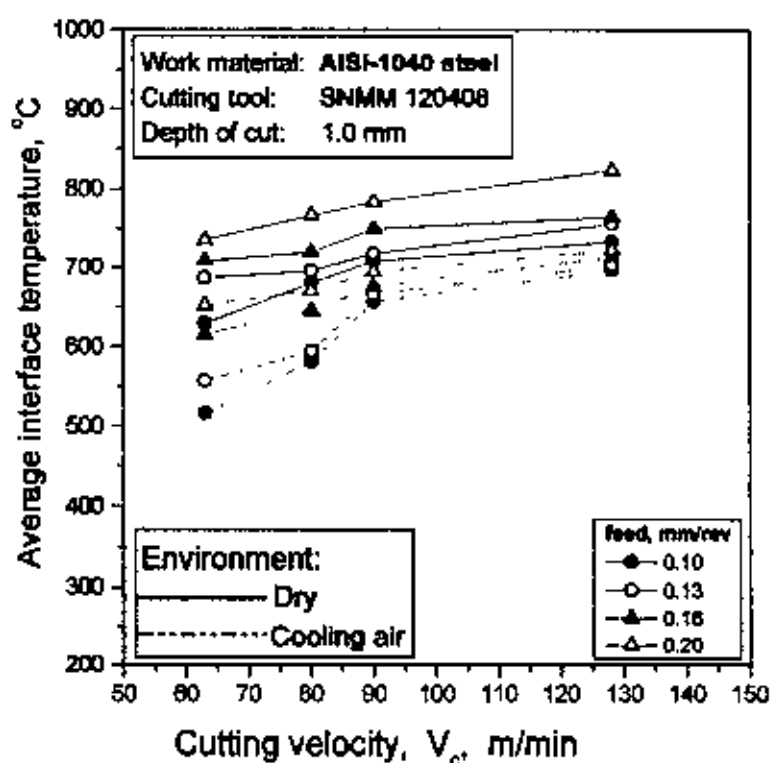


Fig.3.7 Variations in average interface temperature that of V_c and S_0 in turning AISI-1040 steel by SNMM insert under dry and cooling air condition.

3.2.2 Machining chips

The chip samples collected while turning the AISI 1040 steel by the insert of configuration SNMM at different V_c - S_0 combinations under both dry and cooling air condition have been visually examined and categorized with respect to their shape and color.

The results of such categorization of the chips produced at different conditions and environments by the AISI-1040 steel at different feeds have been shown in Table-3.4.

The actual forms of the chips produced by the AISI-1040 steel during machining by the SNMM type insert with a different feeds at different cutting velocities under dry and cooling air conditions are shown in Fig.3.8, Fig.3.9, Fig.3.10 and Fig.3.11.

Table-3.4 Shape and color of chips of AISI-1040 steel at different feeds.

V_c , m/min	Env.	Feed, S_o , mm/rev			
		0.10	0.13	0.16	0.20
		shape and color	shape and color	shape and color	shape and color
63	Dry	● golden	● bluish grey	● gray	● bluish grey
	Cooling air	● metallic	● metallic	● metallic	● metallic
80	Dry	● light blue	● bluish grey	● grey	● bluish grey
	Cooling air	● metallic	● metallic	● metallic	● metallic
90	Dry	▶ deep blue	● grey	● grey	● grey
	Cooling air	● metallic	● metallic	● metallic	● metallic
128	Dry	□ golden	● burnt blue	● deep blue	● burnt blue
	Cooling air	▶ metallic	● metallic	● metallic	● metallic
Group		● half turn arc	▶ tubular/helical	□ spiral	○ ribbon

When examined under microscope, no significant change in the microstructure was found at the undersurface of the chips when machining environment was changed from dry to cooling air, but micro-hardness was found to change to some extent due to cooling air. The nature and extent of increase in micro-hardness of the chips of AISI-1040 steel due to cooling air under different conditions are typically shown in Table-3.5.

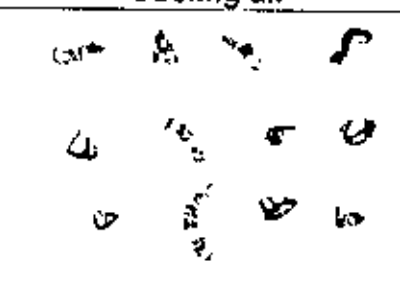
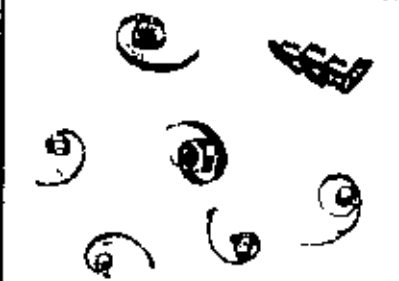
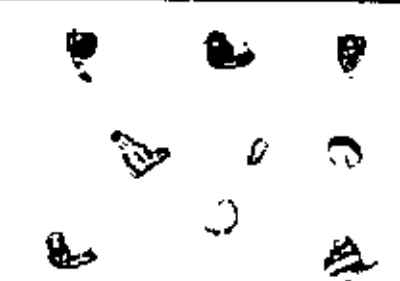
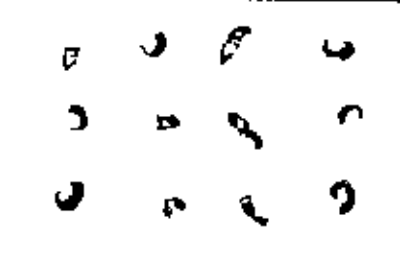
Cutting velocity, V_c , m/min	Feed, $S_o=0.10$ mm/rev	
	Environment	
	Dry	Cooling air
63		
80		
90		
128		

Fig.3.8 Chips produced while turning AISI-1040 steel by SNMM insert at different V_c and 0.10 mm/rev feed rate under dry and cooling air condition.

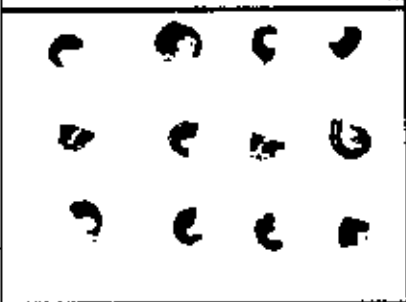
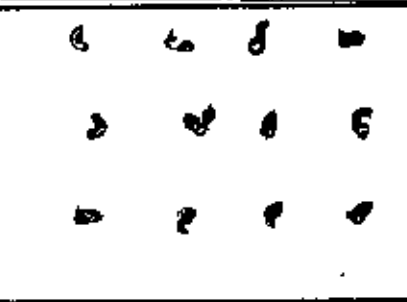
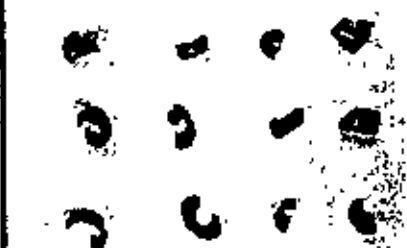
Cutting velocity, V_c , m/min	Feed, $S_o=0.13$ mm/rev	
	Environment	
	Dry	Cooling air
63		
80		
90		
128		

Fig.3.9 Chips produced while turning AISI-1040 steel by SNMM insert at different V_c and 0.13 mm/rev feed rate under dry and cooling air condition

Cutting velocity, V_c , m/min	Feed, $S_o=0.16$ mm/rev			
	Environment			
	Dry		Cooling air	
63				
				
				
80				
				
				
90				
				
				
128				
				
				

Fig.3.10 Chips produced while turning AISI-1040 steel by SNMM insert at different V_c and 0.16 mm/rev feed rate under dry and cooling air condition

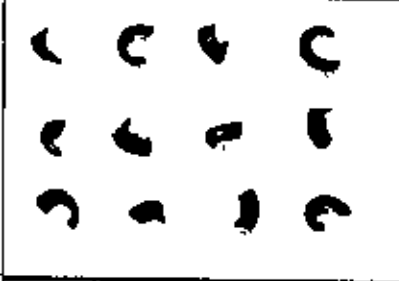
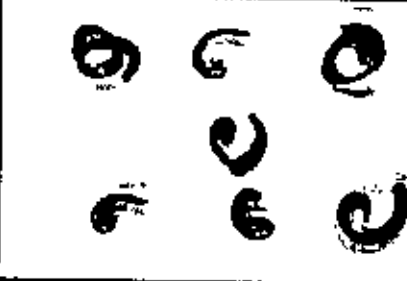
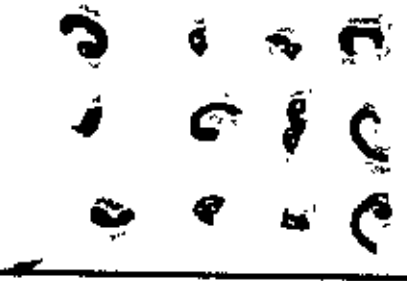
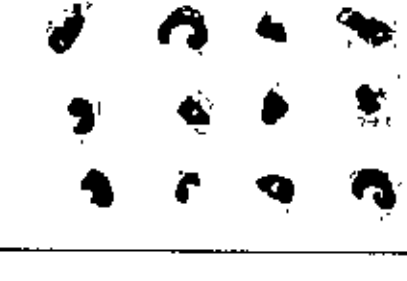
Cutting velocity, V_c , m/min	Feed, $S_o=0.20$ mm/rev Environment	
	Dry	Cooling air
63		
80		
90		
128		

Fig.3.11 Chips produced while turning AISI-1040 steel by SNMM insert at different V_c and 0.20 mm/rev feed rate under dry and cooling air condition

Table-3.5 Micro-hardness of the chips (under surface) of AISI-1040 steel

Cutting insert	Cutting velocity (m/min)	Environment	M-hardness, HV		
			Feed, S_o , mm/rev		
			0.13	0.16	0.20
SNMM 120408	90	Dry	140	168	192
		Cooling air	201	220	241
	128	Dry	160	195	200
		Cooling air	195	208	231

Another important machinability index is chip reduction coefficient, ζ (ratio of chip thickness after and before cut). For given tool geometry and cutting conditions, the value of ζ depends upon the nature of chip-tool interaction, chip contact length and chip form all of which are expected to be influenced by cooling air in addition to the levels of V_c and S_o . The variation in value of ζ with change in V_c and S_o as well as machining environment evaluated for AISI-1040 steel have been plotted and shown in Fig.3.12.

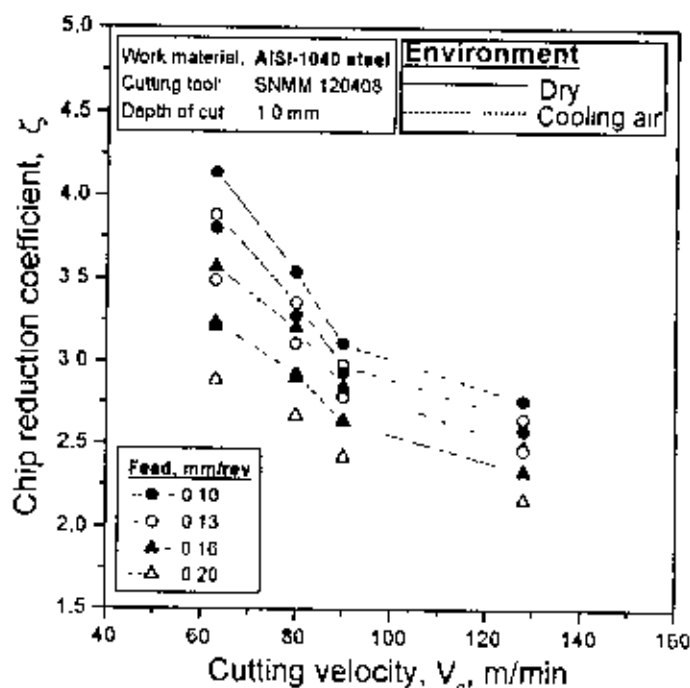


Fig.3.12 Variation in ζ with that of V_c and S_o in turning AISI-1040 steel by SNMM insert under dry and cooling air condition

3.2.3 Dimensional deviation

The performance and service life of any machined part are governed largely by quality of that product, which for a given material is generally assessed by dimensional and form accuracy and surface integrity of the product in respect of surface roughness, oxidation, corrosion, residual stresses and surface and subsurface micro cracks.

In the present work, only dimensional deviation on diameter have been investigated to evaluate the relative role of cooling air on this major aspects

During straight turning in a center lathe, the diameter of the machined part is generally found to

- i. increase along length of cut due to gradual wear of the tool tip
- ii. decrease due to thermal expansion and subsequent cooling of the job if the job temperature rises significantly during machining
- iii. increase due to system compliance of the machine-fixture-tool-work (M-F-T-W) system under the action of the cutting forces

The order of dimensional deviations possible due to thermal expansion of the job even under dry machining and due to compliance of the M-F-T-W system were calculated for the steel specimens being machined under the present conditions and the values appear to be extremely small (less than 1 μm) compared to that possible due to wear of the tool tips. Therefore, in the present study, the dimensional deviations are considered to be mainly due to wear of the tool tips.

The variation in diameter of the job was precisely measured along its axis after one full pass of the machining over 400 mm length with full depth, at reasonably high feed and cutting velocity suitable for the tool-work combination.

The gradual increase in dimensional deviations on diameter observed along the length of cut on the AISI-1040 steel rod after one full pass of machining at cutting velocity of 90 m/min, 1.0 mm depth of cut and 0.2 mm/rev feed under dry and cooling air conditions have been shown in Fig.3.13.

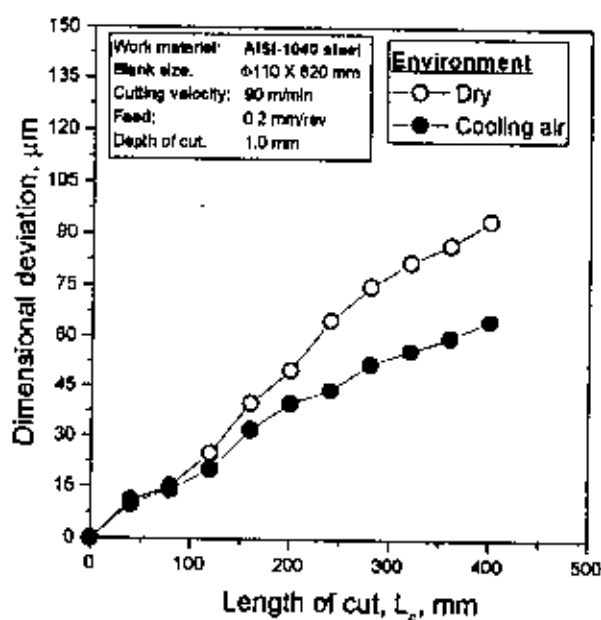


Fig.3.13 Dimensional deviations observed after one full pass turning by SNMM insert at cutting velocity, 90 m/min under dry and cooling air condition

Chapter-4

Discussion on Experimental Results

4.1 Cutting Temperature

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

Tool-work thermocouple technique is as such simple and reliable to measurement of average cutting temperature. The literature shows a wide range of the calibration methods and procedures. Most of these methods calibrate the tool and the workpiece in an isolated environment, without consideration to the machining experimental setup. This presents problems, because the experimental setup is different than the calibration setup. The calibration setup used in this study is close to the experimental setup and thus many factors such as parasitic e.m.f's are included into the calibration.

The experimental setup consisted of an electrically insulated carbide tool insert clamped into a tool holder. A K-type thermocouple is spot welded onto the insert at the tool-chip interface and is secured further by a coating of ceramic cement. Embedding it in several layers of mica electrically insulates the alumel lead wire, which measures the e.m.f generated at the interface. A small aperture is cut on the top layer of mica to allow the wire to contact the insert as shown both in Fig.3.4 and Fig.3.5 respectively. During calibration, the e.m.f is measured and the temperature is measured by a K-type thermocouple at the point where the tool and chip would contact during cutting. An oxygen-acetylene torch or a propane torch applies the necessary heat for approximating the heat generated during metal cutting. Measurements are taken after a few minutes of heating to insure a quasi-steady state. Also, only the cooling of the insert is used to maintain a consistent calibration.

A plot of the measured potential for a given temperature during calibration is shown in Fig.3.6 for carbide tool and AISI-1040 steel workpiece. In this case, linear correlation between the temperature and e.m.f is observed. Although result from the calibration varied slightly for this test, good correlation was attained when regression was performed ($R^2 = .92-.97$).

The average chip-tool interface temperature, θ_{avg} have been determined from the tool work thermocouple technique and plotted against cutting velocity for different feeds and environments undertaken. The figure Fig.3.7 is showing how and to what extent θ_{avg} has decreased due to cooling air application under the different experimental conditions. With the increase in V_c and S_o , θ_{avg} increased as usual, even under cooling air, due to increase in energy input.

Apparently more drastic reductions in θ_{avg} are expected by employing cooling air jets. But practically it has not been so because the cooling air has been employed in the form of thin jets along the cutting edges and towards only the chip-tool interface and tool flanks instead of bulk cooling. Also the jets,

like any cutting fluid, could not reach deeply in the chip-tool interface for plastic or bulk contact, particularly when V_c and S_o are large.

The roles of variation of process parameters on percentage reduction of average interface temperature due to cooling air have not been uniform. This may be attributed to variation in the chip forms particularly chip-tool contact length, C_N which for a given tool widely vary with the mechanical properties and behaviour of the work material under the cutting conditions. The value of C_N affects not only the cutting forces but also the cutting temperature. In the present thermal modelling also the value of C_N had to be incorporated as the span of heat input at the chip-tool interface. Post cooling of the chips by cooling air jet is also likely to influence θ_{avg} to some extent depending upon the chip form and thermal conductivity of the work materials.

4.2 Machining Chips

The pattern of chips in machining ductile metals are found to depend upon the mechanical properties of the work material, tool geometry particularly rake angle, levels of V_c and S_o , nature of chip-tool interaction and cutting environment. In absence of chip breaker, length and uniformity of chips increase with the increase in ductility and softness of the work material, tool rake angle and cutting velocity unless the chip-tool interaction is adverse causing intensive friction and built-up edge formation.

Table-3.4 shows that the AISI 1040 steel when machined by the pattern type SNMM insert under dry condition produced more or less half turn at different higher feeds. The geometry of the SNMM insert is such that the chips of this steel (AISI-1040 steel) first came out continuously got curled along normal plane and then hitting at the principal flank of this insert broke into pieces with regular size and shape. When machined with cooling air the form of these ductile chips did not change appreciably but their back surface appeared much brighter and smoother. This indicates that the amount of reduction of temperature and presence of cooling air application enabled

favourable chip-tool interaction and elimination of even trace of built-up edge formation. It appears from Table-3.5 that the hardness of this low carbon steel (AISI 1040 steel) is as such low and did not increase appreciably by air-cooling action to cause substantial change in its chip forms.

The color of the chips have also become much lighter i.e. metallic or golden from blue or grey depending upon V_c and S_p due to reduction in cutting temperature by cooling air.

Almost all the parameters involved in machining have direct and indirect influence on the thickness of the chips during deformation. The degree of chip thickening which is assessed by chip reduction coefficient, ζ , plays sizeable role on cutting forces and hence on cutting energy requirements and cutting temperature.

The value of ζ depends [Kronenberg 1943] mainly on apparent coefficient of friction, μ_a at the chip-tool interface and effective rake as,

$$\zeta = e^{\mu_a \left(\frac{\pi}{2} - \gamma_e \right)} \quad (4.1)$$

In machining ductile metals, particularly steels, the actual value of τ_s is affected [Abuladze 1962] by the values of tool rake angle and as,

$$\tau_s = 0.74 \sigma_u \epsilon^{0.6 \Delta} \quad (4.2)$$

where,

- σ_u Ultimate tensile strength of the work material at normal condition
- Δ Percentage elongation of the work material
- ϵ Average cutting strain ($= \cot \beta + \tan (\beta - \gamma_e)$)
- β Shear angle ($\cot \beta = \zeta - \tan \gamma_e$)
- τ_s Dynamic yield shear strength of the work material

The figure Fig.3.12 clearly shows that throughout the present experimental domain the value of ζ gradually decreased with the increase in V_c though in different degree for the different tool-work combinations, under both dry and cooling air conditions.

The value of ζ usually decreases with the increase in V_c particularly at its lower range due to plasticization and shrinkage of the shear zone for reduction in friction and built-up edge formation at the chip-tool interface due to increase in temperature and sliding velocity. In machining steel by carbide tool, usually the possibility of built-up edge formation and size and strength of the built-up edge, if formed gradually increase with the increase in temperature due to increase in V_c and also S_o and then decrease with the further increase in V_c due to too much softening of the chip material and its removal by high sliding speed.

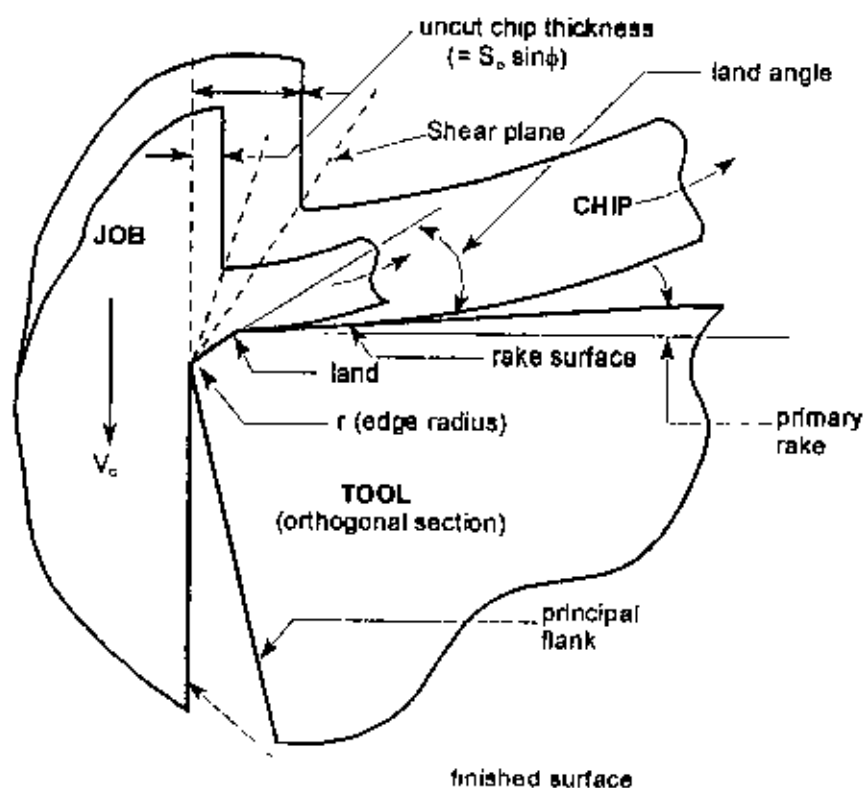


Fig.4.1 Schematic view of machining with varying uncut chip thickness.

It is also noted in this figure that decreased all along also with the increase in S_0 expectedly due to increase in average rake angle with increase in uncut chip thickness as has been schematically indicated in Fig.4.1.

Fig.3.12 shows that cooling air has reduced the value of ζ particularly at lower values of V_C and S_0 when the SNMM insert machined the steel rod. By cooling air applications, ζ is reasonably expected to decrease for reduction in friction at the chip-tool interface and reduction in deterioration of effective rake angle by built-up edge formation and wear at the cutting edges mainly due to reduction in cutting temperature and also possibly for removal of oxygen from the cutting zone by cooling air.

4.3 Dimensional Deviation

The quality of any machined product of given material is generally assessed by dimensional accuracy, which govern the performance and service life of that product. For the present study, only dimensional accuracy has been considered for assessment of quality of product under dry and cooling air machining. Fig.3.12 clearly shows that dimensional inaccuracy can be remarkably reduced by the present method of air-cooling in machining AISI 1040 steel rod by carbide insert.

It has been mentioned earlier that the diameter in straight turning of long rod may deviate from the theoretically expected value due to progressive wear of the tool-tip, variation of compliance of the M-F-T-W system along the axis of lathe and thermal expansion or distortion of the job, if much heated. The substantial reduction in dimensional deviation observed in the present investigation can be reasonably attributed mainly to reduction in the auxiliary flank wear of the inserts by cooling air. The order of dimensional deviation possible due to other two reasons for the present job specimen of so large diameter and L/D ratio less than 4.0 and the cutting conditions undertaken has been roughly estimated and found to be around 1.0 μm .

Careful observation of the figures presenting dimensional deviations under various machining conditions and those presenting average auxiliary flank wear visualises that dimensional deviations observed have close relation with corresponding auxiliary flank wear, particularly V_{SM} for which actual depth of cut is reduced from the apparent depth of cut by the depth of maximum flank wear. Assuming absolutely sharp cutting edges without edge rounding, reduction in depth of cut, Δt corresponding to V_{SM} should be,

$$\Delta t = V_{SM} \times \tan \alpha \quad (4.3)$$

where,

α Normal clearance angle

For $V_{SM} = 200 \mu\text{m}$, therefore, increase in diameter, ΔD should be

$$\Delta D = 2 \Delta t = 2 \times 200 \times \tan 6^\circ = 42.4 \mu\text{m}$$

which is in reasonable agreement with the experimental results. However, it is quite likely that the experimental values of ΔD will be somewhat different from the corresponding values calculated based on observed V_{SM} because of edge rounding, chipping, notching etc. at the auxiliary flank including the radiused tip of the inserts. Wide notch at the tool tip is expected to increase the job diameter further.

Fig.3.13 shows that the nature of increase of dimensional deviation with the progress of machining AISI 1040 steel rod. Dimensional inaccuracy has been respectively enhanced and reduced under dry condition and cooling air, expectedly. The machining tests conducted for studying the role of cooling air on dimensional inaccuracy was separately carried by fresh insert after completion of tool wear test. Dimensional deviation, for each tool-work-environment combination, was measured along the job axis after one complete pass.

Chapter-5

Conclusions

Usage of coolant has become more problematic in terms of both employee health and environmental pollution. This research is a feasibility study for using a new cooling system. This system does not use coolant as in the past. The system is designed for reducing the temperature of the cutting tool. The cooling system utilizes a unit for cooling ejected air. Hence, it is clear that using a dry cutting system has great implications for resource preservation and waste reduction. Therefore using cooling air proposes a technological, economical and ecological alternative for metal processing companies.

- Application of cooling air not only can provide environment friendliness but also substantial technological benefits as has been observed in machining steel by carbide tool.
- The present cooling air systems enabled reduction in average chip-tool interface temperature upto 10% depending upon the work materials, tool geometry and cutting conditions and even such apparently small reduction, unlike common belief, enabled significant improvement in the major machinability indices.
- Due to cooling air application, the form and colour of the steel chips became favourable for more effective cooling and improvement in nature of interaction at the chip-tool interface

- Cooling air reduced the cutting temperature, such reduction has been more effective for those tool-work combinations and cutting conditions, which provided higher value of chip reduction coefficient, ζ for adverse chip-tool interaction causing large friction and built-up edge formation at the chip-tool interface. Favourable change in the chip-tool interaction and retention of cutting edge sharpness due to reduction of cutting zone temperature seemed to be the main reason behind reduction of cutting forces by the cooling air jet.
- Dimensional accuracy also substantially improved mainly due to significant reduction of wear and damage at the tool tip by the application of cooling air.
- Cooling air, if properly employed, can enable significant improvement in both productivity and product quality and hence overall machining economy even after covering the additional cost of cooling air system.

Chapter-6

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