Effect of High Pressure Coolant Jet (HPCJ) in Drilling Different Steels

A Project Thesis

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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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Declaration

I do hereby declare that this work has been done by me and neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma except for publication.

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Abstract

High production machining, grinding and drilling inherently generates large amount of heat leads to high cutting zone temperature for its higher cutting velocity, feed and depth of cut. Such high cutting temperature if not reduced impairs surface integrity of the product and reduce dimensional accuracy as well as tool life. Application of cutting fluids changes the performance of machining operations because of their lubrication, cooling, and chip flushing functions. However, the conventional cutting fluids are not that effective in such high production drilling. Low boiling temperature cause vaporization of cutting fluid and prevent it to enter into cutting interface making a barrier to flow. In addition, flowing chips through drill flute prevent the fluid to enter into the cutting zone. Further, they also deteriorate the working environment and lead to general environmental pollution.

High-pressure coolant presents itself as a viable alternative for drilling with respect to heat dissipation, roundness deviation and taper of the hole, chip formation mode and tool wear. This study compares the mechanical performance of high-pressure coolant to completely dry lubrication for the drilling of AISI-4340 steel and AISI-1040 steel based on experimental measurement of roundness deviation and taper of the hole, chip formation mode and tool wear. Results indicated that the use of high-pressure coolant leads to lower roundness deviation and taper of the hole, favorable chip-tool interaction and reduced tool wear.

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Chapter-1

Introduction

1.1 Introduction

In the present days, production industries are concerned with high productivity and superior quality. Productivity depends on the work materials and machining processes, which are associated with many parameters like machining speed, feed rate, depth of cut, and cutting environment. Cutting environment is one of the most important parameter to increasing the product quality. Product quality and overall economy in manufacturing by machining, grinding and drilling, 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. However, high production machining, grinding and drilling with high cutting velocity, feed rate 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 and quality. Worst Quality of product is affected on customer satisfaction and reduces customer demand.

Longer cut under high cutting temperature cause thermal expansion and distortion of the job particularly if it is slender and small in size, which lead to dimensional and form inaccuracy. On the other hand, high cutting temperature accelerates the growth of tool wear and enhances the chances of premature failure of the tool by plastic deformation and thermal fracturing. The changing of cutting tool within a sort time is committed due to tool wear and tool fracture, for this tool cost and tool changing time increases.

In both the cases, production cost is increased. 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 drilling where cutting temperature is, as such, very high due to much higher specific energy requirement and cutting velocity. Such problem becomes more acute and severe 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, geometry of the cutting tools and proper selection and application of cutting fluid and
- using heat and wear resistant cutting tool materials like carbides, coated carbides and high performance ceramics

In the metal cutting operation, temperature is the apprehensive element. If we are able to reduce or minimize the temperature, quality will also be developed. Temperature can be reduced by using cutting fluid. Cutting fluid not only reduces temperature but also provide lubrication between the tool and work interface. Temperature can be reduced in different ways like flood cooling, near dry cooling or micro lubrication, MQL cooling, cryogenic cooling and high-pressure jet cooling. Near dry cooling is based on air coolant, a little amount of temperature is reduced. MQL is same in fashion of dry. Large amount of small partials are produced which affect inhalation of the operator. Flood cooling reduces temperature to some extent by bulk cooling but is not very much effective because it cools only the top surface of the job and the tool due to its overhead application. It has some bad effects too, when cutting fluid comes in contact with the human body, it creates skin irritation, lung cancer etc [**Heisel et al. 1998**]. Cryogenic coolant effectively reduces temperature from the cutting zone but it is very costly and in nitrogen rich atmosphere notch wear of the tool takes place. Best performance is found in high-pressure cooling jet (HPCJ). High–pressure jet of conventional coolant has been reported to provide some reduction in cutting temperature **[Robert et al. 2004]**. It reduces temperature very quickly due to high pressure jet coolant reaches very easily in to the chip - tool interface. Mazurkiewicz et al. [1998] 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.

1.2 Literature Review

Well dimensional accuracy and fine surface integrity both are desired for finished product. Coolant plays the major role to bring all the elements within acceptable limits by reducing temperature. Large amount heat is produced during machining which leads to high cutting zone temperature. High temperature very quickly wears the tool and due to tool wear, rubbing is made in between tool and work material. For this dimension, accuracy is found worst. Coolant enters in to the tool-chip interface, reduce friction-welding by its lubricating property and also bring away temperature by its cooling property.

Hole making had long been recognized as the most prominent machining process, requiring specialized techniques to achieve optimum cutting condition. Drilling can be described as a process where a multi-point tool is used to remove unwanted materials to produce a hole. It broadly covers those methods used for producing cylindrical holes in the work piece. While removal of material in the form of chips new surfaces are cleaved from the work piece accompanied by a large consumption of energy. The mechanical energy necessary for the drilling operation is transformed in to heat leading to conditions of high temperature and severe thermal / frictional conditions at the tool- chip interface **[Ezugwu and Lai 1995]**.

The magnitude of the cutting temperature increases though in different degree with the increase of cutting velocity, feed and depth of cut. At such elevated temperature the cutting tools if not enough hot hard may lose their form stability quickly or wear out rapidly resulting in increased cutting force, dimensional inaccuracy of the product and shorter tool life **[Kitagawa et al. 1997]**. This problem increases further with the increase in strength and hardness of the work material.

During drilling process, the most important factor affecting the cutting tool performance and work piece properties is cutting temperature that emerges between drill bit and chip.[**Eyup and Babur 2006**]. The cutting temperature directly influences hole characteristics such as diameter, perpendicularity and cylindricity, as well as surface roughness and tool wear [**Eyup and Babur 2006**]. They also investigated the effects of cutting depth, cutting speed, web thickness and helix angle on the temperature. The temperatures associated with the drilling process are particularly important, because drilling is one of the predominant industrial machining processes and heat effects in drilling are generally more severe than in other metal cutting operations. Drills often experience excessive temperatures because the drill is embedded in the work piece and heat generation is localized in a small area. The resulting temperatures can lead to accelerate tool wear and reduce tool life and they can have profound effects on the overall quality of the machined work piece. Drill designers often select the geometrical features of a drill based on the expected temperature profile in the drill point, so accurate prediction of the temperature distribution is imperative **[Matthew and Jun 2006]**. Temperature not only be exaggerated the tool wear but also affect the surface, hole quality and chip formation. The cutting temperature directly influences hole sensitivity, surface roughness, and tool wear [**Eyup and Babur 2006**]. A turning tool typically will not fail due to thermal shock, because it is subjected to this quenching only three or four times per minute when it is withdrawn from the cut at the end of each pass. A face milling operation running at 1000 rpm, on the other hand, subjects every insert to 1000 damaging quenches per minute. Drilling fails somewhere in between with thermal shock occurring every time the drill pulls out of the cut [**Gregory 1999**].

A major portion of the energy is consumed in the formation and removal of chips. The greater the energy consumption, the greater are the temperature and frictional forces at the tool–chip interface and consequently the higher is the tool wear [**Senthil Kumar et al 2002**]. Drill wear not only affects the surface roughness of the hole but also influences the life of the drill bit [**Panda et al. 2006**]. Wear in drill bit is characterized as flank wear, chisel wear, corner wear, crater wear and margin wear [**Panda 2006 and Sanjay 2005**]. Since wear on drill bit dictates the hole quality and tool life of the drill bit [**Panda et al. 2006**].

Worn drills produce poor quality holes and in extreme cases, a broken drill can destroy almost all finished parts. A drill begins to wear as soon as it is placed into operation. As it wears, cutting forces increases, the temperature rises and this accelerates the physical and chemical processes associated with drill wear and therefore drill wears faster [**Sanjay et al. 2005**]. Thrust and torque depend upon drill wear, drill size, feed rate and spindle speed. Researches results show that tool breakage, tool wear and work piece deflection are strongly related to cutting force [**Sanjay et al. 2005**].

The material is removed in the form of chips and evacuated through the drill flutes. It has been demonstrated [**Litvinov 1990, Ackroyd 1998 and Sahu 2003**] that smaller chips are more easily removed from the drill by the action of the flutes, centrifugal forces, and/or metal working fluids. Long chips can become tangled around the drill, can lead to poor hole quality and are more difficult to manage once outside the hole thereby increasing production costs and lowering productivity. Furthermore, while drilling deep holes friction between the drill flutes and chips causes the chips to be evacuated slower than chips are produced. This leads to chip clogging, which in turn causes sudden increase in torque and thrust that may cause drill breakage. Improved chip evacuation will lead to less drill breakage, lower production costs, better hole quality, and increase productivity [**Degenhardt et al. 2005**].

Chips must be small enough to move up the tool's flutes and out of the way. Long, stringy chips can damage surface finish and cause premature tool wear or breakage. Coolant has to get to the tool tip to keep the tool and workpiece cool, as well as force chips out of the hole. A rigid machine tool with good damping characteristics and low spindle run out is required to hit targets for accuracy, repeatability and surface finish. Of course, the right drill geometry will make deep-hole drilling operations much more efficient.

Currently in industries, this high temperature problem is partially tried to be controlled by reducing heat generation and moving heat from the cutting zone through optimum selection of machining parameters and geometry of the cutting tools, proper cutting fluid application and using heat resistant cutting tool materials like carbides, coated carbides and high performance ceramics (CBN, PCBN, PCD etc). The thermal deterioration of the cutting tools can be reduced by using CBN tools **[Narutaki and Yamane 1979]**. If properly manufactured, selected and used, CBN tools provide much less cutting force, temperature and hence less tensile residual stress **[Davies et al. 1996]**. Though CBN tools are extremely heat and wear resistive, those are too expensive and are justified for very special work materials and requirements where other tools are not effective **[Ezugwu and Lai 1995]**.

The application of cutting fluid during machining operation reduces cutting zone temperature and increases tool life and acts as lubricant as well **[Beaubien and Cattaneo 1964]**. Also Dhar et al. **[2004]** states that without cooling and lubrication, the chip sticks to the tool and breaks it in a very short cutting time. It reduces cutting zone temperature either by removing heats as coolant or reducing the heat generation as lubricant. In addition it serves a practical function as chip- handling medium **[Cassin and Boothroyed 1965]** But it has been experienced **[Cassin and Boothroyed 1965]** that lubrication is effective at low speeds when it is accomplished by diffusion through the work piece 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 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. On the other hand, the cooling and lubricating effects of cutting fluid influence each other and diminish with increase in cutting velocity [**Kitagawa et al. 1997**]. Since the cutting fluid does not enter the chip-tool interface during high speed machining, the fluid action is limited to bulk heat removal only.

A large amount of heat is created in dry machining because of rubbing between cutting tool and work piece interface. Dry machining has not fully established itself in drilling technology, mainly because of extremely high thermal load on the drilling tools resulting in accelerated tool wear and unsatisfying overall process stability [**Ezugwu and Lai 1995**]. The optimization of cutting conditions to make them more suitable for dry cutting is done through the increase of feed and decrease of cutting speed. With this, roughly the same amount of heat is generated, but the area of the tool which receives this heat is bigger, making the temperature lower and the amount of chip removed per minute constant (without increasing cutting time). This action may damage the work piece surface finish due to the increase of the feed [**Durval et al. 2002**]. And also in Dry drilling, the drilling tool has to withstand harsh environment conditions, including high temperatures, frictional forces and large mechanical and thermal loads [**Eyup Bagci and Babur, 2006**].

Therefore, it is also necessary to increase the tool nose radius in order to keep the surface roughness at the same level [**Klocke et al. 1997**]. So those processes where dry cutting is either not possible or not economical [**Durval et al. 2002**]. The drilling of aluminum–silicon alloys is a process where dry cutting is impossible [**Derflinger et al. 1999**] due to the high ductility of the work piece material.

Minimum quantity lubrication is the same in fashion and small amount of heat is reduced like dry cooling. Usually the high cutting temperature is controlled by profuse cooling [**Sokovic and Mijanovic 2001**]. Sometimes, the costs of tools may increase with the use of minimum lubrication, due to the increase of tool wear [**Durval et al. 2002**]. The MQL system has shown encouraging potentials for precision machining at low feed and high-speed conditions [**Machado 1997**]. Considering the use of the MQL in machining, the vapor, the mist and the smoke of oil can be considered undesirable sub-products, characterizing an increase in pollution by suspension in the air [**Heisel 1998**]. In Germany, the maximum polluter pollution concentration in the air under the mist form is limited in to 5mg/m^3 and for vapor oil the limit is 20 mg/m^3 [**Heisel 1998**]. During machining with MQL only the top most layer of the work piece experiences bulk cooling and air-coolant mixture can't reach to the tool tip due to the hindrance caused by the spiral flute of the drill bit and the counter flow of the chip.

However, such profuse cooling with conventional cutting fluid 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. But in the drilling process, once the hole depth exceeds 2–3 times the drill diameter, very little or no cutting fluid can reach the drill tip mainly because the drill and the counter-flow of chips restrict further penetration [**Weinert et al. 1999** and **Kubota et al. 1999**]. In addition, conventional Cutting fluids, most of the times, are difficult and expensive to recycle, can cause skin and lung diseases to the machine operator and air pollution [**Durval et. al. 2002**].

Flood cooling in the cutting zone can effectively reduce the cutting temperature when machining at lower speed conditions with significant sliding region and where relatively low cutting temperatures are generated. The coolant also acts as a lubricant, thus minimizing friction and lowering component forces and consequently tool life. There is very limited access of the coolant to the tool-workpiece or tool-chip interfaces, which are mainly under seizure condition when machining at high speed conditions. Coolants tend to be vaporized by the high temperature generated close to the tool edge, forming a high temperature blanket that renders their cooling effect ineffective [**Ezugwu 2004**].The film boiling temperatures of conventional cutting fluids is about 350°C [**Ezugwu and Bonney 2003**].

In flood cooling, less and less coolant reaches the tool tip as the deeper the drill penetrates in to the workpiece. Eventually, no coolant can get to the bottom, and machining occur dry. As a result, chips become impacted in the flutes of the tool even though coolant is visibly flowing over the top of the hole. In fact, the hole ends up being dry cut, while the tool heats up and is subjected to premature wear or breakage.

The main problem [**Wertheim and Rotberg 1992**] with conventional coolant is that it does not reach the real cutting area. The extensive heat generated evaporates the coolant before it can reach the cutting area. The high cutting forces generated during machining will induce intensive pressure at the cutting edge between the tool tip and the workpiece. Conventional coolant might not be able to overcome this pressure and flow into the cutting zone to cool the cutting tool. Hence, heat generated during machining is not removed and is one of the main causes of the reduction in tool life. With the use of high-pressure coolant during machining, the tool life and surface finish are found to improve significantly [**Mazukiewicz 1989 , Lindeke 1991 and Kovacevic 1994**], which is said to be due to the decrease in heat and cutting forces generated. There have been several studies on applying coolant at high pressure at the tool–chip interface, focused on a stationary single cutting edge in a turning operation.

Cryogenic cooling is an efficient way of maintaining the temperature at the cutting interface well below the softening temperature of the cutting tool material. This technology is exploited mainly in the grinding industry because of the high specific energy requirements, which results in high grinding zone temperature which if not properly controlled will lead to surface damage [**Ezugwu 2004**]. Ezugwu [**2004**] found that in cryogenic machining high cutting and thrust forces are generated than in conventional and flood cooling or dry machining applications. This anomaly is attributed to the fact that sub zero temperatures has the consequence of increasing hardness and strength of the work material, hence higher forces are generated with cryogenic cooling [**Hong et al. 2001**]. Tool wear rates when machining titanium alloy Ti-6Al-4V with cemented carbide using Liquid Nitrogen and under conventional cooling at a cutting speed of 132 m min^{-1}, feed rate of 0.2 mm rev^{-1} and a depth of cut of 1.0 mm showed a five fold increase in flank wear for tools subjected to the conventional cooling [**Wang and Rajurkar 2000**]. This type of cooling is effective but not cost effective. Cryogen handling is difficult and it may cause cold diseases if operator wears no safety wear.

High–pressure jet of conventional coolant has been reported to provide some reduction in cutting temperature [**Robert 2004**]. High-pressure coolant can often cut cycle times in half or better and improve surface finish and double or quadruple tool life while delivering a reduction in cycle time [**Frederick Mason 2001**].The idea of delivering coolant under high pressure to the cutting region in order to increase tool life during machining began in early 1950s [**Pigott and Colwel 1952**]. The primary objective of this machining technique is to significantly reduce the temperature generated at the tool-workpiece and tool-chip interfaces when cutting at higher speed conditions. This is achieved by directing coolant under high pressure at the chip-tool interface. This process can also achieve high chip breakability and control through increased chip up curl and compressive stress [**Ezugwu 2004**]. Ezugwu [**2004**] stated that ability to deliver coolant at high pressure very close to the critical point on the secondary shear zone can improve machinability at higher speed conditions. The credibility of this technique of coolant delivery has been thoroughly investigated over the years. The high speed coolant jet traverses the surface faster, thus significantly lowering the film boiling action of the coolant at the cutting area. This consequently minimizes heat transfer to the cutting tool. The high pressure coolant jet creates a hydraulic wedge between the tool and the workpiece, penetrating the interface with a speed exceeding that required even for high speed machining and also alters the chip flow conditions [**Mazurkiewicz 1989**]. The penetration of the high energy jet into the tool-chip interface reduces the temperature gradient and eliminates the seizure effect, offering an adequate lubrication at the tool-chip interface with a significant reduction in friction [**Ezugwu 2004**].

The temperatures generated by the cutting speeds of today's advanced tooling can actually prevent low-pressure flood coolant from entering the cutting zone. The majority of the cooling and lubricating aspects of a flood coolant stream are lost as the coolant is vaporized prior to entering the cutting zone [**Frederick Mason 2001**]. It is the great problem for machining, HPC play well role to minimize this type of problem. Frederick Mason [**2001**] found better solution from it and he states that HPC systems generates high velocity coolant streams moving at several hundred mph. This high-speed coolant easily penetrates the vapor barrier to effectively lubricate and cool the tool. In fact, when machinists apply high-pressure coolant to a longstanding process, which has always produced dark blue chips, they are often amazed that the same or even higher speeds and feeds produce shiny, silver chips that are cool to the touch.

Heat from the drill may also work harden or "heat treat" the workpiece in the vicinity of the hole. Friction from the drill heats the workpiece, and when coolant finally reaches the heated material, the coolant quenches it. On the subsequent peck, the drill encounters the hardened material, causing excessive tool wear or a broken tool and damaged part. The high pressure of the coolant breaks up chips and forces them up the flutes and out of the hole. Cycle times go down, because the pecking process is eliminated while spindle speeds and feed rates can be increased. With higher feed rates, chips tend to form better.

The need for high pressure and high volume coolant in drilling became apparent when gun drills came into use over 100 years ago. The essence of the problem (then and now) with standard low pressure coolant systems is that so much heat is produced that the coolant boils away before it can reach the chip-tool interface where metal is actually cut. The super heated steam forms a barrier that low pressure coolant can't penetrate. Effective cooling does not occur and there is little real lubrication provided. Unfortunately, the vapor barrier that forms is not powerful enough to keep chips from falling back into the chip-tool interface and causing damage. Properly applied high pressure and high volume coolant prevents this vapor barrier from forming by causing a localized pressure increase. So much liquid is forced into the cutting zone that heat is removed and no vapor can form because of the pressurization. When machinists tried high-pressure coolant on standard drilling operations, they found that the benefits of increasing coolant pressure improved the performance of these operations as well. Properly applied high-pressure, high-volume coolant prevents the formation of a vapor barrier by causing a localized pressure increase. This force liquid into the cutting zone, removing heat, providing lubrication, and flushing chips away from the cut. Damage from heat and chips is eliminated, and tools can cut until they wear out. High-pressure coolant discourages chip welding, prevents the damaging chemical reactions that may occur at high temperatures, and allows drills to last longer [**Gregory 1999**].

High-pressure coolant also provides lubricity by blasting lubricating fluid between the chip and the cutting edge at hundreds of miles per hour. Combined with much lower temperature, this increased lubricity often causes surface finishes to be twice as good With conventional coolant, the cutting edge comes up to a very high temperature as it enters the cut, and stays hot until it finishes the cut and is exposed to an extreme thermal shock as the coolant quenches the exposed tool.

Coolant is supposed to cool and lubricate but it can only perform these functions at the point of chip formation if the coolant actually reaches the cutting zone. When coolant is turned to steam or otherwise fails to reach the target, it does not perform its two essential functions. High-pressure is often the solution to getting the coolant to the target so it can cool, lubricate, and sometimes perform its third function-breaking chips that do not break neatly with ordinary machining processes **[Frederick Mason 2001]**. Frederick Mason **[2001]** states that high-pressure coolant reduces or eliminates the random tool failure from chip damage, resulting in much improved consistency of the machining process.

Cutting fluids have the dual tasks of cooling the cutting surface and flashing chip. In some operations such as drilling, for example, cutting fluid is important to remove the chips from inside the holes, thus preventing drill breakage **[Klocke 1997 and Derflinger 1999]**. They also help to control cutting-face temperature and this can prolong tool life, improve cut quality, and positively influence part finish. It has the benefit of a power full stream that can reach onto the cutting area, provides strong chip removal and in some cases enough pressure to deburr **[Robert 2004]**. Possibility of controlling high cutting temperature in high production machining by some alternative method has been reported. High-pressure coolant injection technique not only provided reduction in cutting forces and temperature but also reduced the consumption of cutting fluid by 50% **[Robert 2004]**. Mazurkiewicz et al. **[1998]** 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.

1.3 Objectives of the Present Work

The main objective of the present work is to make a experimental investigation on the role of high-pressure coolant jet in drilling AISI-1040 steel and AISI-4340 steel with HSS drill bit and overall benefits in respects of

- cooling capacity of the fluid
- tool wear
- roundness deviation of the hole and
- taper of the hole
- chip formation

Chapter-2

Design and Development of High Pressure Coolant System

2.1 Introduction

HPC machining has developed very quickly day by day. The idea of delivering coolant under high pressure to the cutting region in order to increase tool life during machining began in early 1950s [**Pigott and Colwel 1952**]. Mainly HPC has used in high production manufacturing industries where product quality and dimension accuracy are needed within acceptable limit and difficult-to-machine materials are processed to get the desired job. High speed machining is needed to increase productivity in manufacturing technology. High speed machining is related with high temperature, such high temperature creates lot of problems. So for reducing this high temperature HPC jet is used as a heat removing as well as lubricating agent.

Flood cooling has some problem in machining. A lot of heat is created during high speed machining. Low pressure cutting fluid of flood cooling is vaporized due to high temperature when it comes in contact with the tool- chip-work, makes a barrier (film), for this no cutting fluid reach in the tool-chip interface or cutting zone [**Ezugwu 2004**] The film boiling temperatures of conventional cutting fluids is about 350°C [**Ezugwu and Bonney 2003**]. But in HPC machining coolant is supplied with high pressure (min 40 bars). Due to high pressure coolant reach sufficiently in to the tool-chip interface and break down the vapor barrier and easily enter into the cutting zone.

2.2 Design and Fabrication of the HPC Jet Delivery System

HPC set up contains motors, vena pump, flow control valve, regulating composite device and filter is shown in Fig.2.1. These devices are mounted at the top of a tank that is made of mild steel sheets and angle bars. This tank contains the cutting oil that is used as a coolant. And the capacity of the coolant tank is 200 litters. A coolant indicator is mounted beside the wall of coolant tank; it is used to know the quantity of coolant present in the tank during machining. A 5 hp motor is used to operate the vena pump. A gear coupling is used between the vena pump and motor to transmit power. This pump pressurized the coolant to pass through the flow control. Flow control valve controls the amount of flow. The flow control valve is turned to minimize and maximize flow during machining. A relief valve has mounted with the flow control regulating composite. Relief valve control the pressure and discharge excess oil to the tank. A pressure gauge is also mounted to observe the pressure of coolant. A direction control valve is used for changing the direction of supply. A perfect nozzle is used to supply high pressure coolant towards the cutting zone. From the nozzle pressurized fluid impinged at the chip-tool interface and reduces the cutting temperature. A recycling pump and a filter are used to recycle the used coolant.

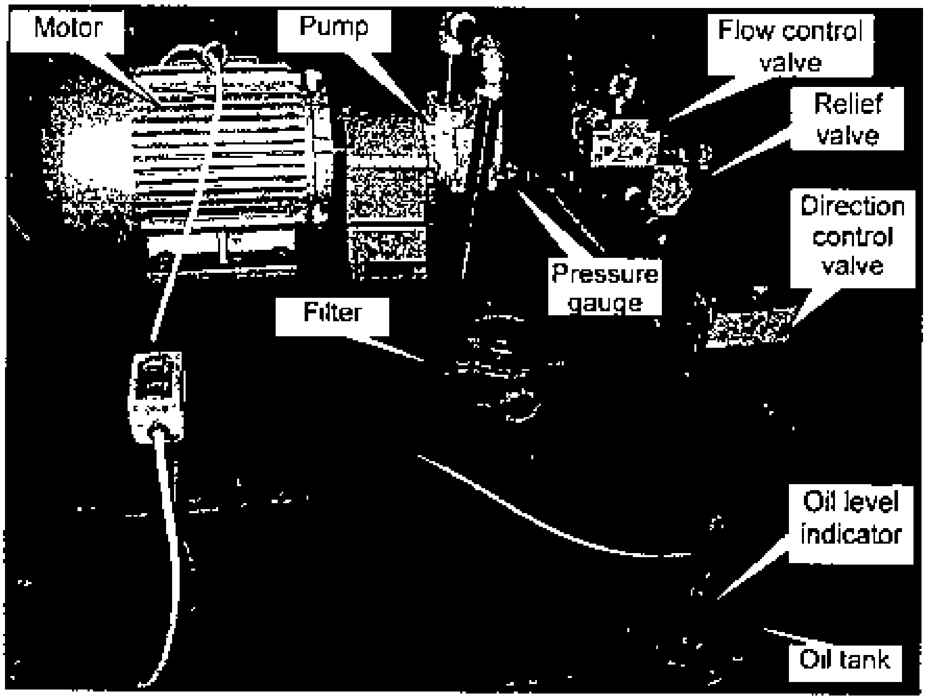


Fig.2.1 Photographic view of high-pressure coolant delivery system

2.3 Design and Fabrication of the Nozzle

A nozzle play major role to supply coolant towards the tool-chip and tool-work interface. Better velocity of jet and higher pressure is produced by a nozzle. Nozzle has been designed for proper jet.

The designed nozzle tip is composed of 1.5 mm tip diameter; 5.6 mm inlet inner diameter and 11.0 mm inlet outer diameter is shown in Fig.2.2 to get desirable jet so that the perfect jet can pass through the tool-chip interface. Nozzle tip plays an important role to supply coolant very superiorly.

Nozzle tip was placed closed to the work piece and drill bit contact point so that the jet impinged at the contact zone. The nozzle was placed at a distance 15 mm from the top surface of the specimen and maintained an angle approximately about 35^0 with the axis of the drill bit so that jet can easily enter in to the hole along the drill flute to function properly.

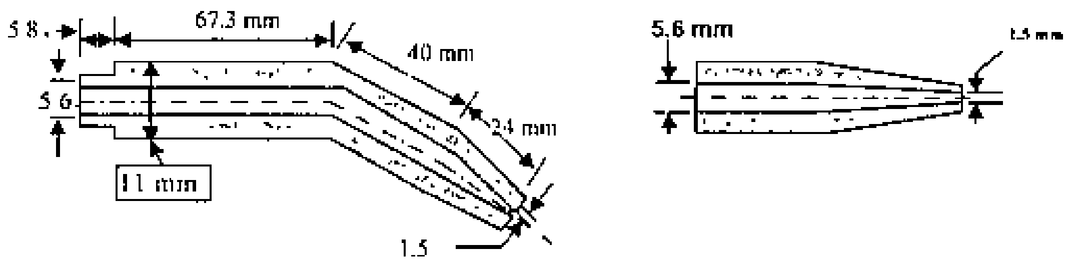


Fig. 2.2 Schematic view of the nozzle tip

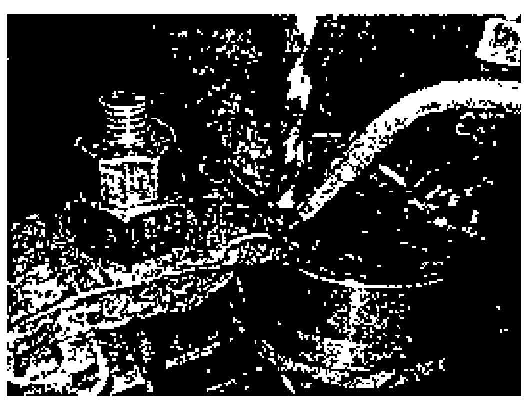


Fig. 2.3 The Photographic view of the nozzle tip

Chapter-3

Experimental Investigations

3.1 Experimental Procedure and Condition

Machining ferrous metals by HSS 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 and AISI-4340 steel has been undertaken for the present investigations.

Considering common interest and time constraint, only HSS drill bit have been used for the present investigation. Wide scope will remain for further study on high-pressure coolant effect in drilling steels by HSS bit and exotic materials by high performance drill bit. The drilling tests have been carried out by drilling of AISI- 1040 and AISI-4340 steel on a drill machine (R915L, Italy, 3.7 k w) by HSS drill bit under both dry and high-pressure coolant condition.

Drilling ferrous metals by HSS drill bit is a major activity in the machining industries. Drilling 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 and AISI-4340 steels have 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]**

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
AISI-4340 steel	275	110	C - 0.360 Mn - 0.920 Ni - 2.850 Cr - 1.410 Mo - 0.520 V - 0.200	• Crank shafts • Differential shafts • Heavy duty gears • Turbine discs • High strength studs and bolts

The positioning of the nozzle tip with respect to the HSS drill has been settled after a number of trials. The photographic view of the experimental set-up is shown in Fig.3.1 and the conditions under which the machining tests have been carried out are briefly given in Table-3.2.


Fig. 3.1 Photographic view of the experimental set-up

Table-3.2 Experimental conditions

Machine tool	: R915L (30-40) Drill Machine, ITALY (power 3.7Kw).
Work material	• AISI-4340 steel • AISI-1040 steel
Cutting tool	• High speed steel (Φ=10 mm) • High speed steel (Φ=8 mm)
Cutting oil	• HC straight run, VG 68
Process parameters	
Cutting velocity, Vc	: 30.75 m/min
Feed rate, So	: 0.10 mm/rev
Depth of cut, t	: 40.40 mm
HPC supply	: Pressure: 40 bar, Coolant: 6 liters/min through external nozzle
Environment	: Dry and High Pressure coolant condition

The cooling capacity of the cutting oil (HC straight run, VG 68) at different pressure and flow rate used in this experiment is important. They were found out using an electric furnace. The maximum temperature measured in the middle of the work piece was 400°C, obtained after keeping it inside the furnace for a period of 8 minutes. After heating, the work pieces were submitted to cooling condition similar to the experiments, i.e. High-pressure coolant (HPC) condition at different pressure.

The temperature was measured by a K-type (cromel-alumel) thermocouple for 8 minutes. This thermo-sensor was connected to the work piece through a hole that allowed it to reach the center of the work piece. The hose of fluid was in a distance of 15 mm from the upper part of the work piece. The cooling capacity of the fluid at deferent pressure is shown in Fig 3.2. Initial data was taken during coolant passed over through the hot specimen. After completing first data coolant was kept on the open air to reduce the temperature of the coolant that came from the hot specimen and coolant temperature were reduced up to room temperature. Then the coolant was placed for next work. It is evident that from Fig.3.2 that the cooling capacity of the cutting oil is more at 40 bar so the experiment was carried out at coolant pressure of 40 bar. Fig.3.3 shows the cooling capacity under air and flood cooling condition.

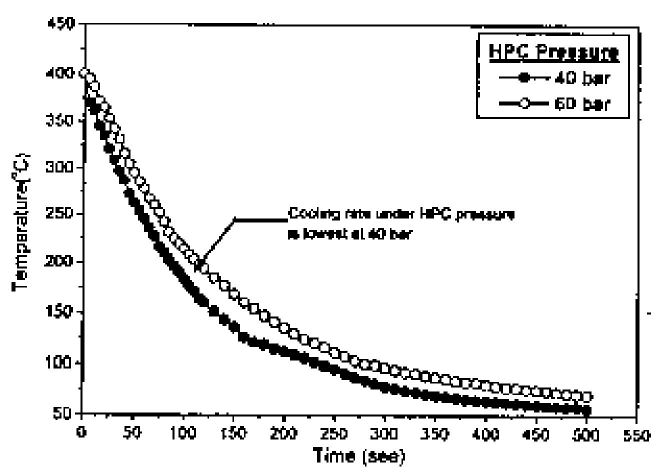


Fig. 3.2 Cooling capacity of the fluids used in the experiments

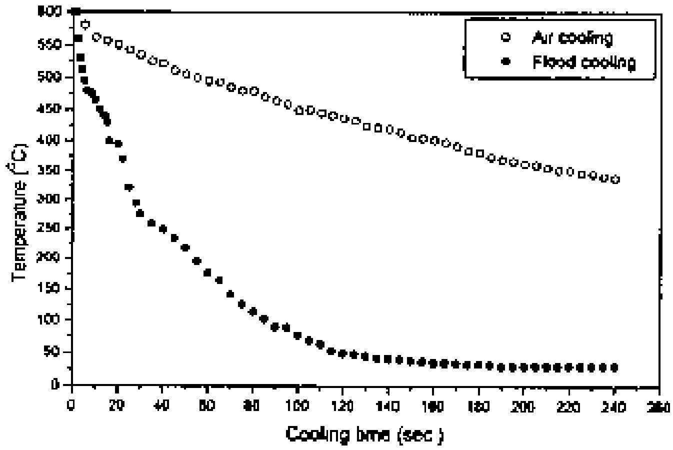


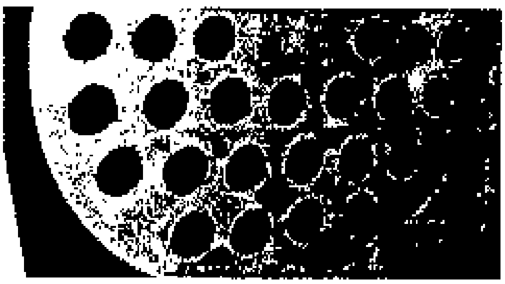
Fig. 3.3 Cooling capacity of the air and cutting fluid **[Rahman 2004]**

3.2 Experimental Results

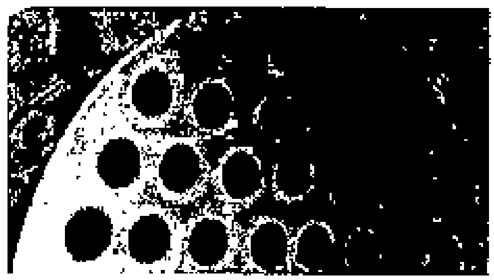
3.2.1 Number of Hole

Both specimens were shaped by turning and facing in traditional lathe machine. Both surfaces were finished by using surface grinding machine; Punching has been done on the top surface of the specimen in right way in order to locate the drill bit at right place. Punching was done on the specimen maintaining equal distance in between centres.

Work piece was placed on the table of the drill machine and clamped very rigidly. A hollow cylinder was placed keeping the work piece at its centre, whose sole purpose was to control chips and coolant flow is shown in Fig.3.1. Drill bit was placed on the top surface of the located work piece and holes were drilled sequentially (like 1, 2 3, 4.......) on both two parts of the divided specimen, one for dry condition and another for HPC condition. AISI-1040 steel was drilled by 8 mm HSS drill bit. On the other hand, AISI-4340 steel was drilled by 10 mm HSS drill bit. Both AISI-1040 and AISI- 4340 steels were drilled under HPC jet condition at 40 bar pressure with coolant supply at 6 litter/ min because of high cooling capacity. The photographic views of the holes are shown in Fig.3.4 and Fig.3.5 respectively.



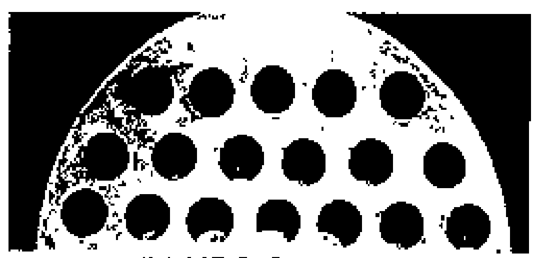
(a) Dry condition



(b) HPC Condition

Fig. 3.4 Photographic view of number of holes under (a) dry and (b) HPC conditions when drilling AISI- 1040 steel by HSS drill bit (Φ=8 mm).

(a) Dry condition

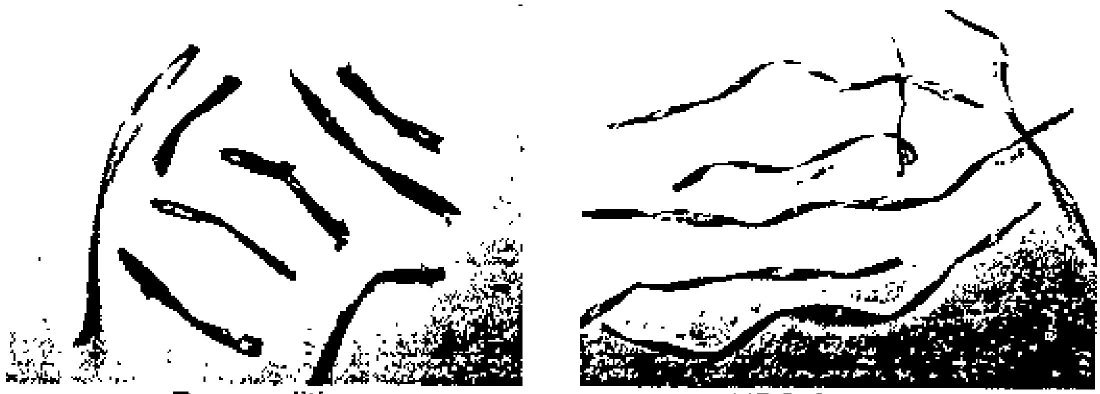


(b) HPC Condition

Fig. 3.5 Photographic view of number of hole under (a) dry and (b) HPC conditions when drilling AISI-4340 steel by HSS drill bit (Φ=10 mm).

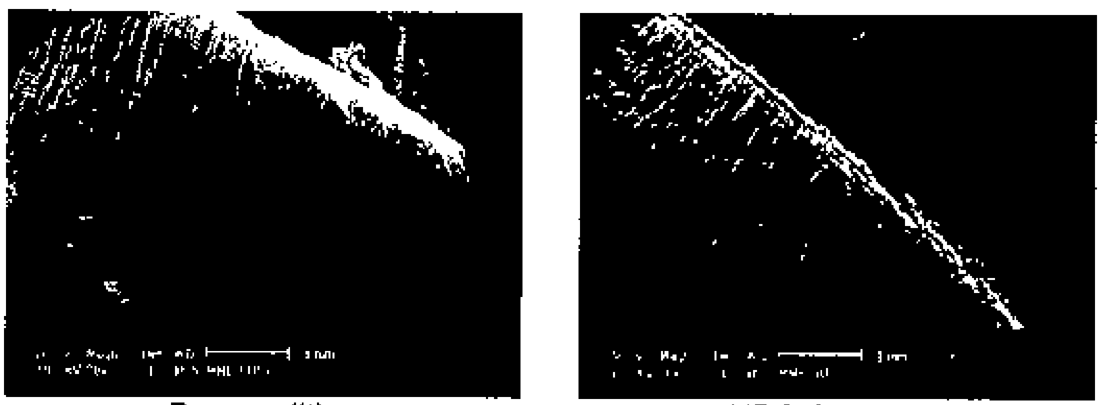
3.2.2 Chip Formation

Chips were collected after the completion of every drilling operation. Drilled chips were allowed for some time to become clean from coolant and cool down. Collected chips were washed out with acetone, dried and preserved in a desicator packing with aluminum foil. The photographic views of chip are shown in Fig.3.6 and Fig.3.7 respectively.



Dry condition HPC Condition

Fig. 3.6 (a) Photographic view of chip under (a) dry and (b) HPC conditions when drilling AISI- 1040 steel by HSS drill bit (Φ=8 mm).

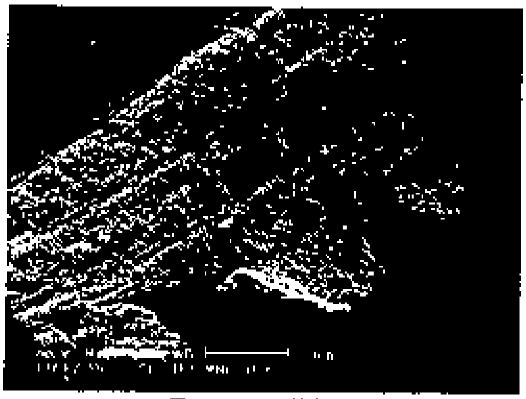


Dry condition HPC Condition

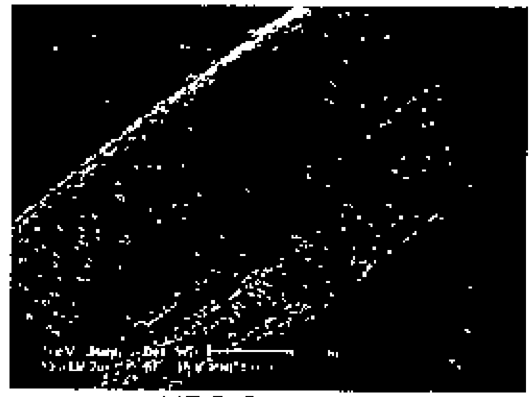
Fig. 3.6 (b) SEM view of chip under (a) dry and (b) HPC conditions when drilling AISI- 1040 steel by HSS drill bit (Φ=8 mm)

Dry condition HPC Condition

Fig. 3.7 (a) Photographic view of chip under (a) dry and (b) HPC conditions when drilling AISI- 4340 steel by HSS drill bit (Φ=10 mm).



Dry condition



HPC Condition

Fig. 3.7 (b) SEM view of chip under (a) dry and (b) HPC conditions when drilling AISI- 4340 steel by HSS drill bit (Φ=10 mm).

3.2.3 Roundness Deviation

The deviation in diameter and roundness of the holes were measured by a precision digital slide caliper having least count 0.01 mm. At least 16 measurements with same alignment were taken for each hole. Digital slide caliper was turned to anti-clock wise direction while measuring the roundness. Table-3.3 and Table-3.4 show the average, maximum and minimum diameters measured in the first third part of the hole length under both dry and HPC conditions. It can be seen in the table that the standard deviation of average diameter obtained under HPC conditions is lower than that obtained using dry condition, which means that the HPC presented a better quality. Fig.3.8 to Fig.3.11 shows the roundness of the holes close to the entrance respectively. Fig.3.12 to Fig.3.15 shows the roundness of the holes close to the end of the holes obtained during drilling the steel.

Table-3.3 Diameter close to the entrance and end of the hole when drilling AISI-1040 by HSS drill bit (Φ=8 mm)

Lubrication system	Diameter close to entrance of the hole				Diameter close to the end of the hole			
	$D_{maximum}$ (mm)	$D_{minimum}$ (mm)	$D_{average}$ (mm)	Standard deviation	$D_{maximum}$ (mm)	$D_{minimum}$ (mm)	$D_{average}$ (mm)	Standard deviation
Dry	8 229	8 054	8 170	0.04291	8.119	8.038	8.068	0.01885
HPC	8.063	8.013	8.031	0.0122	8.027	8.012	8.020	0.00412

Table-3.4 Diameter close to the entrance and end of the hole when drilling AISI-4340 by HSS drill bit (Φ=10 mm)

Lubrication system	Diameter close to entrance of the hole				Diameter close to the end of the hole			
	$D_{maximum}$ (mm)	$D_{minimum}$ (mm)	$D_{average}$ (mm)	Standard deviation	$D_{maximum}$ (mm)	$D_{minimum}$ (mm)	$D_{average}$ (mm)	Standard deviation
Dry	10.094	10 045	10 075	0 01588	10.054	10 031	10 041	0 00781
HPC	10 072	10 031	10.051	0.01105	10 046	10.012	10.030	0.00752

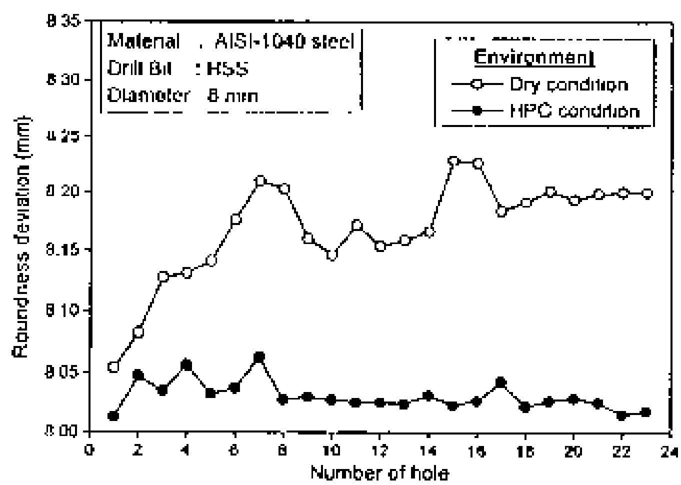


Fig. 3.8 Roundness deviation close to the beginning of holes under dry and high-pressure coolant conditions when drilling steel AISI–1040 by HSS drill bit (Φ=8 mm).

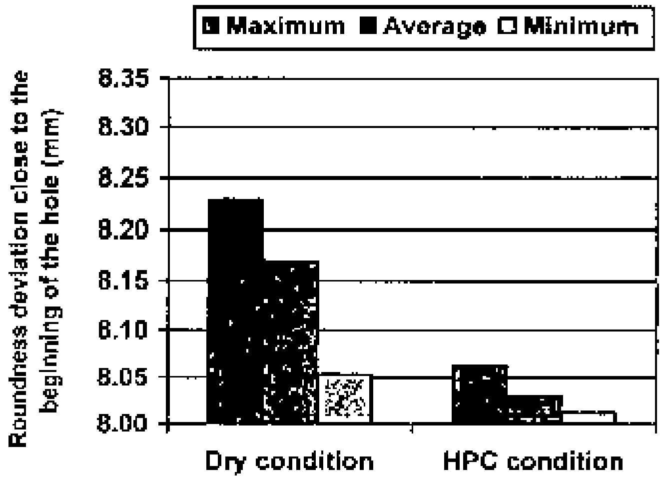


Fig. 3.9 Roundness deviation of maximum, average and minimum value close to the beginning of holes under dry and high-pressure coolant conditions when drilling AISI-1040 by HSS drill bit (Φ=8 mm)

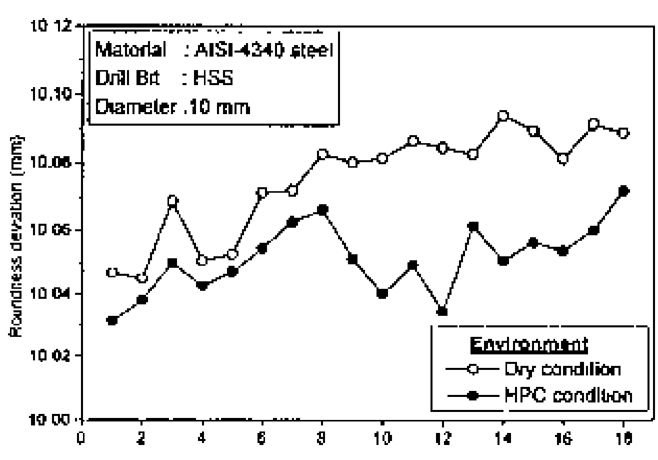


Fig. 3.10 Roundness deviation close to the beginning of holes under dry and high-pressure coolant conditions when drilling AISI-4340 steel by HSS drill bit (Φ=10 mm)

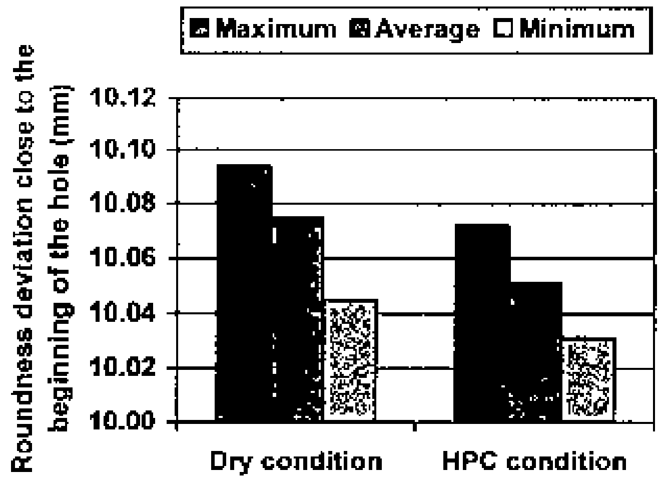


Fig. 3.11 Roundness deviation of maximum, average and minimum value close to the beginning of holes under dry and high-pressure coolant conditions when drilling AISI-4340 steel by HSS drill bit (Φ=10 mm).

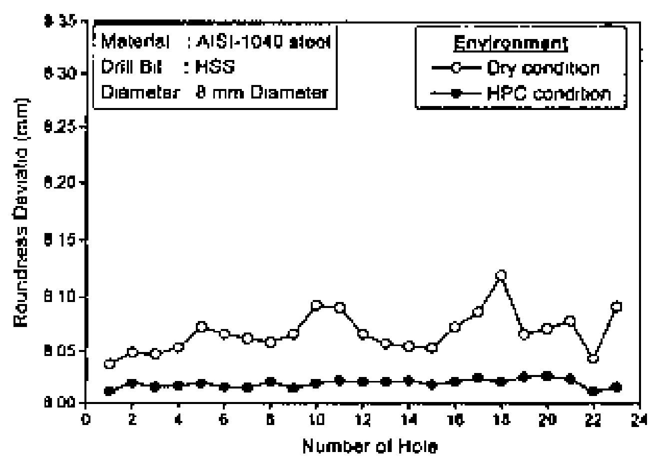


Fig. 3.12 Roundness deviation close to the end of holes under dry and high-pressure coolant conditions when drilling AISI-1040 steel by HSS drill bit (Φ=8 mm).

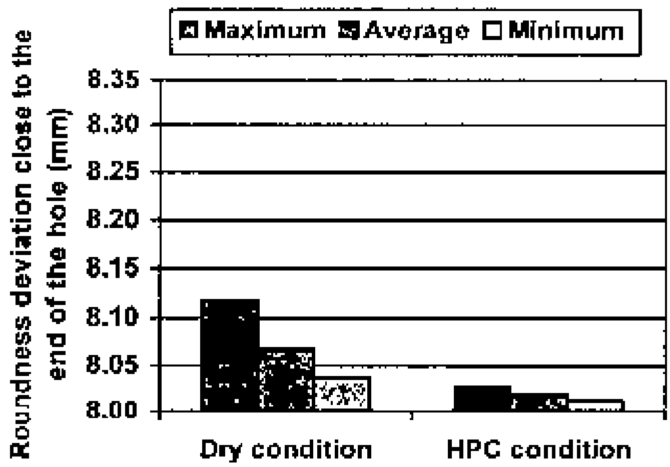


Fig. 3.13 Roundness deviation of maximum, average and minimum value close to the end of holes under dry cooling and high-pressure coolant conditions when drilling AISI-1040 steel by HSS drill bit (Φ=8 mm).

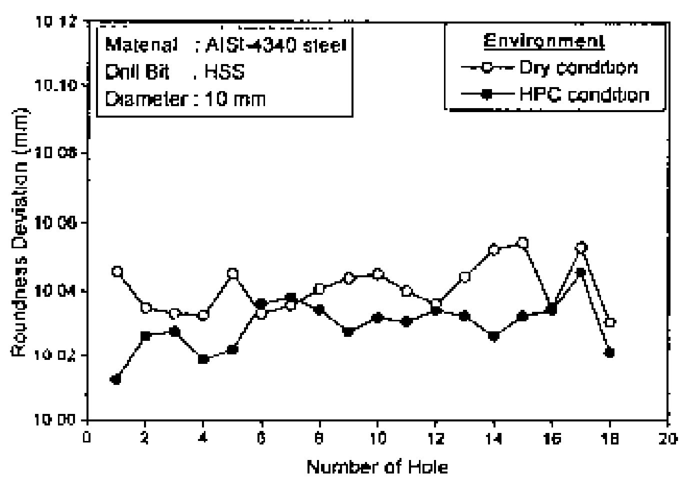


Fig. 3.14 Roundness deviation close to the end of holes under dry and high-pressure coolant conditions when drilling AISI-4340 steel by HSS drill bit (Φ=10 mm).

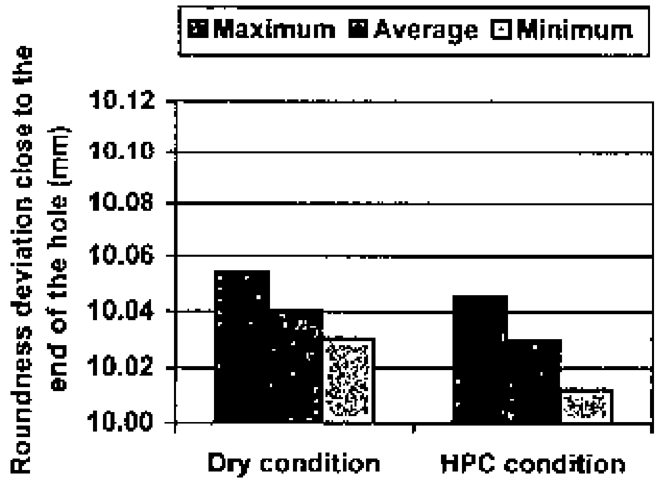


Fig. 3.15 Roundness deviation of maximum, average and minimum value close to the end of holes under dry cooling and high-pressure coolant conditions when drilling AISI-4340 Steel by HSS drill bit (Φ=10 mm).

3.2.4 Diameter Deviation or Taper

Fig.3.16 to Fig.3.19 shows the taper values under dry and high-pressure coolant condition. The average taper values and their dispersion were smaller under high-pressure coolant condition. Moreover, in both conditions the average taper values were positive, i.e., the diameters in the entrance of the holes were bigger than at the end. These bad results found for the holes made under dry condition are due lack of lubrication action, which made the diameter in the beginning of the holes to increase.

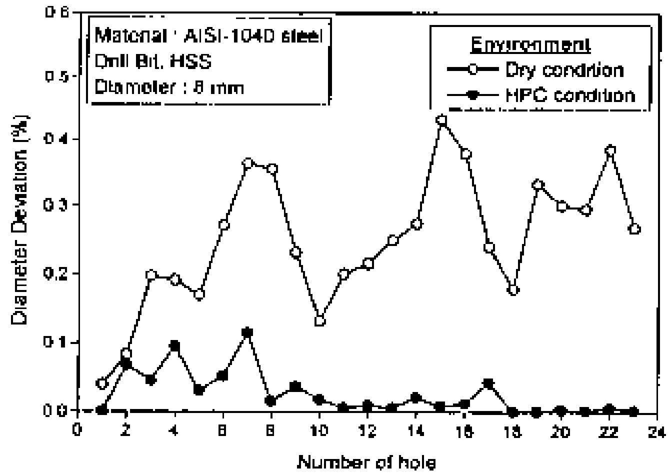


Fig. 3.16 Variation of diameter deviation with number of holes under both Dry and high-pressure coolant conditions when drilling AISI-1040 steel by HSS drill bit (Φ=8 mm).

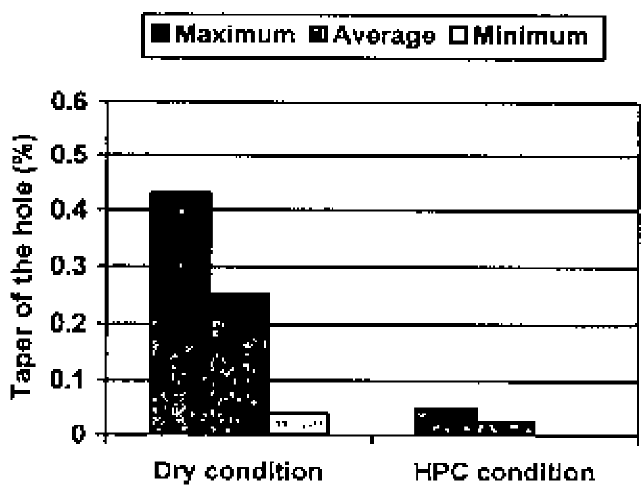


Fig. 3.17 Taper values of maximum, average and minimum under Dry and high-pressure coolant conditions when drilling AISI-1040 steel by HSS drill bit (Φ=8 mm).

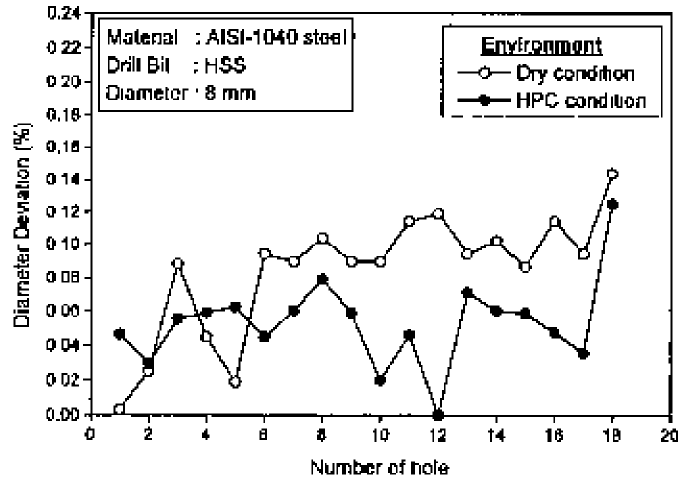


Fig. 3.18 Variation of diameter deviation with number of holes under both Dry and high-pressure coolant conditions when drilling AISI-4340 steel by HSS drill bit (Φ=10 mm).

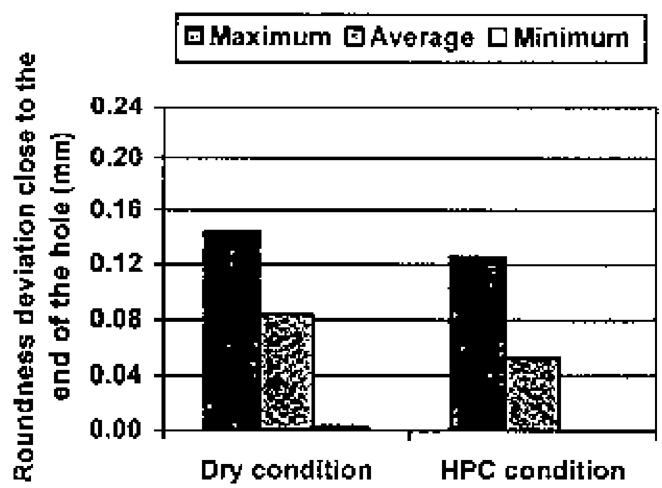
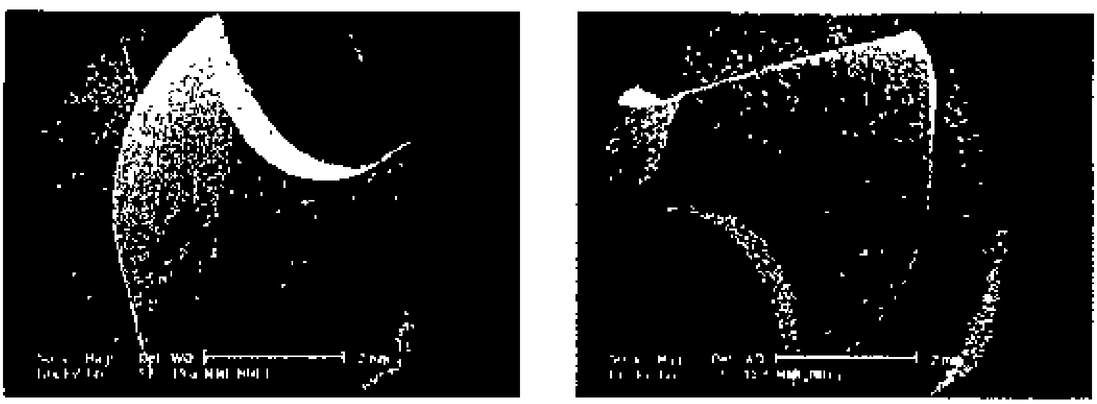


Fig. 3.19 Taper values of maximum, average and minimum under Dry and high-pressure coolant conditions when drilling AISI-4340 steel by HSS drill bit (Φ=10 mm).

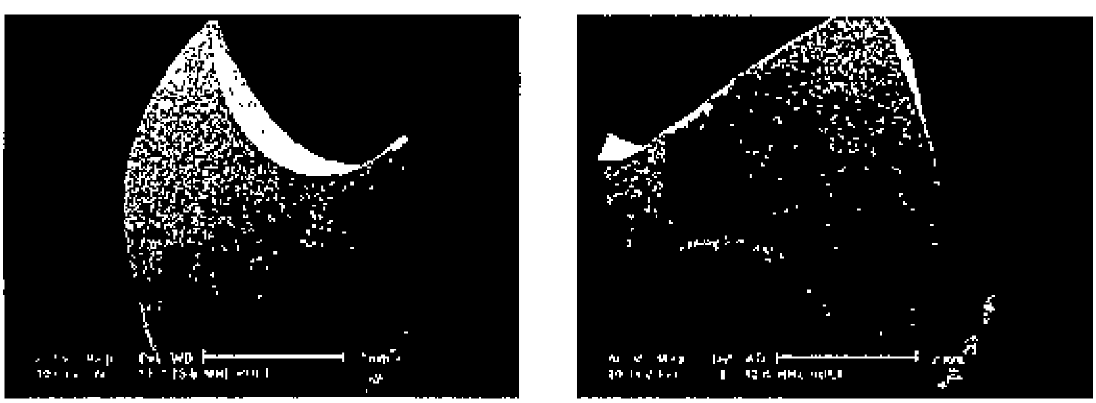
3.2.5 Tool wear

Tool wear play important role in drilling operation. Tool wear caused to poor quality of hole surface, irregularity of roundness and unacceptable diameter deviation.

Drill bits were cut by wire EDM up to 5 mm from the tip of drill bit. Then drill bit tips were scanned under SEM for measuring the tool wear. The SEM views of tool wear are shown in Fig.3.20 and Fig.3.21.

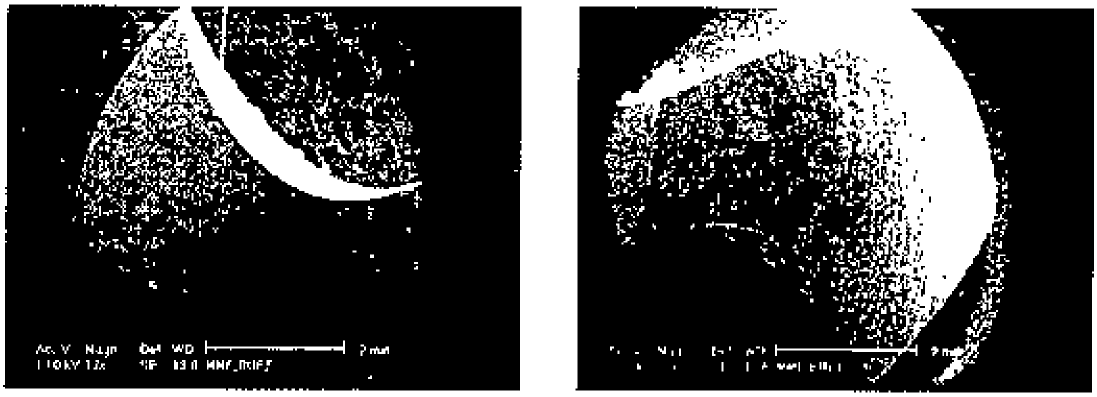


(a) Dry condition

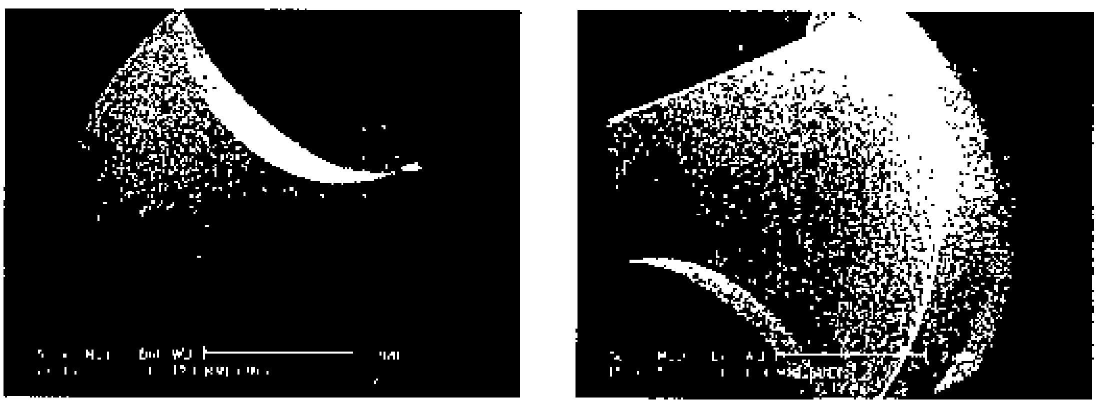


(b) HPC condition

Fig.3.20 SEM views of the worn out drill bit under (a) dry and (b) high-pressure coolant condition when drilling AISI-1040 steel by HSS drill bit (Φ=8 mm).



(a) Dry condition



(b) HPC condition

Fig. 3.21 SEM views of the worn out drill bit under (a) dry and (b) high-pressure coolant condition when drilling AISI- 4340 steel by HSS drill bit (Φ=10 mm).

Chapter-4

Result and Discussion

4.1 Number of hole

Number of hole in drilling operation is a major concern. Small number of holes drilled by one bit increases the manufacturing cost due to tooling cost and cost for replacement of the tool. Maximum possible numbers of drilled holes with a single piece of bit are the prime necessity for high production manufacturing. During drilling huge amount of heat is produced due to shearing of metal, friction between chips and flute and rubbing the flank with newly cleaved surface. Machining with higher speed flank of drill bit wears out, drill bit tip burns and melts by higher temperature produced in the cutting zone. Dhar et al. [2004] found that in dry condition, for AISI-1060 steel, after completing 10 holes carbide drill bit was too worn out to do further operations impossible. For this wearing tendency due to lot of heat sometimes drill bit break down within a sort time.

AISI-1040 and AISI-4340 steel are drilled under dry and HPC condition by 8 mm and 10 mm HSS drill bits respectively are shown in Fig.3.4 (a) and Fig.3.5

(a). In dry condition drill bit becomes burnt blue in color after completing 23 holes on AISI-1040 steel and 18 holes on AISI-4340 steel and creates very rough surface with changed roundness. Very small chips are found on the surface of the hole as wielded matter due to accumulation of huge heat while cutting. On the other hand in HPC condition drill bit remains its original color and with out any burning 25 holes are drilled on AISI-1040 and 18 holes on AISI-4340 with metallic color chips are shown in Fig.3.4 (b) and Fig.3.5 (b), Holes dimension are very close to acceptable limit having proper shape and no wielded chip is found in the HPC drill. High pressure coolant washout all the chips and cools tool chip and work piece rapidly. High-pressure coolant jet results effective outcome at pressure 40 bar at a flow rate 6 lit/min.

4.2 Chip Formation

Chips play significant role in the manufacturing technology as maximum heat is carried out from the cutting zone through the chip that commits maximum tool wear while passing over the tool. In drilling, the material is removed in the form of chip and evacuated through the drill flutes. High-pressure coolant (HPC) played very effective role for cooling and provided lubrication between drill bit and chip interface. Fig.3.6 (a) and Fig.3.7 (a) shows the shape of chips during drilling steels by HSS drill bit under both dry and high-pressure coolant (HPC) conditions. The shape of the chip produced under both dry and high-pressure coolant condition become spiral when drilling AISI-4340 steel whereas discontinuous burn blue and continuous metallic color chips are produced while drilling AISI-1040 steel . The color of the chips have also become much lighter i.e. metallic from burnt blue due to reduction in drilling temperature by high-pressure coolant condition.

It is evident from SEM view of drilled chip, Fig.3.6 (b) and Fig. 3.7 (b), that chips produced in high-pressure coolant (HPC) condition is smooth due to proper cooling and lubrication in drilling both the steel which creates a lubricant film that protects the tool face from rubbing with the work material and pretend sharp edge of the drill bit. On the other hand saw toothed chips are produced in dry condition due absence of lubrication and serration of chips.

4.3 Roundness Deviation

Before the analysis of the quality parameters of the holes, it is important to note that neither diameter nor any other quality parameter of the hole was influenced by tool wear. In other words, these parameters presented no tendency as feed length increased. Table 3.3 and Table 3.4 shows the average, maximum and minimum diameters measured in the first third part of the holes length in the both dry and HPC lubrication systems. It can be seen in the table that the standard deviation of the average diameter obtained under HPC condition is lower than that obtained using dry condition, which means that the HPC presented a batter quality with presence of adequate cooling and lubrication at the chip-tool interface.

Fig.3.8 and Fig.3.9 show the roundness of the holes close to the entrance and Fig.3.12 and Fig.3.13 show the roundness of the holes close to the end of AISI-1040 and it can be seen from these figures that the roundness deviation did not change from the beginning to the end of the holes under HPC condition in compare to dry condition, this result can be attributed to the lower cutting force and the shorter diameters. In dry condition due to excessive heating, scarcity of coolant and lubricant, rubbing the tool face with work material and commencement of tool wear, the deviation is very large which is clearly shown in figure 3.8.

Fig.3.10 and Fig.3.11 show the roundness of the holes close to the entrance respectively Fig 3.14 and Fig.3.15 show the roundness of the holes close to the end of the holes obtained during drilling AISI-4340 steel and it can be seen from these figures that the roundness deviation has a little change from the beginning to the end of the holes under HPC condition in compare to dry condition, this result can be attributed to the lower cutting force and smaller roundness deviation due to effective cooling and efficient lubrication. Even with the drill penetrating further into the hole, the forces were not be able to deviate the drill more than in the entrance of the hole, and the roundness deviation was kept almost constant. For both the steel under dry condition the pattern and extent of roundness deviation is same but in case of AISI-4340 steel under HPC condition, shown in fig. 3.10, the roundness deviation is not uniform and steady in comparison with AISI-1040, shown in fig. 3.8, because of high hardness due to high alloying elements. The roundness deviation was smaller at both the entrance and end of the holes under HPC condition in compare to dry condition for both the steel, because of high lubricant capacity.

4.4 Diameter Deviation or Taper

Bottom surface roundness deviation has influential role to make taper value. Taper value was appeared in both dry and HPC condition for both AISI-1040 and AISI- 4340 steel. Drilling under HPC jet, taper value and its dispersion was within acceptable limit for both the steel shown in Fig.3.16, Fig. 3.17, Fig. 3.18 and Fig 3.19. But some fluctuation in taper value was found in dry drilling on both the work piece.

Moreover, in both conditions the average taper values were positive, i.e., the diameters in the entrance of the holes were bigger than at the end. These bad results found for holes made under dry condition are due lack of lubrication action, which made the diameter in the beginning of the holes to increase.

When the tool reached the end of the holes, the diameter decreased, due to the alignment of the tool caused by the hole's wall. When high depth of cut is used, the drilling using dry condition is not possible because of high tool wear.

4.5 Tool Wear

Tool wear causes poor quality of holes surface, irregularity of roundness and unacceptable diameter deviation. Insufficient cooling, blocking of flowing chips within the drill flute and rubbing of blocked chip with newly cleaved surface increase temperature further. This increment in temperature increase tool wears. Fig.3.20 and Fig.3.21 show that drilling under dry condition tool wear is evident for both the steel but no significant wear is found under HPC condition . High pressure coolant condition reduces cutting temperature and provide lubrication entering into chip-tool interface making a lubrication film at high pressure, thus reduces tool wear as a result tool life is increased.

Chapter-5

Conclusion

Based on the experimental results the following conclusions can be drawn:

- Cooling capacity of the cutting oil used in the experiment is better at 40 bar pressure than at 50 & 60 bar. At higher pressure cutting oil temperature raises due to intermolecular friction between the atoms results a lower cooling capacity.
- The quality of the holes obtained using HPCJ is much better than that obtained in dry cutting. Roundness deviation was very small both at the entrance and end of the holes under HPCJ condition in compare to dry condition, because of high cooling capacity of lubricant.

- Taper values were also smaller under HPCJ condition in compare to dry condition for both the AISI-1040 and AISI-4340 steels, because of high lubrication capability of the cutting oil.

- In HPCJ the chips were long in shape and continuous, so it was not stocked in the holes. This indicates that lubrication effects under HPCJ in compare to dry condition is much better, because the cutting fluid effectively works here in lubrication and cooling. On the other hand in dry condition the chips were short in size and not continuous, so it stocked in the holes.

- The beneficial effects of HPCJ may be attributed to effective and efficient lubrication action, which prevents the chip sticking on the tool and makes the operation easier. To carry out the operation with dry cutting is very much difficult, because the chip sticks to the spiral channels of the drill.

- HPC improves tool wear and results smaller diameter deviation and taper deviation.

Chapter-6

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