# INVESTIGATIONS ON SURFACE GRINDING OF HARDENED STEELS WITH PULSE JET MQL NANOFLUID UNDER COMPRESSED AIR WHEEL CLEANING

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**DHAKA, BANGLADESH**

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# INVESTIGATIONS ON SURFACE GRINDING OF HARDENED STEELS WITH PULSE JET MQL NANOFLUID UNDER COMPRESSED AIR WHEEL CLEANING

By
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**DEPARTMENT OF INDUSTRIAL & PRODUCTION ENGINEERING**
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The thesis entitled as **Investigations on Surface Grinding of Hardened Steels with Pulse Jet MQL Nanofluid under Compressed Air Wheel Cleaning** submitted by Md. Imran Hasan Tusar, Student No. 0416082012, Session-April 2016, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of M. Sc. in Industrial and Production Engineering on May 28, 2019.

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# Declaration

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

Md. Imran Hasan Tusar

*This work is dedicated to my*

*Loving Parents*

*Abul Hashem Bakul*

*And*

*Asmaul Husna*

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# ABSTRACT

Grinding is a finish machining task in which excess material is removed from the surface of the workpiece material with grinding wheel containing abrasive grains. High temperature is generated in the work-tool interface because of rubbing and friction. This elevated temperature has various detrimental effects on the performance and the longevity of the material being ground. So an effective solution to this universal problem has been a matter of great concern for the researchers. Convention flood cooling method has several drawbacks like health problems to the workers, environment pollution, soil contamination and huge wastage of expensive material. As a result, some alternative cooling techniques comes to the spot like high pressure cooling, Minimum Quantity Lubrication, cryogenic cooling, compressed air etc. The techniques are better in terms of reducing grinding force, surface roughness, residual stress, wheel loading and surface burning. Application of Minimum Quantity Lubrication is economically viable and environment friendly.

This study focuses on the effects carbon nanofluid on grindability of hardened steel. Mixing carbon nanotube with the cutting fluid has demonstrated excellent cooling and lubricating properties. Adding compressed air at the time of machining operation enhances surface properties by keeping the abrasive grains sharp. Main purpose of this thesis is analyze the effect of nanofluid and compressed air and their flow rate for grinding AISI 1060 steel at some industrially available two different speeds, four different infeed and another four different cutting conditions. Graphical representation of experimental investigation reveals that CNT mixed MQL with compressed air has the best cooling and lubricating properties among the four different cutting conditions used in this research work. Four independent variables (wheel speed, infeed, material hardness and cutting condition) are used in formulating the mathematical model using Response Surface Methodology (RSM). Statistical analysis suggests that there are strong correlations between these parameters with the output response. The model is validated by comparing with the experimental data and found accurate reasonably. Slight variation in the result was due to natural processes and some physical phenomena.

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## INTRODUCTION

### 1.1 Introduction

Grinding is popularly used in manufacturing process to manufacture those types of parts and components which need precise surface finish with a tight tolerance. It is also the first choice for machining hard materials. Grinding is also called abrasive machining process in which materials is removed by the friction with the abrasive particles of the grinding wheel. General rule is that the hardness of the tool used for grinding process is higher than the materials on which grinding is done. Most suitable and commonly used abrasives for grinding are aluminum oxide (corundum), silicon carbide and cubic boron nitride. Silicon carbide is an abrasive used for grinding gray iron, chilled iron, brass, soft bronze and aluminum, as well as stone, rubber and other non-ferrous materials. Ceramic aluminum oxide is the newest major development in abrasives. This is a high-purity grain manufactured in a gel sintering process. The abrasive aggregate is selected according to the hardness of the material being cut. Grinding wheels with diamond or CBN grains are called super-abrasives. Grinding wheels with aluminum oxide (corundum), silicon carbide, or ceramic grains are called conventional abrasives. Grinding is not only used for small parts like contact glass lenses, silicon wafers, rolling bearings, needles and electronic components but also used for large parts such as machine tool slide ways where it is more important whether the component is straight or not. Tolerance is usually specified in microns (μm) for large parts but in case of small precise parts tolerance can be extended to nanometer level.

Grinding has a remarkable role in efficient manufacturing in terms of both volume and value. For example: in a process of planar grinding a lot of parts can be ground simultaneously on single worktable. High material removal rate (MRR) as well as high accuracy can be achieved in planar grinding. In grinding, material is removed generally by the action of shearing and ploughing in the form of micro-chips. Grinding is heavily used in industries for different purposes. It is mainly used in those areas which have greater importance for a smooth finished surface. Grinding is normally used in

- Cylindrical grinding process is used for grinding the outer surface of cylindrical object
- Center less grinding process is used for preparing the transmission bushing, shouldered pins and ceramic shafts for circulator pumps
- Internal grinding process is used for finishing the tapered, straight and formed holes precisely
- There are few special grinders used for sharpen the milling cutters, taps, other various machine cutting tool cutter and reamers

If tensile residual stress is present in the sample after grinding it may reduce both static and dynamic strength and corrosion resistance which may cause distortion at any stage during the service life. In case of brittle materials, it can cause surface and sub-surface micro cracks. Another problem associated with machining ductile and sticky materials is accumulation of the micro chips into the grit-space of the wheel. It requires frequent dressing which ultimately reduces the efficiency of the grinding. Wheel loading also shorten the total effective lifetime of the wheel. Wheel loading can also contribute to the rise of force, temperature and vibration, re-deposition, dissatisfactory surface finish.

So, excessive temperature generation during grinding is one of the main concerns of the researchers over the years. Suitable application of proper grinding fluid can reduce the problem to some extend by the action of both cooling and lubrication. Most commonly used grinding fluids are neat oil, synthetic and semi-synthetic oil, with or without inorganic salt and additives. The application technique of these fluids also varies and plays a great role in reducing the temperature of the grinding zone. The most commonly practiced application techniques are flood cooling, minimum quantity lubrication, forming pulse jet or even creating misty even misty environment.

Last but not the least, a problem often faced by the expert is the extent to which the coolant can penetrate into the grinding zone. Due to the high speed of the grinding wheel a thin layer of air continuously rotates with the grinding wheel which prevents the coolant to enter into the grinding zone. It is the matter of great concern to reduce the grinding zone temperature.

A vast research has been done to reduce the facts which hinder the overall grinding efficiency. Still research is going in this field to get suitable techniques which will minimize the problems associated with grinding to a significant level. Minimum Quantity Lubrication (MQL) has shown an effective cooling and lubrication property which is far better than traditional flood cooling, dry machining and cryogenic cooling. Pulse jet MQL is a modified technique which performs slightly better than traditional MQL reducing the wastage of cutting oil as it has the ability to penetrate into the zone of interest. Recently, researchers have shown that a stabilized mixture of Carbon Nanatube with cutting oil (nanofluid) has superior thermal properties which is able to reduce the cutting zone temperature much more effectively than all other techniques previously used for this purpose.

## 1.2 Literature Review

Cutting temperature, cutting forces, interaction between chip and tool, accuracy of dimension, surface integrity and quality, specific power consumption during machining, wear and life of the cutting tool in under various cutting conditions are the main concerns in the research and investigation done so far on different types of machining operations. Temperature control is necessary for preventing the unwanted heat treatment of the material being machined. Major portion of the machine power is unfortunately converted to heat during machining. During metal cutting the primary source of the heat is the due to the deformation of the material and formation of the chip. The secondary heat source is located at the chip tool interface which is the result of the secondary plastic deformation. Tertiary heat source is located at the tool flank-workpiece interface **[Abukhshimet et al. 2006]**. At the time of machining process, the tool removes material from the surface of less resistant body. The chips slide on the face of tool submitting it to high and normal shear stresses. Mechanical energy used to form chips ultimately becomes heat which increases the temperature of the cutting zone. The higher the energy consumption, the higher the friction between the chip and the tool, higher the temperature and ultimately higher the tool wear. This is why various types of conventional coolant are used to prevent the overheating. However, one of the biggest problems of the conventional coolant is it could not reach to the cutting zone most of the time. The temperature is high enough to evaporate the cutting fluid before entering to the cutting zone [**Dhar and Kamruzzaman 2009**]. So, the heat generated during machining do not transferred which contributes greatly to the reduction of the tool life.

Excessive temperature, damage due to thermal action, dimensional inaccuracies resulting from the energy generated during the machining process is the reason why cutting fluid is an essential element. Basically, a cutting fluid has three main functions when applied to the grinding process like bulk cooling of the workpiece, flushing away the grinding chips and remove wheel grits and lubrication **[Ebbrell et al. 2000]**. Both lubrication and cooling have some good positive effects on machining. Lubrication reduces the friction between the workpiece and the tool, leading to less generation of heat resulting in a lower tool wear and good surface finish. Cooling effect removes the heat from the tool workpiece contact area. So, lubrication effect of the cutting fluid takes preventive action of heat generation and the cooling effect of cutting fluid take the corrective action heat generation.

Conventional cutting fluid fails remove heat effectively as it cannot penetrate the chip-tool interface in high speed machining **[Paul et al. 2000, Dhar et al. 2006].** Even extreme pressure applied to the cutting fluid does not ensure its presence in the chip-tool interface **[Cassin and Boothroyd 1965].** Nevertheless, high pressure jet of soluble oil applied at the chip-tool interface successfully to reduce cutting temperature and increase tool life **[Mazurkiewicz et al. 1989; Alexander et al. 1998]**.

Large amount of cutting fluid applied during grinding makes it environmentally unfriendly. Mist generation in grinding is larger than that of turning **[Chen et al. (2002a, 2002b)]**. Recently, the detrimental effect of this huge amount of cutting fluid on human health and the environment and also the cost associated with it (17 %) has become a matter of great concern in the manufacturing industry. It is very tough to recycle cutting fluid. It can be responsible for different skin diseases and can have deadly effect on the respiratory system of the close workers **[Sokovie and Mijanovie, 2001; Kalhofer 1997; Derflinger et al. 1999; Anon 2003]**. Improperly handled and inappropriately disposed cutting fluid has severe environmental impact **[Brinksmeier and Eekebrceht 1994]**. For these reasons, strict legitimate action is needed to stop this unhealthy practice. In the days of growing competition, cost effectiveness needs high production rate which needs high speed machining. High speed machining needs special cooling techniques such as cryogenic cooling, minimum quantity lubrication, high pressure cooling. Cryogenic machining **[Paul and Chattopadhyay 1996; Dhar et al. 2002].** Additionally, high pressure cooling [**Dhar et al. 2008; Rahman et al. 2000]** have improved the machining technique of steel remarkably. But, cryogenic cooling is not that much popularly practiced due to high cost and hazardous nature of liquid nitrogen. On the other hand, high pressure coolant technique requires a large amount of coolant which increases the production cost such a level that makes it infeasible. Another option available is dry machining which involves using no cutting oil. In spite of using dry machining in some cases **[Klocke and Eisennblatter 1997, Aronson, 1995],** it has a lot of detrimental issues related to surface roughness, temperature etc. Minimum quantity lubrication (MQL) is a nice trade-off between the dry and the flood cooling. MQL is often called Near Dry Machining (NDM). The amount of lubricant applied to the cutting zone is very small in case of MQL. Most of the time no excess lubricant remains in the cutting zone even if remains some oil they form a thin protective layer over the workpiece to protect it from being oxidized. This method has been adopted over the years for various metal cutting, sawing and forming operation. The prospect of this technique is very convincing because of its vast advantageous features. MQL basically use water insoluble cutting fluid. Vegetable based fluid becoming more popular. These oils are less hazardous for the respiratory system of the workers **[Heisel et al. 1998].** Research suggest that MQL is better than conventional soluble oil in providing effective lubrication thus reducing the grinding power, specific energy and grinding wheel wear **[Hafenbraedl and Malkin 2001]**.

MQL is a good escape route from the misting environment and unhealthy skin-exposure. No chance of contamination in this case. MQL is cost effective in many ways. Firstly, MQL requires less amount of fluid. Secondly, the machine doesn't need frequent interruption due to cleaning. It keeps the machine temperature lower than dry machining by providing some cooling in the chip-tool interface. Another benevolent feature is that it keeps both the machine and chip dry which makes it easier to handle and collect the chip for further analysis **[Itoigawa et al. 2006]**. Cutting performance of MQL has found to be better than both dry and flood cooling **[Dhar et al. 2006]**. A mixture of pressurized air and oil micro droplet is mixed in a mixing chamber which is directly applied to the chip tool interface **[Rahman et al. 2009]**. It prevents the wastage of cutting fluid to a great extent (needs only 50-500 ml/hr), usually 3 to 4 times less than the conventional flood cooling **[Autret et al. 2003]**. This is why MQL is often called near dry lubrication or micro lubrication **[Klocke and Eisennbla 1997]**.

MQL has been applied widely in drilling, turning and milling. Nonetheless, MQL has been studied well, only few researchers have studied MQL grinding **[Silva et al. 2005, 2007; Tawakoli et al. 2009, 2010, 2011]**. A lot of studies have been done to identify and quantify the lubricating and cooling capabilities of MQL analyzing surface roughness, surface temperature, residual stress, micro structure and micro hardness. MQL grinding was studied by **[Brunner 1998]** with 4 ml/min ester oil, as compared to 11 ml/min mineral oil, during grinding of 16MnCr5 in addition with microcrystalline aluminum oxide and found that it reduces the normal and tangential force to 30% but increases the surface roughness by one-half **[Brink et al. 1997]**. Investigation by Dhar et al. **[2005]** on the grinding of 16MnCr5 showed that MQL works better than dry and wet environment in terms of temperature though roughness value of MQL grinding was better than dry but slightly worse than flood cooling. A research group led by Silva (2007) showed that in case of machining ABNT 4340 steel (HRC 60) under MQL condition, chips slides more conveniently as the lubricant penetrate easily leading to finer surface finish. Compressive residual stress is good for the work piece as it increases the fatigue strength of the material. It has been observed that MQL produced compressive residual strength of around 380 MPa which is much than that of conventional cooling (20 MPa and 160 MPa). The microstructure of dry and MQL machining do not differ much. The effect of MQL was observed by **[Tawakoli et al. 2009]** for both soft steel (42CrMo4) and hard steel (100Cr6) with wheel speed of 25m/s and depth of cut 25 µm and conclude that the surface quality and integrity is more noticeable in MQL in comparison with dry and wet machining. The tangential force and the specific grinding force were lower but no uniform trend was found in case of normal force. At low MRR (less than 0.42 $mm^3$/min) tangential force do not change much but normal force tends to vary with highest value for dry machining and lowest value for MQL and flood cooling in between. However, tangential force tends to decrease for both hard and soft material if the MRR is high. Barczak et al. [**2010**] studied the comparative performance of MQL for mild steel (BS 970 080M40, 32±2 HRC), bearing steel (BS534A99, 62±2 HRC) and tool steel (BSBM2, 52±2 HRC) with alumina wheel which was evaluated in terms of tangential force, surface roughness, and grinding temperature. A Taguchi analysis is performed to find the most influential parameters among of wheel speed, worktable speed, infeed and material hardness. It has been observed surface temperature, tangential force and the force ratio has a strongest co-relation with the infeed and surface roughness highly depends on hardness. The effect of mist environment in grinding was studied by **[Tawakoli et al. 2010]**. Several parameters are varied to see the effect on grinding force and surface roughness such as the oil flow rate, the air pressure, MQL nozzle position and nozzle distance from the wheel workpiece contact area using the material of 100Cr6 hardened steel with alumina wheel. The effective position of the spray nozzle was determined to be 10-20°. Another observation was the wheel with higher porosity and coarser dimension have lesser active grains and smaller wear area which is suitable for MQL as is ensures proper penetration of the fluid.

From the background study above suggest that MQL is still in developing stage and further study is needed to establish it as an attractive fluid application technique in the manufacturing arena. Manufacturing by machining constitutes major industrial activities in global perspective. Like other manufacturing activities, machining also leads to environmental pollution **[Ding and Hong 1998; Hong et al. 1999]** mainly because of use of cutting fluids. These fluids often contain sulfur (S), phosphorus (P), chlorine ($Cl_2$) 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. Expert opinion is that **[Aronson 1995]** the major problems arise due to use of cutting fluids are-

- Environment 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.
- Disposal of the spent cutting fluids, which also offer high risk of water pollution and soil contamination.

Since beginning of twentieth century people **[Welter 1978; Kennedy 1989 and Thony et al. 1975]** were concerned with possible harmful effects of various cutting fluid application. Water mixed fluids generally determine irritant contact dermatitis and allergy contact dermatitis when they are in touch with workers skin. Non-water-miscible fluids usually cause skin disorders such as folliculitis, oilacne, keratoses and carcinomas. 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]**.

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 are state 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. Mists are aerosols comprised of liquid particles (less than 20 μm), **[Iowa Waste**

**Reduction Centre 1996]** reported that besides potential skin and eye contact, inhalation is also a way to occupational exposure.

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]**. The Occupational Safety and Health Administrations (OSHA) standard for airborne particulate (largely due to fluid mist) is 5 $mg/m^3$, and the United Auto Workers (UAW) has proposed a reduction in the standard to 0.5 $mg/m^3$. The oil mist level in a plant ranged from 4.2 to 15.6 $mg/m^3$ but fell to between0.47 to 1.68 $mg/m^3$ when a different cutting fluid was substituted in the system **[Welter 1978]**.

Anti-misting compounds, such as a polymethyl-acrylate polymer, polyisobutylene 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 research literature identifies two primary functions of cutting fluids 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, recirculate 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 mass production 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 planthouse keeping.

There are mainly three members in the family of carbon nanoparticle. They are graphene, carbon nanotube (CNT) and fluorescent carbon quantum dots (CQDs). Scientists and researchers are very much attracted to their extra-ordinary features. They possess some attractive physical, chemical, optical, mechanical and thermal properties. Graphene is the thinnest two-dimensional material having $Sp^2$ hybridization in its atomic structure. It is the structural unit of graphite, carbon nanotubes and fullerene. Carbon nanotubes can be divided into two types: single-walled carbon nanotubes (SWCNT) and multi-walled carbon nanotubes (MWCNT).

Carbon nanoparticles have a lot of eye-catching properties but the property which is most attractive to a researcher in the field of manufacturing is the heat conductivity **[Mao et al. 2014]**. It is non-toxic and environment friendly. As most of the part of human body is carbon, it is generally supposed to be a biocompatible material. Carbon-based nanomaterials also have strong thermal conductivity which has made it very useful in metal cutting field. Its cooling effect is close to flood cooling **[Zhang et al. 2015]**.

Findings present that compared with dry grinding, the specific tangential grinding force of MQL grinding, nanoparticle jet MQL grinding, and flood grinding decreased by 45.88, 62.34, and 69.33% respectively. Their frictional coefficient was reduced by 11.22, 29.21 and 32.18%. The specific grinding energy declined by 45.89%, 62.34%, and 69.45%. Nanoparticle jet MQL presented ideal lubrication effectiveness, which was attributed to the friction oil-film with strong antifriction and anti-wear features formed by nanoparticles on the grinding wheel/workpiece interface **[Jia et al. 2014]**.

There are some other advantages of nanofluids **[Singh et al. 2017].** These advantages are significant in a sense that all of them are unique.

- Nanofluids have higher dispersion stability.
- For the same degree of heat transfer, nanofluids reduce the required pumping power compared to base fluids.
- Large surface area and higher aspect ratio of nanoparticles enhance the heat-carrying capacity of nanofluids.
- Nanofluids reduce the clogging of particles as in conventional slurry due to the frequent interaction of nanoparticles with base fluids. As a result, they minimize the size of the cooling system.
- The shape, size and concentration of nanoparticles also improve the machining processes.

In order to minimize emissions, cutting fluids/lubricants, which are not toxic and dermatologically safe, favorable lubricating properties and a high thermal stress capacity and the low-emitting metal working with minimum quantity lubrication, the correct selection of the cooling fluid/lubricant is of decisive importance. To select a fluid for an application, advantages and disadvantages of cutting fluid products should be compared through review of product literature and usage history.

However, the following factors should be considered when selecting the fluid **[Aronson 1994; Sluhan 1994; Bienkowski 1993 and Lukas 1994]**. Fluid compatibility with work material and machine components

- Cost and life expectancy
- Ease of fluid maintenance and quality control
- Speed, feed and depth of cutting operation
- Storage practices
- Type, hardness and microstructure of the metal being machined
- Ability to separate fluid from the work and cuttings
- The product's applicable temperature operating range
- Ease of fluid recycling or disposal

The modern industries there are two categories of cutting oil based on their oil continent **[Sluhan 1994 and Bienkowski 1993]**. One is Oil-Based Cutting Fluids- including straight oil and soluble oils. The another is Chemical Cutting Fluids- including synthetics and semi-synthetics. Straight oils are called so because they do not contain water, are basically petroleum or mineral oils. Petroleum-based cutting fluids are frequently used for drilling and tapping operations due to their excellent property of lubricity while water-miscible fluids provide the cooling properties required for most turning and grinding operations. These Oils may have additives designed to improve specific properties **[Aronson 1994 and Tuholski 1993]**.

Soluble oils, also known as water-soluble oils, are generally composed of 60-90% petroleum or mineral oil, emulsifiers and other additives **[Aronson 1994; Bienkowski 1993 and IWRC 1990]**. These offer improved cooling capabilities and good lubrication due to blending of oil and water **[Koelsch 1994]** and suitable for light and medium duty operations involving the variety of ferrous and nonferrous application **[IWRC 1996]**. But the presence of water makes soluble oils more susceptible to rust attack and bacterial growth. Chemical cutting fluids, called synthetic or semi-synthetic fluids, are stable, performed emulsions which contain very little oil and mix easily with water. Such type of cutting fluids relies on chemical agents for lubrication and friction reduction **[Bienkowski 1993]**.

On the other hand, synthetic fluids contain no petroleum and mineral oil **[Sluhan and Foltz 1994]** and generally consist of chemical lubricants and rust inhibitors dissolved in water. These fluids are designed for high cooling capacity, lubricity, corrosion prevention and easy maintenance **[IWRC 1996]** and make them able to handle heavy-duty grinding and cutting operations on tough, difficult-to-machine and high temperature alloys **[Sluhan 1994]**. Semi-synthetic fluids provide better control over rancidity and bacterial growth, generate less smoke and oil mist and have good corrosion protection **[IWRC 1996]**.

The control of cutting zone temperature is an important aspect of modern machining and grinding operations. Dry machining technologies and minimum quantity lubrication (MQL) which uses a fine spray of cooling medium are, therefore, being pursued as alternatives for conventional coolants. However, dry machining and MQL will only be acceptable on condition that the main tasks of coolants in machining processes can be successfully replaced. Considering performance, cost, health, safety and environment, vegetable oils are therefore a viable alternative to petroleum-based metalworking cutting fluids **[Skerlos and Hayes 2003; Krahenbuhl 2005]**, because

- A higher flash point increases rates of metal removal as a result of reduced smoke formation and fire hazard.
- The lubricating film layer provided by vegetable oils, being basically strong and lubricious, improves workpiece quality and overall process productivity reducing friction and heat generation.
- The higher boiling point and greater molecular weight of vegetable oil result in considerably less loss from vaporization and misting.
- Vegetable oils are nontoxic to the environment and biologically inert and do not produce significant organic disease and toxic effect.
- No sign and symptom of acute and chronic exposure to vegetable oil mist have been reported in human **[ACGIH 1991]**

### 1.2.1 Chip Formation Mechanism

It is necessary to understand the chip forming mechanism and material removal rate to study grinding process properly. Pioneering investigators **[Dall 1939, Ernst 1950 and Tarasovs 1950]** have discussed chip formation only considering shear forces like other machining processes, watching the chips under optical microscope since there were no electron microscope available. But, Welton [**1969**] got some fractured grit with the chip while collecting chips for analyzing which made it more interesting and became a matter of great concern. Cashion et al. **[1974]** observed that chips are formed mainly because of shear force when he was studying Mossbauer spectrum from fine grinding chips. Examining the grinding chips under transmission microscope some other scientists also supported that **[Doyle and Aghan 1975]**. They got clear indication of shearing process as the observed lamella or segment. Malkin **[1979]** also states that material removal of grinding is mainly due to shearing. Chips are being categorized in three classes by Doyle and Dean **[1980].** They are lamellar chips, spherical chips and amorphous chips. Lamellar chips are generally produced by traditional metal cutting action by shearing. Spherical chips are produced by the oxidation of the other different kinds of chips. Amorphous chips are actually debris which results from rubbing of wear out flat grits with the work surface and by ploughing. Amorphous chips are associated with poor surface. Sakuma and Tado **[1982]** opined that mechanism of chip formation varies with the hardness of the material, applied cooling and lubricating method and wheel speed. They got leaf like lamellar chip at lower wheel speed but the size of the chips was increasing with the wheel speed. After some critical speed spherical chips was observed. According to Ramanath et al. **[1987],** spherical chips are formed due to exothermic reaction of the chips with the surrounding oxygen or by the sharp bending of excessive thin platelets. These platelets are formed due to elastic action of the wear flat grits on the work piece. As the number of spherical chips was high they suggested that there was severe rubbing between the wheel and the workpiece.

In case of ductile material, long lamellar filament type chips, spherical chips and blocky particles were found **[Pai et al. 1989]**. The length of filament type chips and the amount of spherical type chips were decreasing because of using sharper wheel or harder material or both. Excessive spherical chips in the grinding debris suggest that melting might occur in grinding. However, Outwater **[1952]** and Shaw **[1990]**, says that melting a phenomenon of time-temperature and the material cannot stay at high temperature enough time to be melted.

Simulation is done on grinding by turning and shaping it with highly negative rake tool and found that side flow occurs in place of chip formation when the tool is provided with a huge margin of negative angle **[Kumandari 1971; Moneim et al. 1983].** Lamellar chips are for ductile materials and number of chips reduces with the increase of the hardness of the material **[Konig Schmalt 1978]**. Chattopadhyay et al. **[1990, 1991]** also noticed that mostly crushed chips and the lamellar chips are obtained in case of ductile and hard material grinding with brazed monolayer CBN and diamond wheels.

### 1.2.2 Effects of Grinding Temperature

Grinding is inherently characterized by generation of heat and high cutting temperature. At such elevated temperature the grinding wheel 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. The magnitude of this cutting temperature increases, though in different degree, with the increase of cutting velocity and infeed. So, grinding is constrained by rise in temperature.

The chemical reactions at the ground surface during grinding plays a vital role due to high temperature and higher reactivity of the freshly formed ground surface **[Duwell et al. 1966].** Grinding is associated with much high specific energy requirement which may be an order higher than that required in conventional machining processes. The obvious consequences of this high specific energy are very high grinding zone temperature **[Outwater and Shaw 1952]**.

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 **[Chattopadhyay and Bhattacharya 1968; Chattopadhyay and Chattopadhyay 1982]**. Heat generated due to chip formation in grinding at the shear plane results in high temperature near the cutting edges of the grits and in the material. But this temperature is not of any importance as the material ahead of the grit is removed as chips. The quality of the ground surface would depend upon the surface and subsurface temperature **[Dex Ruisseaux and Zerkle 1970]**.

During machining or grinding if such high temperature is 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 **[Alaxender et al. 1998; Kurimoto and Barroe 1982; Wrethin et al. 1992]**. It was observed that the chips adhering to the wheel act as additional heat source, which may lead to overheating of the wheel and hence more wheel wear **[Kops and Shaw 1962]**. The nature of temperature variation in up and down grinding, the temperature increases with the increase in infeed and work speed and the temperature difference between the up and down grinding follows the same pattern **[Wager and Wu 1991]**.

In grinding, thermal damage is a major limiting factor for production rates. This damage can be reduced by the application of a cutting fluid that remove the heat produced due to shearing by cooling and heat generation due to friction or rubbing between the two surfaces by lubrication. The purpose of the fluid is to flush away chips from the grinding process **[S. Ebbrell et al. 2000]**.

Thermal model developed for the grinding process at the grain zone has a problem with the present model is assigning the grain wear in flat area **[Rowe et al. 1991]**. The application of grinding fluids brings down the temperature, but their film boiling temperature restricts their effectiveness **[Yasui and Tsukuda 1983]**.

Grinding fluids should be used to lubricate and thus reduce the specific energy requirement, as the normal grinding fluids are ineffective in controlling the high temperature **[Malkin and Lenz 1978]**. The applicability of additives and solid lubricants in grinding tool steels with diamond wheels. Some of the additives, especially colloidal graphite, improved the wheel performance but solid lubricant failed to improve the tool performance **[Nee 1979]**.

The high cutting temperature during machining or grinding is controlled by profuse cooling. 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 **[Alaxender et al. 1998; Kurimoto and Barroe 1982; Wrethin et al. 1992]**. Lubricating and the cooling properties of the grinding fluids directly influence the surface integrity of the work piece. But the effectiveness of coolants is lost if the temperature exceeds the film boiling temperature of the fluids **[Howes 1990]**.

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

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

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. Some recent techniques have enabled partial control of the machining temperature by using heat resistance tools like coated carbides, CBN etc. **[Muraka 1979 and Dieter 1981]**.

The thermal deterioration of the cutting tools can be reduced by using CBN tools if properly manufactured, selected and used, CBN tool provides much lesser cutting forces, temperature and hence less tensile residual stresses. But CBN tools are very expensive **[Narutaki and Yamane 1979]**.

Coolants delivered through the pores of the wheels and observed benefits like reduction in the forces, temperature and surface cracking and improvement in wheel life **[Graham and Whitson 1978]**. The following methods are used to control the grinding temperature **[Shaw 1985]**.

- lower material removal rate
- use of proper coolants
- intermittent grinding
- lower wheel speed
- softer wheels

Reduction in the forces and temperature by using slotted wheels, grooved wheels due to intermittent cutting and better coolant delivery was reported by **[Nakayama et al. 1977, Snoeys et al. 1978 and Shaw 1985]**. Disk wheels provided with through holes randomly distributed over their faces are found to perform with less temperature in face grinding mode. This was attributed to intermittent cooling of the work piece **[Shaw 1985]**.

Ultrasonic c1eaning method is to continuously dress the wheel and remove any loaded particle. This helped in maintaining the wheel sharpness and providing less temperature **[Aoyama and Inasaki 1984]**. The use of $CO_2$ snow as the coolant in machining is feasible if $CO_2$ in liquid form under pressure (60 bar) is fed to the cutting zone and diffused through a capillary jet. This results in a change of state and the formation of $CO_2$ snow (endothermic reaction resulting in a temperature of -79°C) **[Chandrasekaran et al. 1998]**. Earlier investigations **[Thoors and Chandrasekaran 1994]** observed that $CO_2$ 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.

The surface characteristics can be expressed as change in the physical and/or chemical characteristics of the upper layers of work piece, fatigue life, stress corrosion, appearance of tensile stresses, surface and subsurface cracks etc. **[Snoeys et al. 1978]**. Burning causes change in color depends on the thickness of the oxide film which develops due to temperature over a certain limit (500°C) **[Shimamune and Ono 1983]**. Redeposition of chips decreases substantially with the application of grinding fluid **[Howes 1990]**. Burning is described as the appearance of the temper color on the ground surface due to high temperature. They observed burning to occur with loaded wheel **[Marshall and Shaw 1952]**. In absence of oxygen, the redeposition of chips on the ground surface increases and this may render a material almost un-grindable. The oxygen, even if present in traces, would form a thin oxide layer on the nascent ground surface and that hinder further redeposition rendering the material's grindability **[Outwater and Shaw 1952]**.

With increasing infeed, the temperature increases hence redeposition increases bond materials were found to exist along with the redeposited chip particles on the ground surface **[Welton 1969]**. A relation between burning and the forces is established. At the onset of the burning the normal and the tangential forces and their ratio suddenly increase burning would occur when the critical temperature for austenite formation has been reached on a sufficiently large portion of the grinding zone **[Malkin and Cook 1971]**.

In grinding hardened steels, burning is associated with a hardened zone at the subsurface followed by a soft tempered zone just beneath it **[Malkin 1974]**. The burning to be characterized by the formation of oxide layers on the surface and transformation of austenitic structure **[Malkin and lenz 1978]**.

### 1.2.3 Grinding Wheel Selection

Silicon Nitride ($Si_3N_4$) can be used as a cutting tool but does not sinter easily to full density. Additions are often made to assist sintering but hot pressing is typically required to achieve good strength. Similar to sialon tools, diffusion into iron makes $Si_3N_4$ tools unsuitable for machining steels. They are generally restricted to grey cast iron and some nickel-based alloys **[Jack 1986]**.

Sialons are materials based on Silicon Nitride ($Si_3N_4$) and are formed by sintering a mixture of $SiO_2$, $Al_2O_3$, $Si_3N_4$, $Y_2O_3$ and MgO powders. Sintering causes the $SiO_2$ to react with $Al_2O_3$ and $Y_2O_3$ to form a liquid that reacts with the $Si_3N_4$ to form Silicon Aluminum Oxy-Nitride. Due to chemical affinity, sialons diffuse rapidly into steels and are not suitable for machining.

Grinding with CBN (Cubic Boron Nitride) wheels is almost free from thermal damages because of retention of its grit sharpness and chemical stability. Polycrystalline cubic boron nitride cutting tools have been developed to machine hard materials in applications where carbide tools do not maintain hardness at high cutting speeds and alumina-based tools do not offer adequate toughness. The main advantages of Cubic Boron Nitride tools are that they maintain hardness even at very high temperatures (1000°C), have low solubility in iron and good fracture toughness for a ceramic **[Bossom 1990]**. But CBN tools are very expensive and justified for very special work materials and requirements where other tools are not effective. Diamond particles are produced by heating carbon to approximately 1500°C and applying pressures of 6 GPa, much like the process to convert boron nitride from hexagonal to cubic form. To form a cutting tool, 1-30 µm diamond particles are sintered at high temperature and pressure onto a cemented carbide base **[DeGarmo et al. 1988]**

- Diamond is the hardest material with good physical and chemical properties of very high compressive and corrosion resistance
- Diamond wheel tools exhibit excellent wear resistance in grinding operation
- It is used for rapid cutting and good finishing
- It shows good performance even in high temperature

Wheel loading occurs due to mechanical interlocking of chips in the inter-grit spaces and due to chemically affinity between the work piece and the wheel material. The degree of adhesion was found to depend on the ductility, adhesiveness, oxidation resistance of the material and on the working environment. Wheel loading as the accumulation of chip particles at the inter grit space on the wheel, then wheel loading is associated with increase in forces, the ratio between the normal and tangential components and appearance of temper color on the ground surface **[Marshall and Shaw 1952]**.

If the grinding is continued, the amount of material loaded to the wheel increases alone with the normal and tangential forces. The Increase in force was attributed to increase in negative rack angle at the cutting point due to clogging. If the grinding is continued with a loaded wheel the force may reach such high levels that, the grits may come out leading to auto-sharpening **[Konig 1978]**. The wheel loading increases with the increase of infeed and material removal in case of cylindrical grinding **[Sato et al. 1983]**.

The power consumption increases with the increase in metal removal in prolonged grinding and the same was attribute to the wheel loading and wear formation **[Mittal and Kumar 1984]**. Wheel loading defined as the adherence of material to the grits or accumulation of chip material in the voids. At loaded condition the force and temperature increase lead to poor surface integrity **[Nagraj and Chattopadhyay 1989]**.

The wheel-work interactions from the view point of wheel loading for grinding soft ductile material exhibit high adhesion. Three distinct mechanism of wheel loading have been identified **[Yossifon and Rubenstein 1982]**. For small and medium removal rate grinding, very small to small scale adhesions of materials extending over a grid or two are observed. But in high material removal rate large scale material buildup takes place extending over a several grids spaces.

Irradiating the wheel surface with x-ray and monitoring the secondary emissions to detect and quantify the amount the loaded chips was observed **[Srivastava et al. 1985]**. Grinding ductile material with monolayer CBN and natural diamond wheel, wheel loading take place due to entrapment of long ribbon type chips. For harder material no wheel loading was observed **[Chattopadhyay et al. 1991]**.

A review of the literature on grindability of various commercial steel focuses on the remarkable 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 of 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 very costly and prone to contamination.

Application of the cutting fluids changes the performance of machining operations because of their lubrication, cooling and chip flushing functions. Basically, in the machining of hardened steel materials, no cutting fluid is applied in the interest of low cutting forces and low environmental impacts. Nanofluid cooling presents itself as a viable alternative for hard machining with respect to tool wear, heat dissertation and machined surface quality. This research compares the mechanical performance of nanofluid cooling to completely dry and wet lubrication for the grinding of steel based on experimental measurement cutting temperature and surface finish.

## 1.3 Objectives of Present Work

Grinding is most popularly used machining process to manufacture precise components. Basically, it is final stage machining. Cutting fluid application technique plays a great role to reduce tool work-piece temperature during grinding. Between two techniques traditionally used in grinding, minimum quantity lubricant (MQL) is better than flood cooling because of environment and health friendly nature, less expensive and high utilization rate. For better cooling and lubrication properties, nanoparticles are added to cutting oil which contains some features like anti-wear, high loading capacity and anti-frictional properties. Nanoparticles make MQL more effective. But it seems that there is a huge scope of improvement some areas like coolant application technique, increasing effectiveness of the applied cutting fluid and the finding a better way to select suitable machining parameters. The objectives of the present work are as follows:

(i) Design and fabrication of a pulse jet nanofluids MQL applicator that can deliver nanofluids at variable delivery rate in surface grinding.

(ii) Experimental investigation on the effects of nanofluids in grinding hardened AISI 1060 steel at four different level of hardness (40HRC, 45HRC, 50HRC and 55HRC).

(iii) Precise machining was done using a horizontal surface grinder with a CBN (Cubic Boron Nitride) grinding wheel at different process parameters in respects of grinding temperature and surface roughness.

(iv) Analyze the effect of wheel speed, infeed, machining conditions and hardness of the material on grinding temperature and surface roughness by experimentation and construct predictive models using RSM.

This investigative work was mainly experimental and partly analytical which is required to develop the predictive models and to verify these models. Proper design of experiment has been done to assess the role of machining and the pulse jet Minimum Quantity Lubrication (MQL) parameters on the technological responses and reasonable prediction of machining responses in terms of cutting zone temperature and surface roughness. The methodology was as follows:

(i) AISI 1060 steel of solid rectangular stock has been heated into the furnace and quenched in an oil bath and hardened to nominal values of different hardness (40HRC, 45HRC, 50HRC and 55HRC).

(ii) For nanofluids MQL machining, 2% (w/v) mixture of carbon nanoparticle and fluid has been prepared with proper stability and homogenous dispersion.

(iii) A suitable pulse jet nanofluids MQL applicator has been designed and fabricated in such a way so that the variable nanofluids MQL could be delivered at the critical zones in grinding hardened steel.

(iv) Grinding zone temperature at variable nanofluids MQL flow rates has been recorded with the help of embedded thermocouple.

(v) The surface roughness has been monitored by a surface roughness checker (Talysurf) to study the effects of different nanofluids MQL parameters on surface finish.

(vi) RSM model has been developed based on central composite design to identify a relationship between input process parameters and output process responses.

## 1.4 Scope of Present Work

Literature review narrates that carbon nanotube has excellent properties to reduce the grinding zone temperature and the surface roughness. It improves machinability and enhances the properties of the ground materials. But, there has been a feeling that enough work has not been done analyzing its effect on grinding hardened steel and thus this investigation is done thereby. The main objective of this work is to find out how grinding wheel speed, infeed, material hardness and cutting condition influences grinding responses and also how carbon nanotube affects the ground material properties. Two different wheel speed 1500 and 3000 RPM; four different infeed 10, 20, 30 and 40 μm; four different hardness 40, 45, 50 and 55 HRC; and four different cutting conditions Dry, Compressed Air, Minimum Quantity Lubrication (MQL), CNT mixed MQL with Compressed Air have been used for this analysis.

**Chapter 1** presents the summary of the previous work and focuses on the role of temperature on machining; technical, environmental and economical problems associated with traditional cooling techniques and the assessment of pulse jet MQL nanofluid as a possible replacement of conventional flood cooling. Literature review on the effect of cutting zone temperature, benefits of controlling temperature, effectiveness of pulse jet nanofluid provide a clear vision of contemporary research on this field.

**Chapter 2** focuses on the design and fabrication technique of pulse jet Nanofluid application using step by step Full Factorial Design of Experiments (DoE) technique.

**Chapter 3** presents the steps of material preparation and carbon nanofluid. It also includes experimental conditions and chip morphology for different combination of cutting parameters.

**Chapter 4** contains development of statistical predictive model for cutting temperature and surface roughness in terms of wheel speed, infeed, material hardness and environments. Both the model validation has been carried out in this chapter.

**Chapter 5** presents discussion on the experimental result of temperature, surface roughness and their possible interpretation and also the chip morphology.

**Chapter 6** provides major contributions and recommendation for future work and necessary references have been attached at the end.

# Chapter-2

## Design and Fabrication of Pulse Jet Nanofluid Applicator

Experimental design and necessary modification are one of the main tasks of this research. The success of the full experiment largely depends of the success in design stage. There are four major part of experimental design that is planning, designing, conducting and analyzing. By doing all these staffs one can get a reliable valid idea about the design. A lot of statistical tools have been used to explore, estimate and validate data acquired through the use of experimental design **[Cash et al. 2016]**. Experimental design has become very effective statistical tool in analyzing data involving process performance and process capability. A well-planned attempt was made to get a result with maximum reliability with minimum wastage of time and money.

A structured approach can obviate the large number of experiments needed to get overall view of manufacturing process. The information obtained can be used to identify the most influential parameters to maintain the precision of the process. Conventional approach of experimental design was mostly empirical in nature. In this approach, only one factor is varied each and every time keeping all the other factors unchanged. This process is highly dependent on intuition, prediction, fortune and experience for success. Additionally, this process is inefficient in a sense that it requires a lot of resources to get a little amount of hint about the process. One-variable-at-a-time experiments often unreliable and time consuming as well and can often yield pseudo optimum condition for the process. Structured statistical thinking and applying statistical method can contribute to better planning, conducting, analyzing and interpreting data from engineering experiments. When certain characteristics of a product is susceptible to several variables then the best suited strategy is to use statistical design of experiment (DOE) which can give valid, reliable conclusion saving wastage of time, effort and money **[Davim 2016]**.

The first and foremost principle of any experimental design is randomization. Randomization refers to assigning specific treatment to the experimental units which is done to create level playing field. Randomization assures the equal likeliness of the system by removing biasness and other external disturbance which is uncontrollable. In addition, randomization forms the basis of any statistical test. Therefore, the treatment must be assigned at random to the experimental units. There are a number of ways to conduct randomization. It can be done by picking up a numbered card form a well shuffled pack of cards, drawing a numbered ball from a properly shaken container or even taking numbers from a table of random numbers. Replication is the second principle of any experimental design. This means the repetition of the basic experiments. In other words, in a full run of the experiments all the treatments are to be tested. In all experiments some amount of variations is included. This type of variations can be removed by replication. The experiments are to be performed more than once. An individual repetition is termed as replicate. The number of replicates depends upon the type of the experimental material. The increase in the number of replications tends to reduce the error occurs by extraneous influence.

Though randomization and replication are done to nullify the influence of extraneous source of disturbance still it is not possible to eliminate it completely. Thus, a revision is done and a design is selected to keep all the extraneous sources under control. For this, local control is used which refers to amount of balancing, blocking and grouping of the experimental units. Balancing means the assignment of the treatments to the experimental units so that the result becomes a balanced arrangement of the treatments. Blocking refers to picking up the similar experimental units to form a relatively homogeneous group. It reduces common irrelevant source of variation between units which ensures greater precision in the estimation of the source of variation.

The primary purpose of the principle of local control is control the experimental error which will eventually increase the efficiency of experimental design. Control in experimental design is used to find out the effectiveness of other treatment through comparison.

Another thing is orthogonality. It refers to the contrasts which can be carried out efficiently and legitimately. Contrast can be represented by the vectors and there is no co-relation among different contrasts and they are independently distributed if the data are normalized. Because of this, no orthogonal treatment provides the same information to others. In some field of this study, it is hard to reproduce exactly the same result. Comparison between treatments is often preferable as it is reproducible.

Getting good results from a DOE involves these seven steps:

- Setting up objectives
- Selecting process variables
- Selecting an experimental design
- Execution of the design
- Checking that the data are consistent with the experimental assumptions
- Analyzing and interpreting the results
- Using/presenting the results (may lead to further runs or DOE's)

## 2.1 Application of Design of Experiment (DOE)

Design of experiment is not only a good problem-solving tool but also an effective tool for improving and optimizing designing a product in manufacturing processes. It helps to find out suitable dimension and tolerance of the product and ensure a robust design by generating predictive mathematical model which describes physical system behavior. Engineers and scientists extract vast amount of knowledge about product and process from experimentation. An experiment is a sequence of test conducted in a systematic process to gain better understanding of the process and to explore a new product or process. Design of Experiment ascertains maximum amount of the knowledge from minimum amount of resources. DOE finds its application in a variety of fields concerning physical and social sciences. Sometimes engineers work on some products or processes where no theory or principle is directly applicable. Experimental design works as extremely powerful tool in those situations to develop a customized products and processes applicable to those very situations. In recent days of technological advancement, any process or product is becoming highly complicated gradually. Numerous factors now affect the stability of the system. It is almost impossible for the scientists and the engineers to test all the factors using trial and error method as it so much time consuming and costly. So, a technique is required to identify the “vital few” factors by overlooking the “trivial many” to improve quality and the productivity efficiently. Comparing with the one-factor-at-a-time experiments, DOE is much better. Though one-factor-at-a-time experiments are easily been understood and simple in nature, it cannot show how any factor can be changed in presence of the other factors. When the effect of any factor is altered (increased or decreased) with the presence of any factor, that is called an interaction. Often interaction effect is much more important than any individual effect. Because, a lot of factors co exist together rather than existing as a single factor. For example, an endothermic chemical reaction might have both temperature and pressure dependency. If only the temperature is increased slightly then the reaction becomes slightly faster. If the pressure alone is increased slightly then there is no effect on the rate of chemical reaction but when both the temperature and the pressure is increased slightly then the reaction rate increases rapidly.

The methodology of DOE ensures the systematic investigations of all factors and their interactions. So, DOE is able to generate a complete result while one-factor-at-a-time process can often give incomplete and misleading result. Normally there are five stages of a designed experiment

- planning
- screening
- optimization
- robustness testing
- verification

Planning is the most important stage of design of experiments because the next stages cannot be successful if the planning is not good. Before going to the process of testing and data collection it is important to plan carefully. Some points should be kept in mind in this state: well defined objective clearly presenting what is to be done, why is to be done, how much time and resources it will take, what limitations might bother any stage of the experimentation. A team composed of expertise from different disciplines involving the product or the process should list possible factors to investigate and most appropriate responses to measure. A carefully planned experiment contributes to the better understanding of the product or the process. Well planned experiments are some other benefits like easy execution and analyze. However, an unorganized experiment may result in data sets from which no valid conclusion can be drawn or even impossible to analyze no matter how efficient statistical tool is used.

Screening experiment is used to find out the important factors among the pool of potential factors. Relatively more important factors get priority for further analysis where less important factors are eliminated. Design is efficient because it usually requires less iterations and the focus is on identifying vital few factors rather than interactions.

After finding out the most important factors affecting the process, the next step is to determine the best setting of these factors to achieve the intended objective. On the basis of the product or the process these objectives may be increasing the process yield or decreasing the variability of achieving the both at the same time.

Once the set of optimal factors have been determined, it is time to make the product or the process resistant to variation that is caused often in the application environment. These variations are due to the change in the factors affecting the process which are not in control of the analyst. Such factors such as temperature of the surrounding, moisture content in air, composition of material is called noise or uncontrollable factors. It is important to identify and handle these variations to make the product or the process insensitive to these factors.

Final stage of the process involves validation of the setup by conducting few experimental runs to check whether the process is running according to the desired objective or not.

Commonly practiced design of experiment is (DOE) multi-variable chart, variable search, full factorial, Taguchi method etc. Among all the methods of DOE, full factorial analysis is popular homing in technique and thus frequently used in DOE method. Fig. 2.1 shows the commonly used DOE method. Almost all the methods follow some basic methodologies which are appended below:

- Selection of the most important parameters effecting quality by extensive brainstorming with expert from different relevant areas.
- Divide the parameters into two categories like Red X (most important parameters: usually less than 4) and Pink X (moderately important parameters).
- Narrow down the variations of Red X and Pink X through redesign and process improvement.
- Other than Red X and Pink X there may have a number of parameters which should not given priority for minimizing the cost.

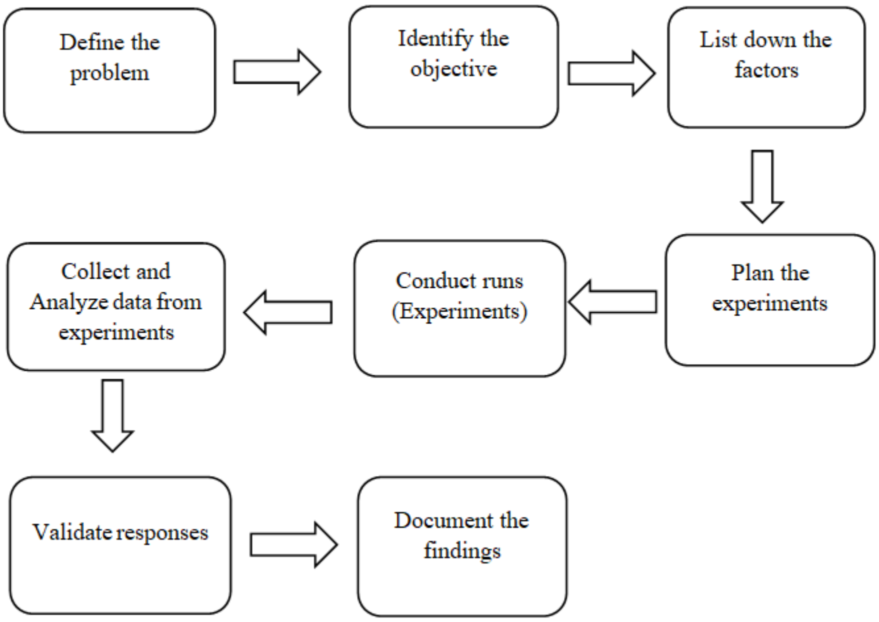



**Fig. 2.1** Model of a typical DOE Methodology

## 2.2 Design and Fabrication of Pulsed Jet Nanofluid Applicator

In full factorial analysis in investigation involving 4 variables and two levels of each factor is called 24 factorials analysis which involve 16 groups of test or combinations. Normally not more than 4 factors/variables at a time are taken to segregate the critical variables effect on the experimental setup. Full factorial DOE method is one of the powerful and popular tools for identifications of the most severe variables which may cause or affect the performance of the product. Basic principle of the analysis is that every variable can be tested with all levels (generally two) of every other variable. Experimental testing of all possible combinations of pre-selected variables and levels allows for the systematic separation and quantification of all main and interaction effects, thereby giving the chance of narrowing down the number of variables to one or two which are comparatively more severe. The complete full factorial analysis involves two main steps such as preparation of combinatorial matrix which identifies the impact of all individual variables having two levels for each variables and preparation of ANOVA table to identify main effect and interaction effect.

First of all visualize the components of the applicator and identify the variables that affect the performance of the applicator functionality. Identify also the response variable i.e. independent variable and dependent variable and some other factors which are not that important but have some impact on the overall performance after interacting with each other's. These variables are **[Bashir 2015]**:

- Height of the container of the cutting oil from the fuel pump
- RPM of the motor running the fuel pump
- Container size (length and diameter), material and sealing
- Number of nozzles of the fuel pump to be used
- Diameter of the nozzle injector
- Milling cutter type and material
- Volume of the container
- Pressure and flow of the cutting fluid
- Process parameters (cutting velocity, table feed and depth of cut)
- Machining responses (surface roughness, cutting force and flank wear)
- Angle of the spray pattern

After several brain storming session with concern technical staff and all levels of experts, it has been provisionally identified that out of the above mentioned variables, depending on the significance there are 4 (four) variables (shown in Table 2.1). The four variables are the diameter of the nozzle injector, volume of the cutting fluid container, angle of fluid spray and the pulsing frequency of nanofluid. These factors seem to be vulnerable for the optimized performance of the applicator.

**Table 2.1** Most influential variables that affect the performance of MQL applicator

| **Symbol** | **Factors or variables** | **Level (+ or -)** | |
|---|---|---|---|
| | | **Present value (-)** | **Experimental value (+)** |
| A | Diameter of the nozzle injector | 1 mm | 0.5 mm |
| B | Volume of the container | 250 cc | 100 cc |
| C | Angle of the spray pattern | 60° | 30° |
| D | Pulsing Frequency | 1450 | 800 |

Based on outcome of full factorial analysis, parameters of the rotary liquid nitrogen applicator are finalized. The final diameter for the nozzle injector was 1 mm, volume of the container was 250 ml, angle of the spray pattern was 30° and the pulsing frequency was selected as 1450 pulses per minute (Table 2.2).

**Table 2.2** Selected parameters for the final design of Pulse jet MQL applicator

| Symbol | Factors or variables | Present value (-) | Experimental value (+) | Selected parameters for final design |
|---|---|---|---|---|
| A | Diameter of the nozzle | 1 mm | 0.5 mm | 1 mm |
| B | Volume of the container | 250 cc | 100 cc | 250 cc |
| C | Angle of the spray pattern | 60° | 30° | 30° |
| D | Pulsing Frequency | 1450 | 800 | 1450 |

The interaction effects among four significant design parameters are given below:

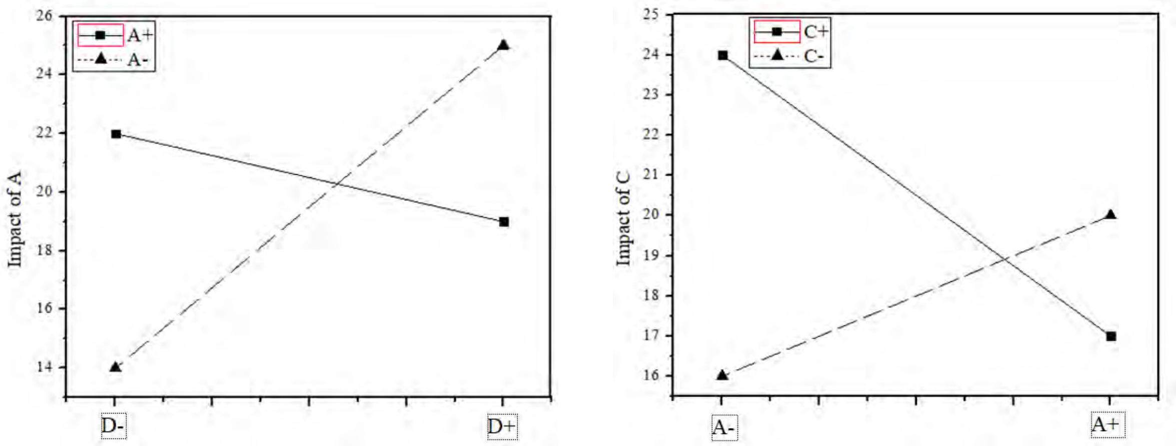



**Fig. 2.2** The interaction between A & D and A & C

The nozzle injector is one of the critical parts of the pulsed jet MQL applicator. The pulse is provided with the help of a fuel pump. The fuel pump has a plunger with helical groove which can rotate about its axis and the degree of rotation of the plunger presets the quantity of fluid delivered per stroke. There is a provision for rotating the plunger so that the quantity of fluid delivered per stroke can be controlled accurately. The plunger reciprocates as an AC motor rotates and delivers one pulse of cutting fluid for each revolution through the fluid injector. The fluid flow alternates in four different outlets. Three of the outlets are closed and only one outlet is connected with the nozzle injector. A regulator is used to provide variable speed of the motor which eventually controls the pulsing frequency of the cutting fluid. The fluid coming out of the nozzle injector consists of tiny droplets of 68 grade cutting oil. The experimental setup facilitates independent variation of frequency of pulsing, rate of fluid application. A container was placed above the fuel pump to provide 68 grade cutting oil. The regulator on the fuel pump was used to control the amount of the cutting oil in each pulse. The nozzle injector was attached with the outlet of the fuel pump by means of a semi flexible channel. The channel was used to provide the nozzle injector the provision to move closer to the milling cutter during the machining process.

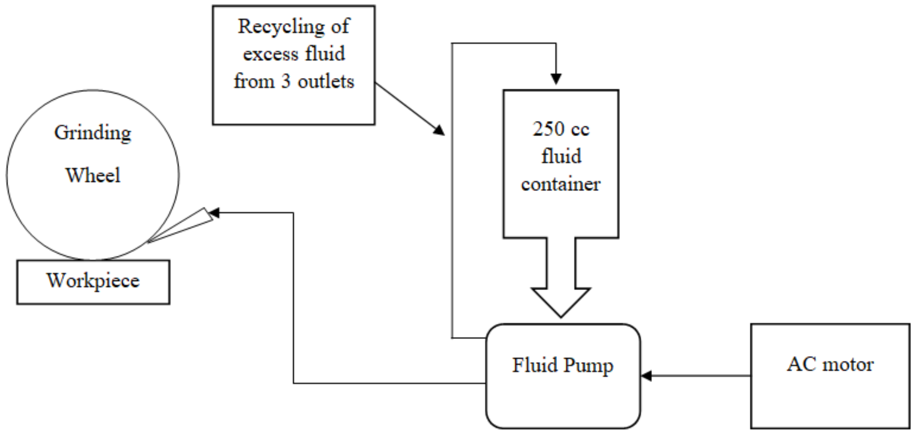



**Fig. 2.3** Schematic view of Pulse jet MQL Applicator

The nozzle injector delivers cutting fluid at single pulse per revolution. This facilitates the application of a minute amount of cutting fluid to be used per pulse during the machining process. For example, if Q is the amount of fluid application in ml/min and F is the frequency of pulsing in pulses/min, fluid application per pulse can be expressed as Q/F. Pulsing jet aids in fluid minimization without compromising the velocity of individual particles as the pressure at the fluid injector remains constant at the set value. If the frequency of the pulsing can be varied, the rate of fluid delivery can also be controlled. If Q is as low as 1 ml/min and the frequency F is 1000 pulses/min then the amount of fluid delivered per pulse is equal to 0.001 ml.

Two types of nozzle injector were used to test the setup and find the minimum surface roughness during the experiment. The nozzle injector varied in respect of the spray angle where one had an angle of 30° and the other had an angle of 60°. The spray angle does not remain constant as spray length increases. Additionally, a number of factors are responsible to determine the nozzle diameter size as well as the spray angle of the nozzle injector. Depending on the flow rate and fluid type the nozzle diameter and spray pattern varies. Liquid which are more viscous than water forms smaller spray angles, or solid streams, depending upon nozzle capacity, spray pressure, and viscosity. Drop size increases with the decrease in spray pattern and high-pressure process streams force narrower spray angles. To achieve a wide spray angle normally low-pressure streams are used. The spray angle tends to collapse or diverge with increasing distance from the orifice. Spray coverage varies with spray angle. The spray angle is assumed to remain constant throughout the entire spray distance.

Application of highly compressed air during surface grinding has shown a remarkable reduction in the surface roughness and cutting temperature. During grinding, a thin air layer is generated due to high speed rotation of the grinding wheel and this layer also rotates with the wheel just like this is attached with the wheel. This stiff layer restricts cutting fluid to penetrate into the cutting zone. Traditional fluid delivery system is not capable of penetrating this strong layer as it gains energy from the centripetal force of the wheel rotation. This force is directly proportional to the angular velocity of the wheel. This strong centrifugal force splits and diverge the fluid spray from the cutting zone rather than to converge into it which leads to huge wastage of the cutting fluid and environmental pollution as well. Several attempts have been made to tackle this problem and this study focuses on overcoming of this layer of air. Compressed air has two functions. One is to cut off the wheel attached layer of air for better penetration of the cutting fluid. If the cutting fluid cannot enter to the cutting zone then the use of fluid will be of no use. So, it is one of the main concerns for the researchers whether the cutting fluid properly reaches to the zone of interest or not. Second one is instantaneous removal of the micro chips from the inter grit space. It is very important to remove inter-grit micro-chips and debris from the wheel as soon as possible. When wheel is loaded with debris then a number of undesirable things occur. Friction increases, surface becomes rougher, temperature increases at high rate, wheel wear increases thus usable life decreases.

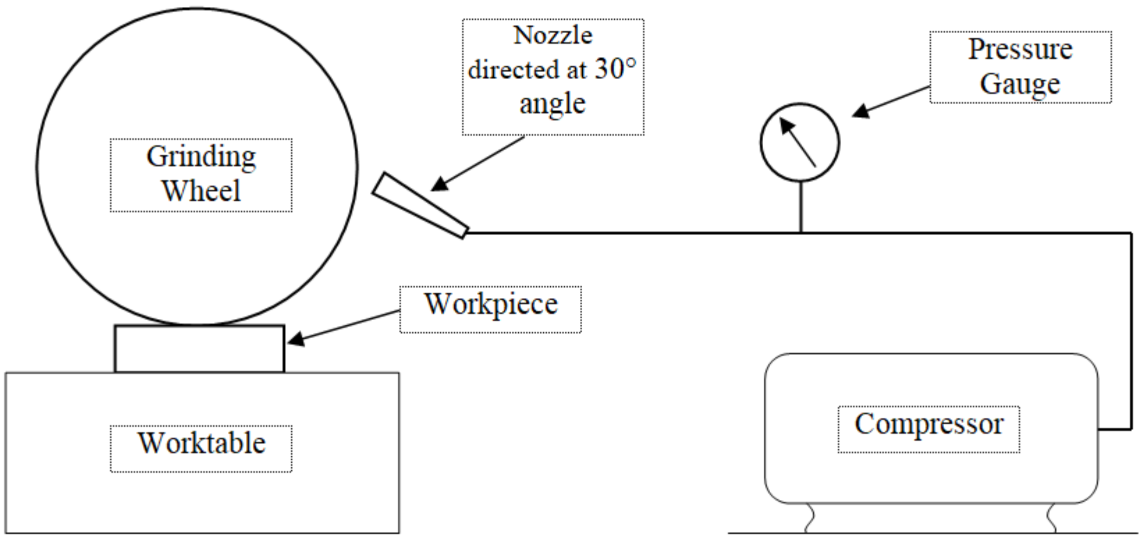



**Fig. 2.4** Setup for application of compressed air

# Chapter-3

## Experimental Investigations

### 3.1 Preparation of Material

AISI 1060 steel has various uses in agriculture, automotive, shipbuilding and aerospace industry. It is heavily used in making jigs and fixtures, shafts, spindles, different purpose gears, crankshaft, coupling etc. Steel is normally hardened by induction or flame hardening. Nitriding is a technique using which a pre hardened or tempered AISI 1060 steel can be further hardened. AISI 1060 is widely used in industrial applications. Composition of key elements of AISI 1060 steel is given below in Table. 3.1.

**Table 3.1** Workpiece material composition

| Element | Content (%) |
|---|---|
| Iron, Fe | 98.35-98.85 |
| Manganese, Mn | 1.25-1.41 |
| Silicon, Si | 0.36-1.30 |
| Carbon, C | 0.60-0.95 |

Handheld XRF (X-ray fluorescence) analyzer was used to check the contents of the workpiece.

Experimental investigations were done on four (04) identical workpiece of length 65 mm, width 35 mm and height 22 mm. Photo of two workpiece is given below in Fig. 3.1

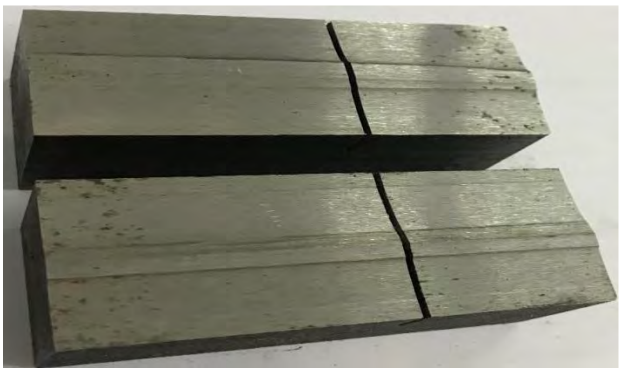


**Fig. 3.1** Photographic view of workpiece specimen (AISI 1060 Hardened steel)

Heat treatment was done using the proper procedure. An electric arc furnace is made oxygen free so that the material doesn't get oxidized. The material was heated up to a desired level at that furnace. Two heat tolerant pipes were attached in the inlet and the outlet. Other end of the inlet pipe is connected to an argon gas cylinder. The process was made adiabatic by sealing the door of the furnace by an asbestos sheet. Then Argon gas is passed through the furnace chamber to make the inside environment inert. The material was kept inside the furnace for three hours to raise the temperature of up to 1500°F and hold there for two hours. This process is popularly known as annealing.

The second step is called quenching. For this purpose a half ton tank was used. Quench bath temperature was kept approximately 25°C. It helps to reduce the temperature far more quickly than water. It is more efficient than water in terms of removing any sort of scales as well. Workpiece is removed from the furnace and immediately dipped into the oil quenching tank. Next action is to stir the oil continuously as long as the workpiece remained hot enough.

Several internal stresses are generated during quenching. It may cause the material to be extremely brittle. To get rid of these, tempering is performed after quenching. Tempering is done in two steps. Firstly the material temperature is elevated to a certain high temperature and secondly the material is allowed to be cooled down slowly in air unlike the sudden drop of temperature during quenching. Resultant hardness, strength and ductility of the material depend on temperature to which the material was raised during the heating process. There are four sample specimens for this research and the range of temperature to which the samples were heated was 300°C - 350°C.

## 3.2 Carbon Nanotube Preparation

Nanofluids are colloidal suspension in which tiny metallic and non-metallic particles are controllably disperse in a base fluid to enhance its properties. It has a number of good properties among which high thermal conductivity is the most desirable one. It is heavily used as heat transfer medium. According to the type of particles mixed in the base fluids, nanofluids can be classified into two categories: metallic nanofluid and non-metallic nanofluid. Metallic nanofliuds are those nanofluids in which metallic particles like copper, nickel, aluminium, iron, lead, platinum, silver etc. are mixed. Non-metallic nanofluids are produced by dispersing nonmetallic nanoparticles such as graphene, Carbon nanotube etc.

different allotropes of carbon and some other non-metallic tiny particles in base fluids. Ensuring stability of nanofluid is very much important to get proper benefit from it. Maintaining proper stability of nanofluid is one of the most challenging facts as has tendency to precipitate. Additionally, when the nanoparticles come into contact with each other, they may form larger size particles combining together. According to Brownian motion theory, stable nanofluid is theoretically possible when the particle size is less than 100 nm.

Nanofluid has been introduced in scientific research in the twenty first century with the breakthrough change in almost every industry. Nobel Prize winning famous physicist Richard Feynman makes a visionary remark in 1959: There is plenty of room at the bottom. The door of nanoscience opens with this comment. Feynman generates the theory of micromechanics. Japanese scientist Norio Taniguchi introduced the term "Nanotechnology" for the first time in 1974. The credit goes to American scientist Choi of Argonne Laboratory for preparing nanofluid successfully. After that event, researchers from all over the world get attracted to various groundbreaking properties of nanofluid. In recent years, nanofluid has been one of the main research topics for researchers and scientists of different fields. Published scientific research papers on nanofluid have been increasing exponentially year to year. Nanofluid is the most dominant keyword in the title of the articles which has been publishing in recent heat transfer and thermal properties journal.

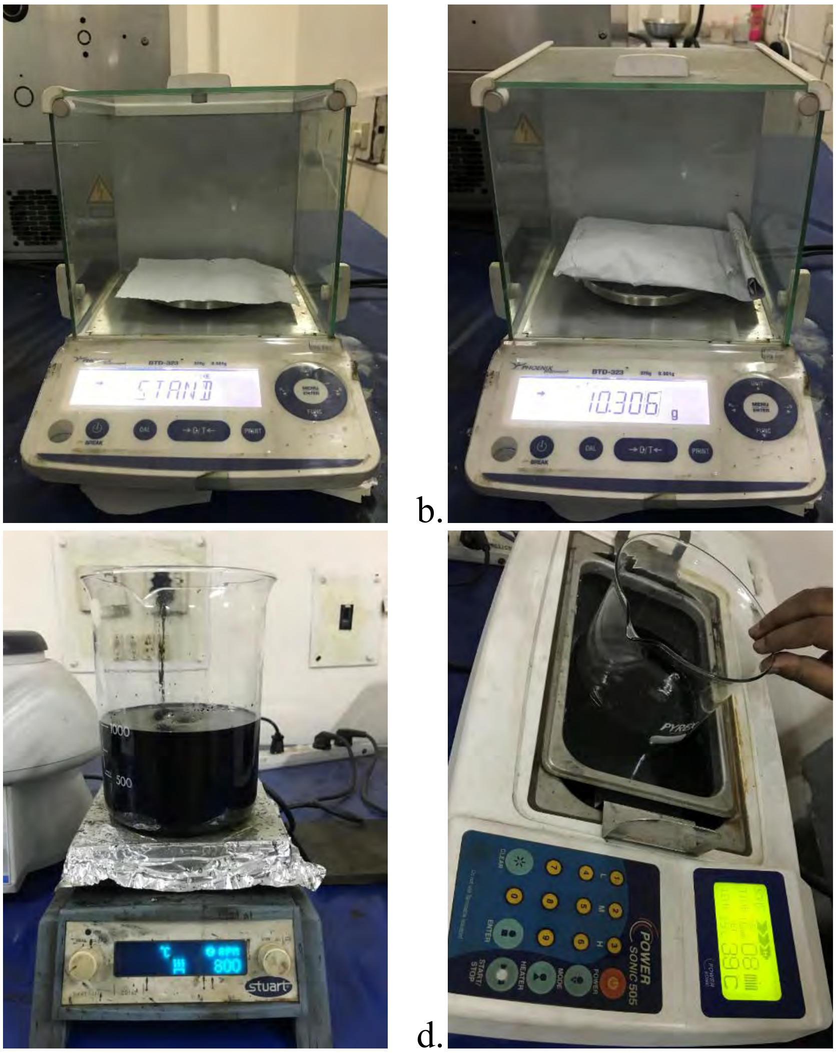
Nanofluids have some distinguished features suitable for many engineering applications. Some of these special features are:

- Exceptional rise in thermal conductivity
- Superfast heat transfer capacity
- Superior stability than other colloidal suspensions
- Proper flow between narrow channel without clogging
- Extraordinary lubrication property

There are two principal methods to prepare nanofluids: single step synthesis method and two-step synthesis method. Both the process is briefly discussed in the following.

**Single Step Synthesis Method:** The name indicates that in this process, nanofluids are prepared in one step. Several single step methods have been proposed. One of those is a single-step direct evaporation method **[Akoh et al. 1978]**. It is similar to VEROS (Vacuum Evaporation onto a Running Oil Substrate). However, it is difficult to segregate nanoparticles from base fluids. To solve this problem, a modified VEROS technique has been developed **[Eastman et al. 1997]**. On the other hand, Zhu et al. **[2004]** proposed another single-step chemical process for preparing nanofluids. Apart from that, Lo et al. [**2005**] developed a technique to find out optimal parameters for nanofluid preparation in submerged arc nanoparticle synthesis system (SANSS) using electrolysis. Nanoparticles are characterized by TEM (Transmission Electron Microscope). Accumulation of nanoparticles is less in one-step process of nanofluid preparation. But this method is not suitable for the fluids with high vapor pressure.

**Double Step Synthesis Method:** Double step synthesis of nanofluid is usually used to prepare nanofluid mixing base fluid with nanoparticle available in market which is prepared by milling, grinding etc. different mechanical and some other physical and chemical technique.




a. b. c. d.

**Fig. 3.2** CNT nanofluid preparation steps: (a) high precision digital balance, (b) measurement of CNT, (c) ultrasonication and (d) magnetic stirring

A magnetic stirrer is used to stir the nanoparticles in base fluid. Then an ultrasonic vibrator is used to stabilize the solution. This process is followed several times to get a stable mixture and to reduce agglomeration. Wang et al. [**1999**] used double step process to produce alumina nanofluid. Murshed et al. [**2005**] also used this method to prepare $TiO_2$-water nanosuspension. Besides oil, base fluid can be water too. Xuan et al. [2000] mixed Cu nanoparticles with both water and oil to prepare nanofluid. On the other hand, Kim et al. [**2005**] used this method to prepare nanolfluids by ultrasonication and without stabilizers. In this process, both single walled and multiple walled carbon nanotube can be mixed with base fluid to produce nanofluid. According to some researchers, two-step nanofluid preparation is suitable for oxide nanoparticles than metallic nanoparticles [**Eastman et al. 2001**].

In this work, nanofluid is prepared using two-step process. The process is depicted sequentially in the following:

- 1 gram carbon nanotube is measured with precision balance to mix with 500 ml straight cut cutting oil to get 2% (wt/vol.) nanofluid.
- A magnetic stirrer (800 rpm) is used to mix the nanoparticles properly with the base fluid for 10 minutes.
- The mixture is then shifted to an ultrasonic device for ultrasonication for 10 minutes.
- Then the mixtures undergoes through magnetic stirring for another 10 minutes.
- Therefore again ultrasonication is done on the mixture for 10 minutes.
- The process is repeated for another time (total of 3 times)

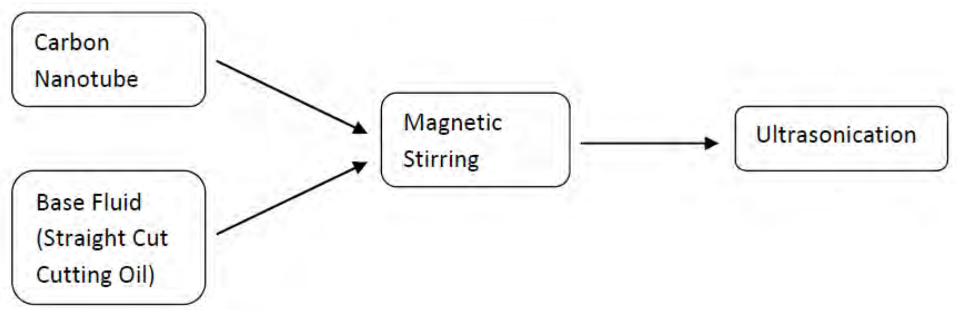



**Fig. 3.3** Sequence of nanofluid preparation

## 3.3 Experimental Investigation

There is a standard operating procedure for any machining works. So, it is necessary to apply proper environments. Physical properties of the material and the performance of machining changes with cutting condition, probable combination of the cutting parameters need to be verified beforehand. It has been discussed earlier in chapter 1 that machining temperature and the surface roughness are the two most important factors to be considered as far as the quality and the performance of the machined material is concerned. In this thesis work, AISI 1060 steel is ground in a horizontal surface grinding machine with CBN (Cubic Boron Nitride) grinding wheel. Process parameters are being selected on the basis of recent industrial practice. Key process parameters which are varied during the experiments are wheel speed, infeed, hardness of the material and the cutting conditions. The primary thing to be worried in grinding operation is the high temperature generation during machining which not only reduces the tool (wheel) life but also deteriorates the product quality and performance characteristics. Cutting fluid is traditionally most popular solution to this problem. Researchers could not be contented with it because of inability to provide desired cooling and lubricating condition, threat of health hazard of the people associated with it, contamination of the natural environment and some other inefficiency. Minimum Quantity Lubrication (MQL) has been a fine replacement of traditional flood cooling considering all the aforementioned aspects. To fulfill the specific requirement of machining MQL often has been applied by special purpose external nozzle. Reduction and control of grinding zone temperature is very essential in case of grinding operation in industrial arena. High precision grinding is subject to distortion and surface stress. MQL can be a nice possible solution of this serious problem. Therefore, MQL is a complementary solution option for flood cooling. It also decreases the wastage of cutting fluid as it needs a minimum amount of cutting oil for its cooling action. But, this tiny amount of cooling oil is directly applied to the zone of interest with high velocity and sharp focus. Application of coolant in this technique helps to obtain desired machined material with specified characteristics. It reduces the cutting zone temperature and subsequently residual stress by reducing the tangential grinding force. To get technological and economical benefit from MQL along with its environmental friendliness, MQL system needs to be properly designed. Some factors to be kept in mind for the proper design of MQL system:

- MQL system should be designed in such a way that the coolant could reach to the cutting zone as deeper as possible.

➢ Bulk cooling of grinding wheel and the workpiece must be prevented to restrict undesirable metallurgical changes.

➢ Ensuring minimum usage of cutting oil by confirming pin-pointed impingement at the workpiece-wheel interface

➢ Flow rate and pressure of the cutting fluid must be optimum and constant.

An MQL system is composed of some key components among which compressor and the MQL applicator are the major parts of it. Compressor used to generate pressure up to 23 bars. It has an ability to supply air continuously at a desired rate. MQL applicator contains three primary components: fluid tank, mixing chamber and a nozzle. Fluid tank used to reserve the particular type cutting fluid (straight cut cutting oil for this research). Mixing chamber make the room of mixing the oil with air at an optimum ratio. Nozzle is the final component of an MQL system. It assists the pin-point impingement of cutting fluid to the heat affected zone during machining.

The motive of this experimental investigation is to observe the trend of average temperature and surface roughness under MQL system in case of grinding. These two factors are the most vital for predicting different machining circumstances. This investigation was done by a horizontal surface grinding machine on AISI 1060 steel of four different hardness levels at varying infeed under MQL environment with nanofluid coolant shown in Fig. 3.4. Table was moved hydraulically at a fixed speed of 6 m/min.

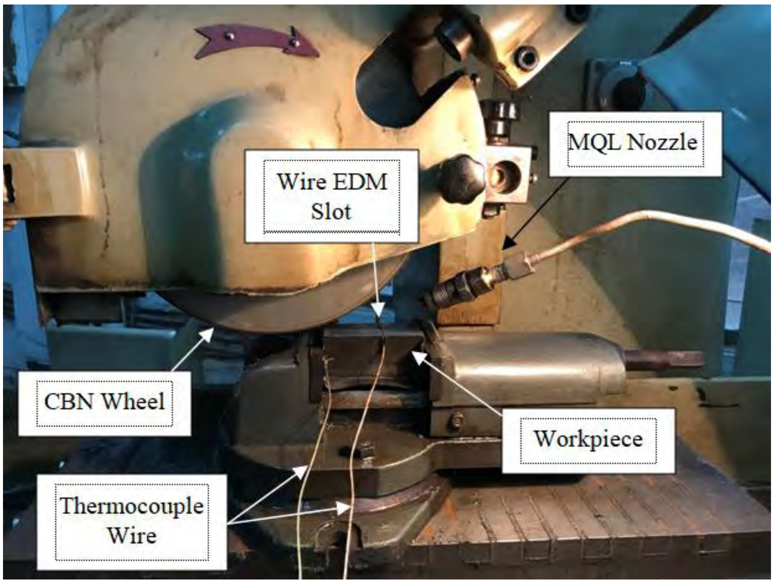



**Fig. 3.4** Experimental setup of grinding with pulse jet CNT MQL

The environment for the present investigation which is selected on the basis of recent industrial practice is briefly described in Table 3.2

**Table 3.2** Experimental Condition

| | |
|---|---|
| Machine tool | : Horizontal Spindle Surface Grinder (2.8 kw, Model: M7120A) |
| Workpiece | : AISI 1060 |
| Workpiece size | : 65 mm × 35 mm × 22 mm |
| Wheel | : CBN Wheel |
| Grinding mode | : Down cut |
| Process parameters | |
| Spindle speed, $\omega$ | : 1500, 3000 rpm |
| Wheel speed, $v_s$ | : 15.71 m/s, 31.42 m/s, |
| Table speed, $v_w$ | : 6 m/min |
| Infeed, $a_o$ | : 10, 20, 30, 40 μm |
| Coolant type | : Straight cut cutting oil (VG-68) |
| MQL flow rate | : 75 ml/hr |
| Environment | |
| | ➢ Dry condition |
| | ➢ Compressed Air (CA) |
| | ➢ Pulse jet MQL (MQL) |
| | ➢ Pulse jet Carbon Nanofluid MQL and Compressed Air (CMCA) |

## 3.3.1 Grinding Zone Temperature

There are many techniques available for measuring grinding temperature during experiment. A number of techniques are described by a leading expert of this field **[Batako et al. 2005]**. Thermocouples can be classified in many ways like single pole thermocouple, double pole thermocouple, infrared thermocouple and many more. There are other contact and non-contact thermocouple as well. Among all the available options, iron-constantan single pole embedded thermocouple technique was used for measuring the contact temperature for this work. A constantan wire was used to prepare a J-type thermocouple. A rectangular slot is cut to place constantan wire head into it. Wire Cut EDM machine was used to cut the slot which is 1 inch deep and 1 mm wide. The diameter of the wire cutter was 0.18 mm. Fig. 3.5 depicts the arrangement of temperature measurement during the experiment.

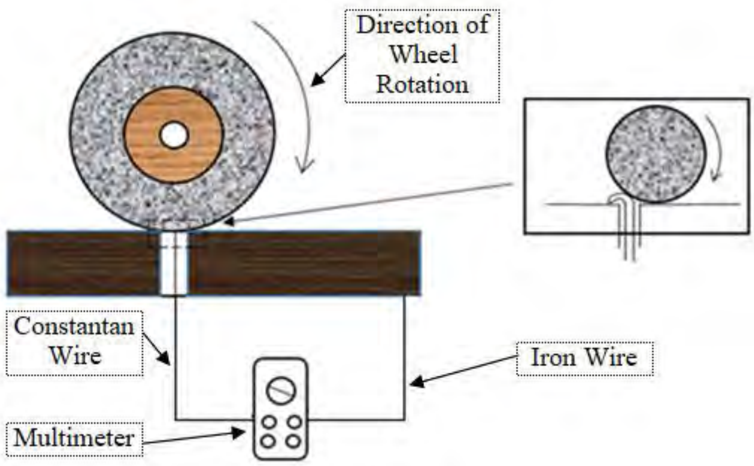



**Fig. 3.5** Measurement of temperature by embedded thermocouple during grinding

One end of the constantan wire was placed into the slot with some insulation sheet (mica- sheet) and the other end of the wire was connected to the multimeter. During the grinding operation when the grinding wheel used the touch the constantan wire, the wheel-wire contact point became the hot junction. The point where the iron wire was attached to the workpiece acted as cold zone. Some voltage was generated in the circuit due to Seebeck effect. That voltage was monitored by multimeter in millivolt (mV) unit. This voltage values were converted to their corresponding (°C) values using a proper calibration curve (shown in Fig. 3.6)

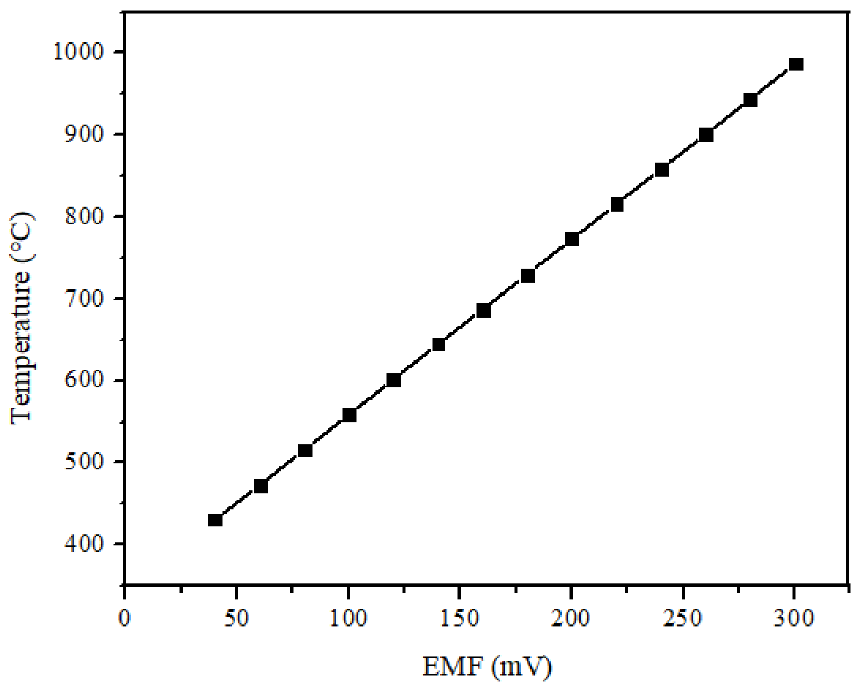
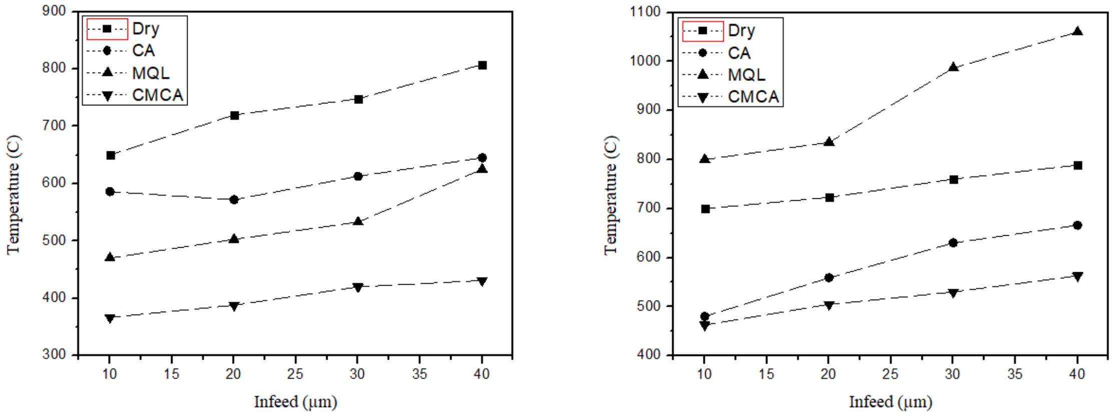


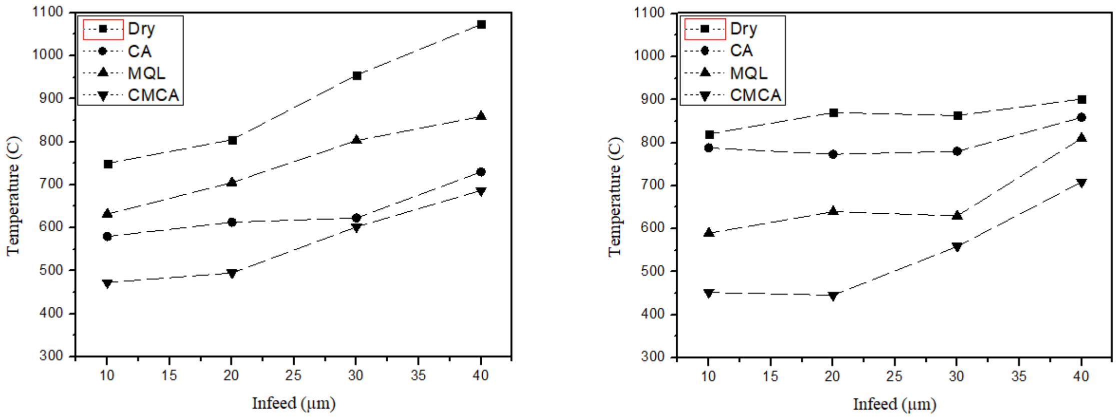

**Fig. 3.6** Calibration curve for AISI 1060 steel

The amount of grinding temperature largely depends on the grinding parameters. Elaborate study on these parameters helps to find out the relationship of them with the temperature. So, it is very important to know the impact of these factors on the grinding temperature. For this purpose, sufficient data was collected to find proper relationship of these factors with the generated temperature. Fig 3.7 to Fig 3.10 illustrates the values of temperature at different cutting conditions.



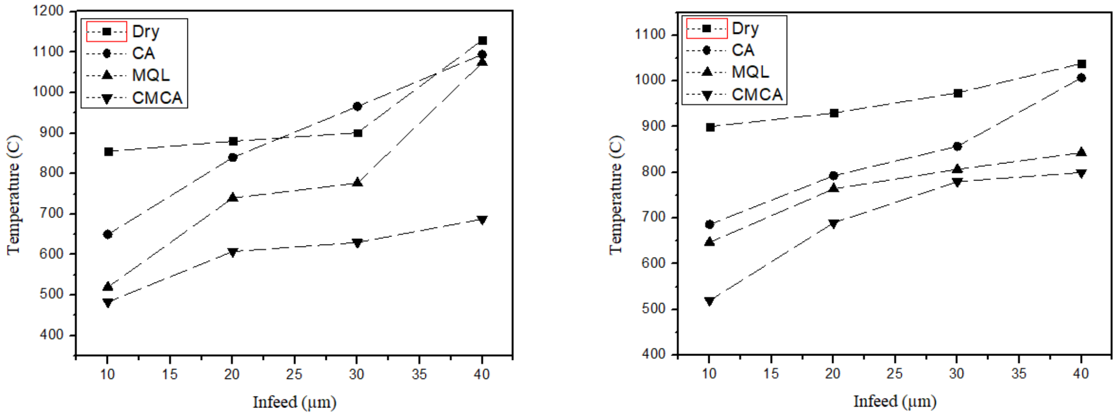

RPM=1500 RPM=3000

**Fig. 3.7** Variation of grinding zone temperature with different infeed at various RPM in grinding hardened steel (40 HRC) under different environments



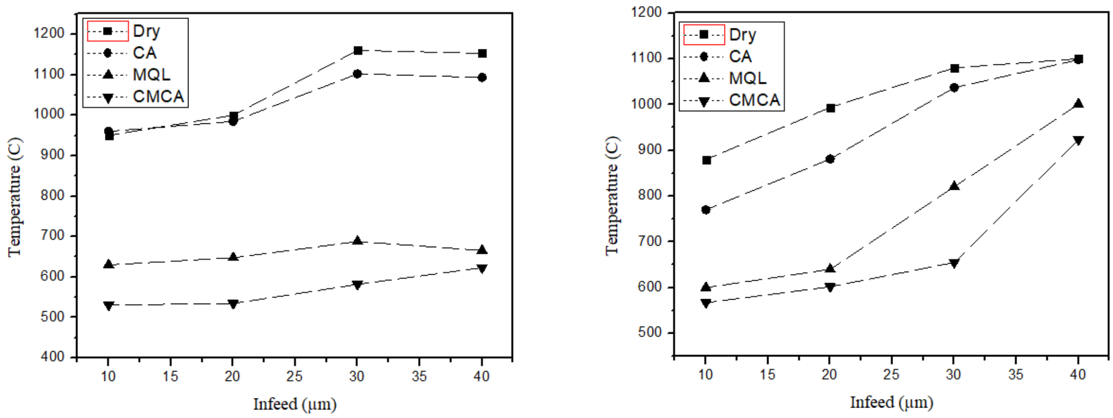

RPM=1500 RPM=3000

**Fig. 3.8** Variation of grinding zone temperature with different infeed at various RPM in grinding hardened steel (45 HRC) under different environments




RPM=1500 RPM=3000

**Fig. 3.9** Variation of grinding zone temperature with different infeed at various RPM in grinding hardened steel (50 HRC) under different environments




RPM=1500 RPM=3000

**Fig. 3.10** Variation of grinding zone temperature with different infeed at various RPM in grinding hardened steel (55 HRC) under different environments

### 3.3.2 Microscopic Study of Grinding Chips

Chips were collected during grinding operation for further analysis. Collecting grinding chips was a tedious task as the chips are so tiny to handle. Chips were collected using a glass sheet which was coated with petroleum jelly so that the flying chips get attached into the sheet. The chips were cleaned using the proper procedure. Then the clean chip samples were observed under Scanning Electron Microscope (SEM). Morphological structure of the chips was thoroughly studied. SEM photographs of the chips which were generated from various environment, wheel speed, infeed and material hardness. Total 10 samples were studied under four different gradual increasing order magnifications. Multiple images were taken for same magnification for greater accuracy of the image. Chips were taken for four different machining conditions: dry, compressed air, MQL and CNT MQL with compressed air (CMCA). According to Tso (1995), grinding chips are of six basic types. They are flowing type chips, shearing type chips, knife type chips, ripping type chips slice type chips and melting type chips. SEM images of grinding chips which are relatively globular and wider than other chip types and can be classified as shearing type chips. Some chips are large, wide and thick with rubbing mark on the chips in the direction of grinding. These chips are slice type chips. The best grinding chips which are flowing type chips. These chips are very thin, curly and cutting edges are the sharpest. Curved type chips are the indication of poor surface finish. These chip surfaces are burnt and most of the cases they are ripping type chips. Grinding chips having subsurface layer and scratch mark over the chip generating direction are known as knife types chips. Meanwhile, the worst type chips are melting type chips. These chips are irregularly melted and having torn and uneven edges. SEM images of the grinding chips are attached in the following.

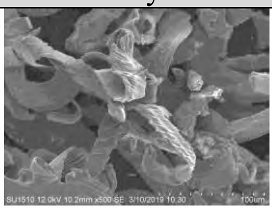
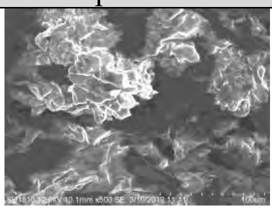
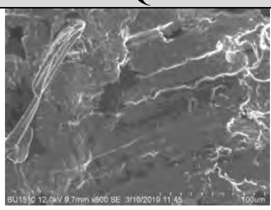
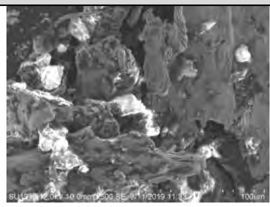
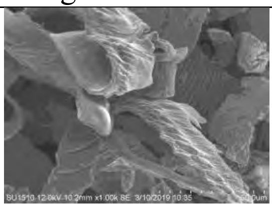
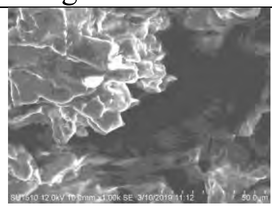
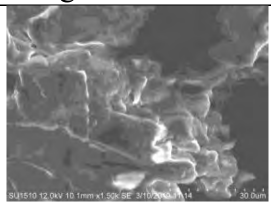
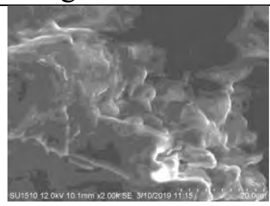
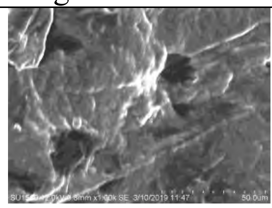
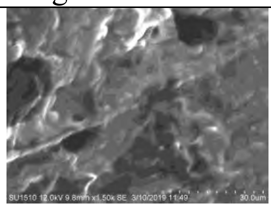
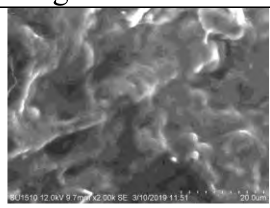
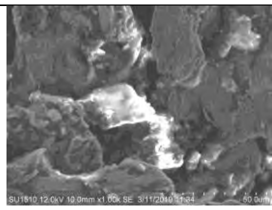
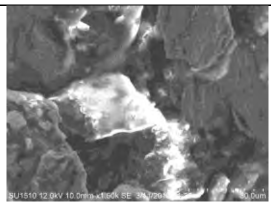
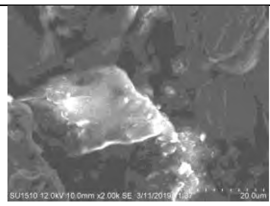
| **Environments** | | | |
|---|---|---|---|
| Dry | Compressed Air | MQL | CMCA |
|  Magnification 500 |  Magnification 500 |  Magnification 500 |  Magnification 500 |
|  Magnification 1000 |  Magnification 1000 |  Magnification 1000 |  Magnification 1000 |
|  Magnification 1500 |  Magnification 1500 |  Magnification 1500 |  Magnification 1500 |
|  Magnification 2000 |  Magnification 2000 |  Magnification 2000 |  Magnification 2000 |

**Fig. 3.11** SEM view (different magnification) of grinding chips under different environments at 3000 RPM and 10 μm infeed

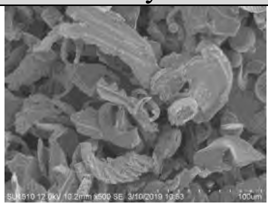
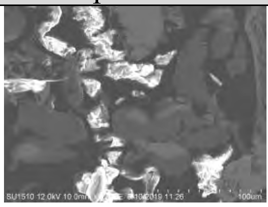
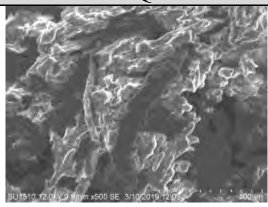
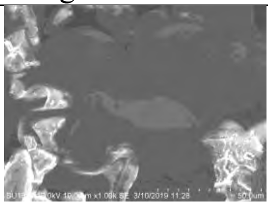
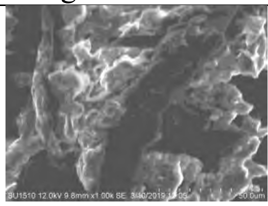
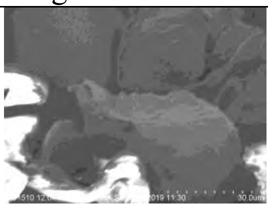
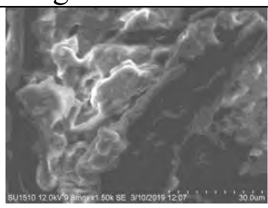
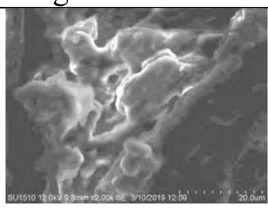
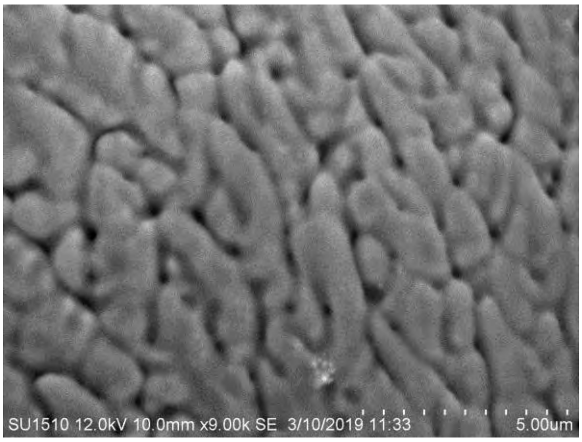
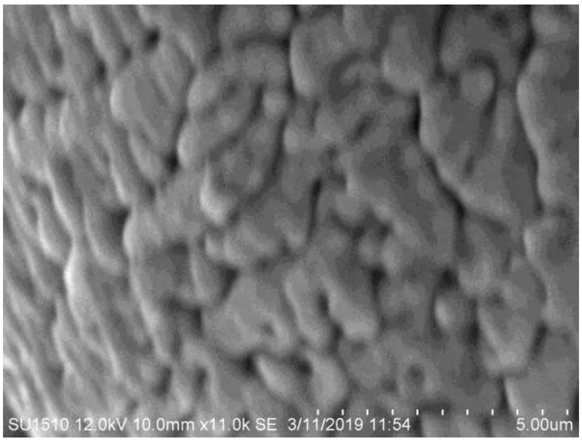
| Environments | | | |
|---|---|---|---|
| Dry | Compressed Air | MQL | CMCA |
| <br>Magnification 500 | <br>Magnification 500 | <br>Magnification 500 | <br>Magnification 500 |
| <br>Magnification 1000 | <br>Magnification 1000 | <br>Magnification 1000 | <br>Magnification 1000 |
| <br>Magnification 1500 | <br>Magnification 1500 | <br>Magnification 1500 | <br>Magnification 1500 |
| <br>Magnification 2000 | <br>Magnification 2000 | <br>Magnification 2000 | <br>Magnification 2000 |

**Fig. 3.12** SEM view (different magnification) of grinding chips under different environments at 3000 RPM and 40 μm infeed



9000X Magnification

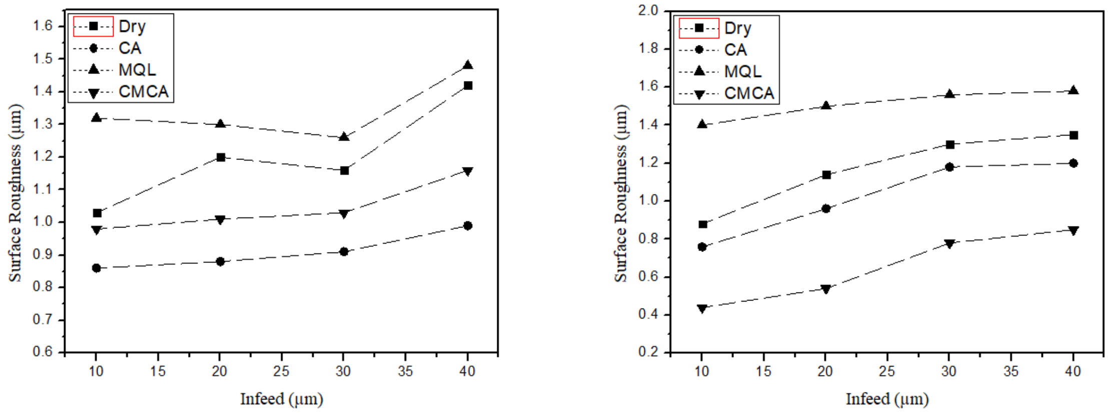


11000X Magnification

**Fig. 3.13** Deep into the chip's surface (Infeed 40, RPM 3000, Environment CMCA)

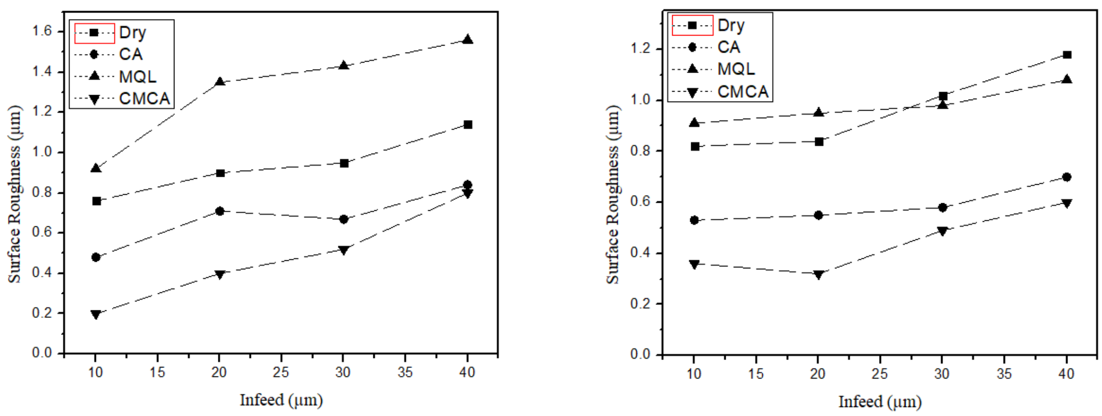
### 3.3.3 Surface Roughness

The quality of surface finish largely depends on the grinding parameters. Intensive study on these parameters helps to find out the relationship of them with the surface roughness. So, it is very important to know the impact of these factors on the surface roughness of the ground workpiece. For this purpose, sufficient data was collected to find proper relationship of these factors with the generated temperature. Fig 3.13 to Fig 3.16 illustrates the values of surface roughness at different cutting conditions. Infeed values are plotted in X-axis and the corresponding temperatures are plotted in Y-axis by varying the wheel speed and hardness of the workpiece material.



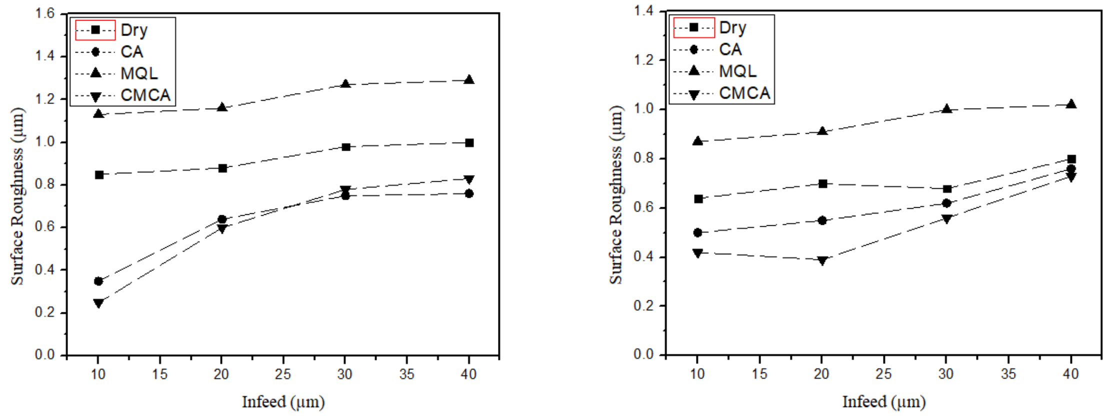

RPM=1500 RPM=3000

**Fig. 3.14** Variation of surface roughness with different infeed at various RPM in grinding hardened steel (40 HRC) under different environments



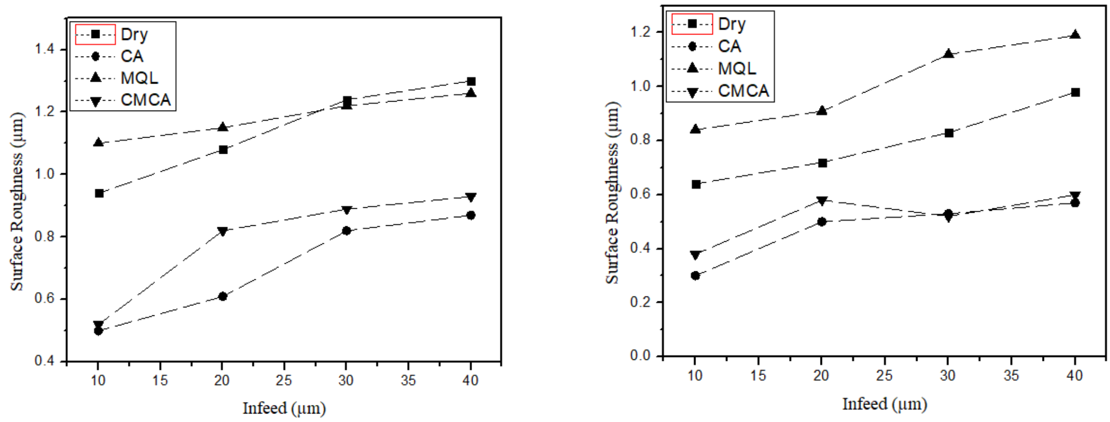

RPM=1500 RPM=3000

**Fig. 3.15** Variation of surface roughness with different infeed at various RPM in grinding hardened steel (45 HRC) under different environments




RPM=1500 RPM=3000

**Fig. 3.16** Variation of surface roughness with different infeed at various RPM in grinding hardened steel (50 HRC) under different environments




RPM=1500 RPM=3000

**Fig. 3.17** Variation of surface roughness with different infeed at various RPM in grinding hardened steel (55 HRC) under different environments

# Chapter-4

## Modeling of Grinding Temperature and Surface Roughness

Generation of excessive heat during grinding operation is a major drawback as it affects the surface finish of the material by introducing high residual stress, cutting forces and power. After analysis the previous works on grinding it can be assumed that the value of this temperature increases with the increase of wheel angular velocity, linear velocity of grinding table and infeed (depth of cut) of the wheel on the workpiece. Thus this factor hinders high production concept. This problem becomes acute when the strength and the hardness of the material increase as well.

Metal cutting is involved with generation of heat and the resultant high temperature. This undesired heat has detrimental effects on the properties of the metal. So, it is very important to learn how to reduce this massive heat during machining. High temperature welcomes oxidation of the base metal and the resultant oxidized metal possesses poorer properties than the base metal itself. Therefore the service life of the material reduces significantly and the dimensional accuracy also becomes erroneous.

Grinding is typically a finishing operation. Material is removed in grinding by the abrasive action of the grinding wheel on the material while passing over it. The acting force can be divided into two categories: tangential force and the normal force. This force pushes the abrasive grains to penetrate the material and therefore to remove the uppermost layer from adjacent layers. Three scenarios may appear when the grains come in contact with the material: cut, rub and plough [**Hahn 1966**]. Cutting refers to the action which cut a layer from the top of the material. Rubbing refers to sliding of the abrasive grains over the surface of the material resulting mild wear of the workpiece surface. Ploughing happens when the abrasive dig into the material surface creating a deep impact but unable to cut off.

Grinding operation can be divided as up-grinding and down grinding according to the relative movement of workpiece and the angular velocity of the grinding wheel. In down grinding, penetration is deepest at the beginning of the cutting action and the intensity of penetration reduces as the workpiece passes through the wheel. The wheel and the work table moves in the opposite direction. On the other hand, the work-piece and the wheel in the same direction in case of up-cut grinding. So, the penetration is initially less but finally it becomes maximum at the workpiece passes through the wheel. However, the direction of the relative movement of the wheel and the workpiece is insignificant in terms of the consumption of energy, generation of grinding force, surface integrity, wheel wear and proneness to burn.

The advantage of down-cut grinding is the grinding force is slightly lower relative to up-grinding, thus it is convenient for smooth surface and tool wear prevention. Chip is removed at the beginning of the contact with an individual grain. In up-cut grinding the grain initially rubs against the workpiece and cuts off the chip at the last part of the contact. In up-cut grinding the abrasive attacks the chip mildly than down-cut grinding. But, the rubbing action is longer lasting here than down cut grinding.

In up-cut grinding the grains often become blunt. This is probably the reason why up grinding generates higher grinding force and causes higher wheel wear. On the other hand, down grinding results initial impact force which causes the grain microfracture. It ensures wheel sharpness and decrease the amount of wheel wear. Up grinding is more suitable for cooling action implementation.

Major portion of the grinding energy is converted to heat which is transmitted to the grinding wheel, chips, cutting fluid and the workpiece. Geometrical grinding zone is the key heat zone and this area experiences the maximum temperature raise.

The basic principle of grinding is very simple. Let, the diameter of the grinding wheel is $d_s$, linear velocity of the periphery of the wheel is $v_s$ and it passes over a workpiece material which has a velocity of $v_{wp}$. The depth of cut of the operation is $a_n$, normal and tangential forces of the grinding wheel over the workpiece are $F_n$ and $F_t$ respectively, geometric contact length is $l_c$.

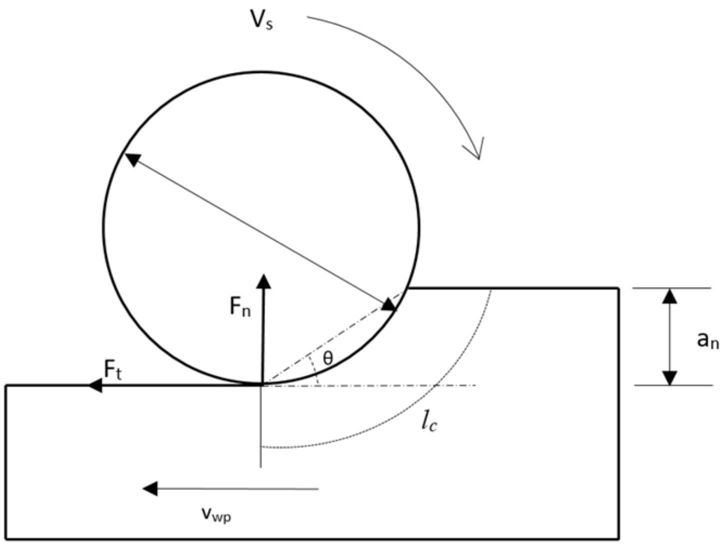


**Fig. 4.1** Important grinding parameters

## 4.1 Temperature Modeling using RSM

Machining is a multidimensional task where a significant number of factors contribute to the input parameters and output responses. For this complex processes (i.e. turning, milling, drilling, grinding etc.) empirical modeling has made its place during last couples of years. Likewise, various data mining techniques such as Design of Experiments (DOE), Response Surface Methodology (RSM), Artificial Neural Network (ANN), Genetic Algorithm (GA), Taguchi Method have been vastly used to predict the interrelationship between the input parameters and output responses. All the techniques are suitable for finding both the individual effect and the combined effect of the parameters on responses. But, Taguchi and RSM are popularly used in those cases where it is not possible to take huge amount of trial data. In some cases, taking sufficient data is very expensive and time consuming. RSM demonstrates its ability of predict unknown response with minimum amount of trial data.

The objective of Response Surface Methodology (RSM) is to optimize an output variable (response) and which is depended on some mutually independent variables (input parameters) with some mathematical and statistical techniques. An experiment is actually a series of tests which are called experimental runs. In each run, some input parameters are changes to observe the effect on the output variable. There may have some sources of error in the whole process. In case of manual data acquisition, there may have error while taking data from the device. The measurement device itself can be erroneous too. In case of computer assisted data acquisition, numerical error may occur such as data uncertainty, round-off error, truncation error and few others. It is assumed that the error in RSM is randomly distributed. There is no trend of this error.

RSM find its huge application in performance measure and quality control functions. This performance measure or quality characteristics is known as response. The input variables are often termed as independent variables. RSM explores the sample space and tries to find out the approximating relationship between the input parameters and the output variables. Let an output response is α, input variable are $\mu_0, \mu_1, \mu_2, \mu_3 \ldots\ldots \mu_n$. So the relationship is

$$\alpha = f(\mu_0, \mu_1, \mu_2, \mu_3 \ldots\ldots \mu_n) + \omega \ldots\ldots(4.1)$$

Here, $f$ is the genuine response function which is not known and it might be very complex function, ω is a compensating term which represents other sources of variability which are not included in $f$ like measurement error, background noise and some other incontrollable effects. Normally, ω is seen as statistical error having a normal distribution with a mean of zero.

The variables $\mu_0, \mu_1, \mu_2, \mu_3 \ldots\ldots \mu_n$ in equation. 5.2 are usually known as natural variable as they are expressed as the natural measurement units such as kg, liter, degree, Kelvin, Pascal etc. It is convenient to covert these natural variables to coded variables $x_0, x_1, x_2, x_3 \ldots\ldots x_n$ . These coded variables are unit less with mean zero and same standard deviation as the natural variables. In terms of codes variables the equation looks like as,

$$G(\alpha) = y = f(\mu_0, \mu_1, \mu_2, \mu_3 \ldots\ldots \mu_n) + G(\omega) = f(x_0, x_1, x_2, x_3 \ldots\ldots x_n) \ldots\ldots(4.2)$$

A first or second order model is necessary to approximate the response function $f$. First order model is used to when we are interested to find out the true response value $f$ for a limited region of the independent variable space and if the curvature of the function is very small. In case of two independent variables, the coded first-order model would be like,

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \ldots\ldots(4.3)$$

Equation 5.3 in this form is often called main effects model as these model only concerned about the individual or main effect on the response without considering the interaction terms. If interaction terms are included then the nature of the model will be as follows,

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1 x_2 \ldots\ldots(4.4)$$

In some cases, first order-model is not sufficient to approximate response values often. In those cases second-order model is introduced,

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_1^2 + \beta_4 x_2^2 + \beta_5 x_1 x_2 \quad \text{...(4.5)}$$

Second-order model has been intensively used for obtaining true response in response surface methodology for few specific reasons. Firstly, second-order model of RSM has demonstrated tremendous flexibility with numerous functional terms to approximate true response quite comfortably. Secondly, it's co-efficient (β) can easily be determined. Least Square Regression method is typically employed here. Thirdly, real life experience indicates that second-order RSM model does well in solving real response surface problems.

Generally, second-order response surface model are of the following shape,

$$y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i<} \sum_{j=2}^{k} \beta_{ij} x_i x_j \quad \text{...(4.6)}$$

Response Surface Methodology has got a fruitful method for analyzing the trend of temperature against various design variables like grinding wheel speed, infeed (depth of cut) and work speed. It is a combined structure of experimental and statistical analysis. The process is involved with a dependent variable (T) and some independent variables. When all the variables are numerically measureable, then the form of response surface can be,

$$T = f(V, F, H) + \omega \quad \text{...(4.7)}$$

where, f represents the response function and V,F and H are the wheel speed, infeed and the material hardness; $\omega$ is the physical error which is normally distributed (mean zero). The second-order response equation for grinding zone temperature which is a function of wheel speed, infeed and material hardness can be written as,

$$T = \beta_0 + \beta_1 V + \beta_2 F + \beta_3 H + \beta_{11} V^2 + \beta_{11} F^2 + \beta_{11} H^2 + \beta_{12} VF + \beta_{23} FH + \beta_{13} VH \quad \text{...(4.8)}$$

To model any response using Response Surface Methodology (RSM), proper response surface design must be selected. Then the following tasks need to be done:

- Number of significant factors need to be identified
- Minimum number of run should be determined
- Sufficient data must be taken to cover all the region of interest

➢ Impact of other issues should be taken into consideration

In this work, a Response Surface Design is created using statistical software Minitab 17. To find out the relationship between the individual factors with the response (Grinding zone temperature) main effect plot has been created. Interaction plot has been generated as well to see the combined effect of the factors on output response.

In main effect plot, points are the means of response at all the levels of each factor [Fig. 4.2]. The plot depicts the variation of the magnitude of the responses individually with three input variables which are grinding wheel speed, infeed and the workpiece hardness. Value of individual parameters at each level is plotted in X-axis and the response value is plotted in Y-axis.

The main effects plot represents that there is no significant change is temperature with the variation of grinding wheel speed. However, the temperature rises sharply as the infeed increases. The rate of increase is relatively slow at the beginning but it is faster at the later portion.

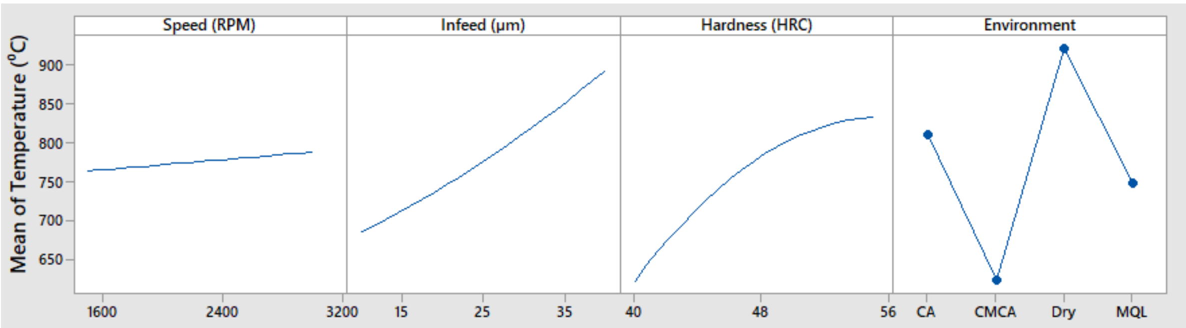



**Fig. 4.2** Main effects plot for grinding zone temperature

The grinding temperature also increases with the increase of the hardness and unlike the infeed effect it is faster at the beginning than the later part. Another thing to notice is the mean temperature is lowest for CMCA condition and highest for Dry condition.

Interaction plot shows the combined effect of input parameters on output response. Fig 4.3 delineates the interaction plot i.e. interaction between speed and infeed, speed and hardness, speed and environment; infeed and hardness, infeed and environment; hardness and environment.

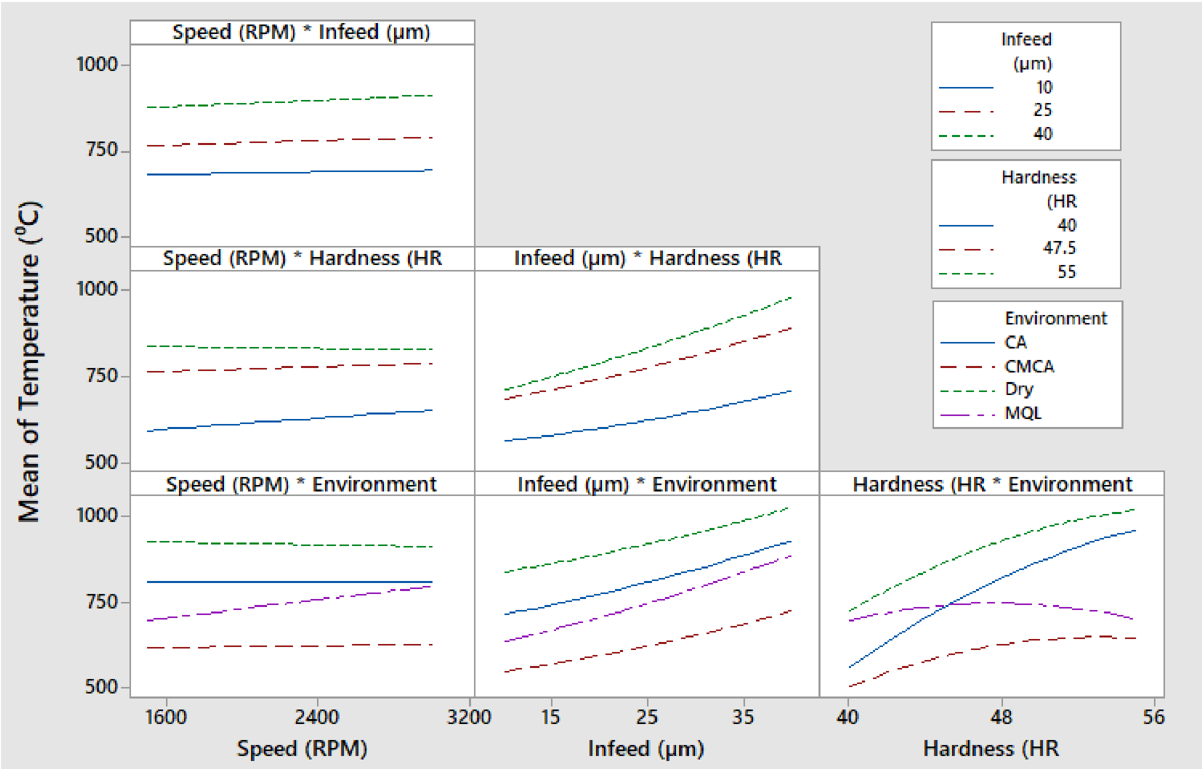



**Fig. 4.3** Interaction among different parameters (infeed, speed, hardness and environment) and grinding zone temperature

From the interaction plot it can be decided that form interaction between infeed and environment and the interaction between infeed and environment are mostly significant. Other than these two interaction effects infeed and hardness interaction is moderately significant. A second-order mathematical model is developed and validated with experimental data to understand the significance of the interaction term as well.

Fig. 4.4 shows all the three temperature distributions of this analysis at a glance. Rather than showing a particular point, contour plot shows a range of points (a region) for optimum response values.

Closer look at each of them shows that in case of grinding zone temperature distribution against infeed and grinding wheel speed the other two factors like hardness (47.5 HRC) and environment (compressed air) were kept constant. The following contour plot indicates that the temperature value is lowest (lower than 750°C) for the infeed of 10 to 15 μm.

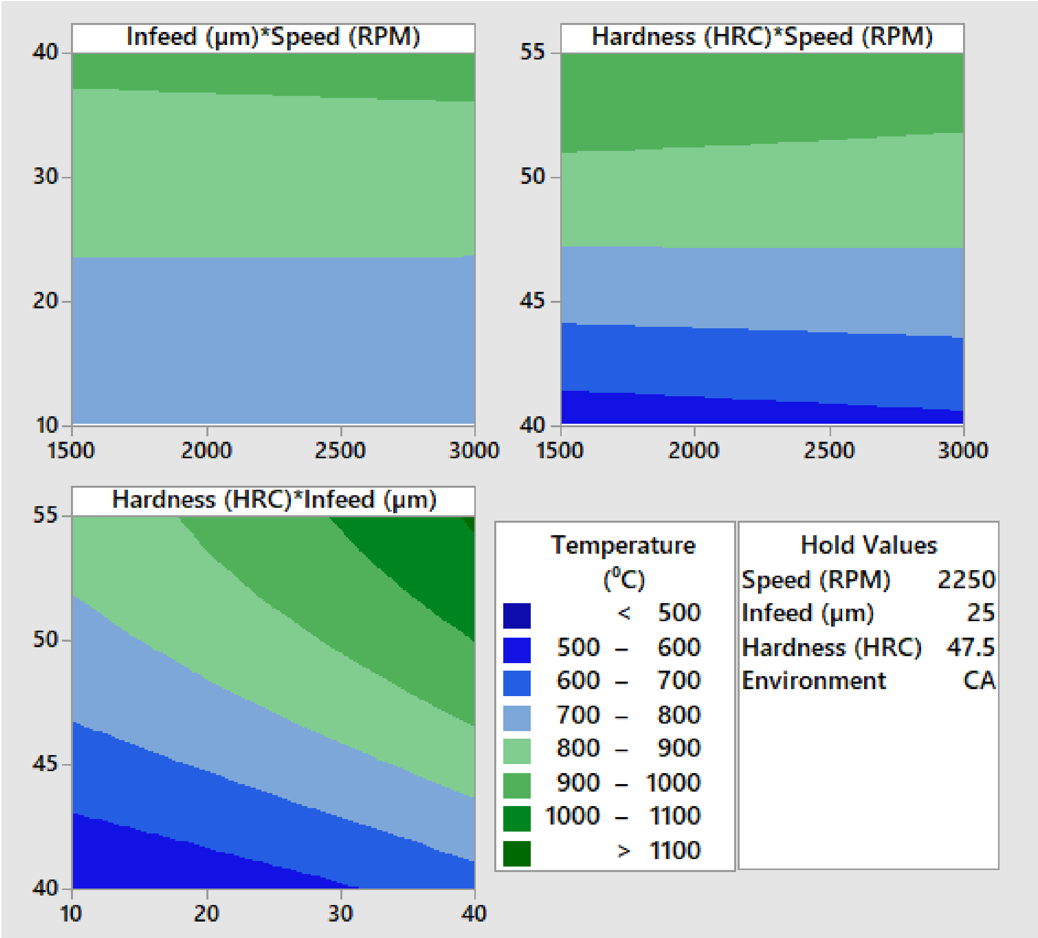
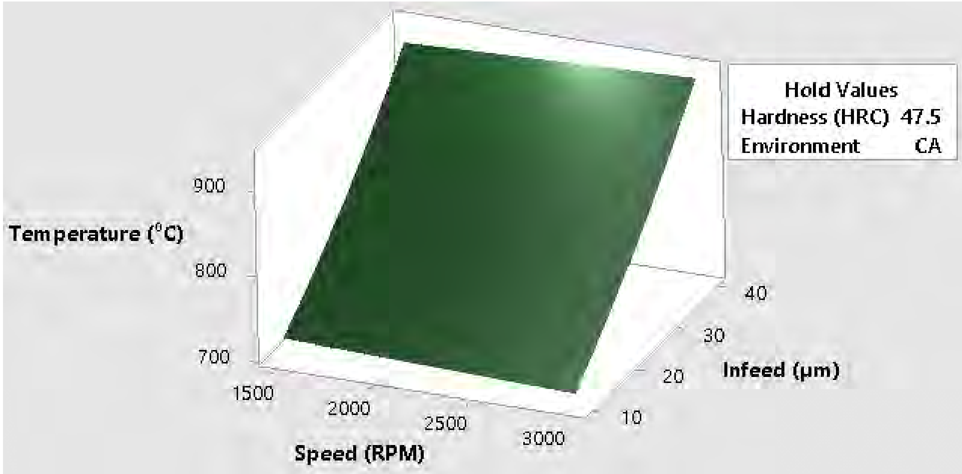



**Fig. 4.4** Computed temperature distribution in workpiece at different infeed, speed and hardness combinations under compressed air condition

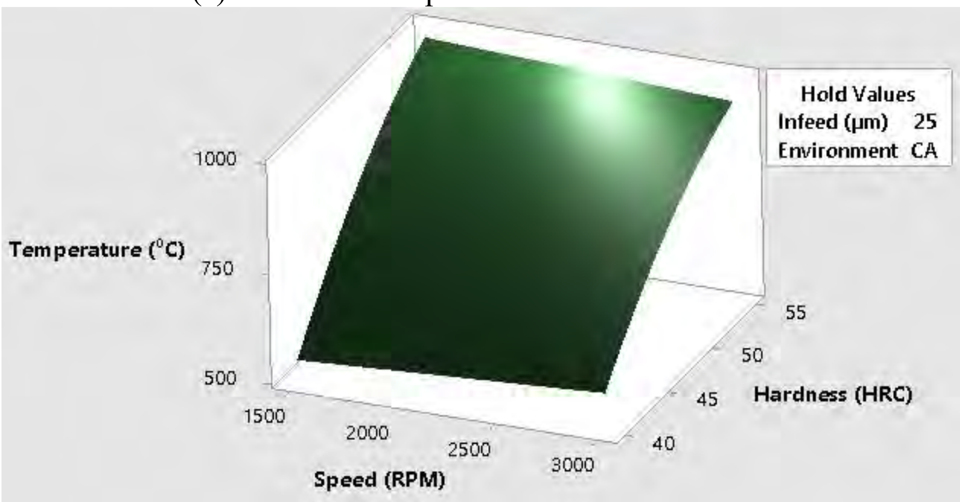
In case of grinding zone temperature distribution against material hardness and grinding wheel speed, the other two factors were kept fixed (infeed at 25 µm and environment at compressed air). The distribution indicates that the temperature value is lowest (lower than 600 °C) for the material hardness of 40 to 41 HRC.

For the grinding zone temperature distribution against material hardness and infeed the other two factors were kept fixed as well (wheel speed at 2250 RPM and environment at compressed air). The distribution indicates that the temperature value is lowest (lower than 500 °C) for infeed of 10 to 31 µm and a material hardness of 40 to 43 HRC.

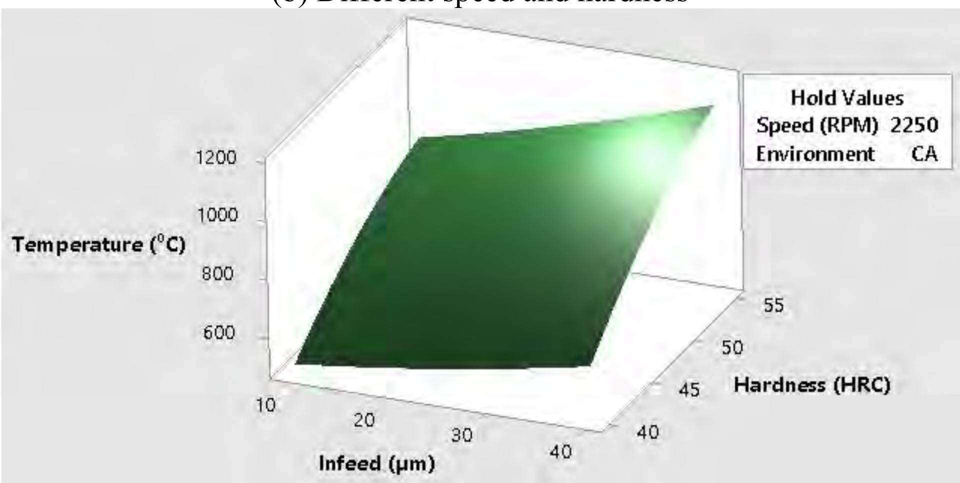
Surface plots are another three dimensional plot which represents surface roughness against different independent variables combination. Among the four predictors here in our analysis, two of them are kept constant and the other two are varied each time to see the effect on grinding zone temperature. Fig. 4.5(a) shows the surface plot of grinding zone temperature with variable infeed and wheel speed. Hardness and environment is kept constant at 47.5 HRC and compressed air respectively. It is observed from the plot that temperature increases with increase of infeed.



(a) Different speed and infeed conditions



(b) Different speed and hardness



(c) Different infeed and hardness

**Fig. 4.5** Surface plot of grinding zone temperature with infeed, wheel speed and hardness under compressed air condition

Fig. 4.5(b) shows the surface plot of grinding zone temperature with variable material hardness and wheel speed. Infeed and environment is kept constant at 25 μm and compressed air respectively. It is observed from the plot that temperature increases with the increase of both wheel speed and the material hardness.

Fig. 4.5(c) shows the surface plot of grinding zone temperature with variable material hardness and infeed. Wheel speed and environment is kept constant at 2250 RPM and compressed air respectively. It is observed from the plot that temperature increases with the increase of material hardness and infeed simultaneously.

Four separate mathematical model were developed for four different environments which are shown in Equation 4.9-4.12

| Environment | Regression Equation |
|---|---|
| CA | T= -2509 + 0.209 V– 11.07 F +105.0 H+0.0863 F*F- 0.796 H*H + 0.00007 V*F - 0.00443 V*H + 0.288 F*H…………………………………………….(4.09) |
| CMCA | T= -1856 + 0.141 V–10.93 F+ 90.7 H+ 0.0584 F*F- 0.853 H*H + 0.00051 V*F - 0.00311 V*H + 0.267 F*H……………………………………………….(4.10) |
| Dry | T= -2017 + 0.199 V– 11.93 F +97.09 H+0.0863 F*F- 0.796 H*H + 0.00007 V*F - 0.00443 V*H + 0.288 F*H…………………….……………………….(4.11) |
| MQL | T= -1502 + 0.275 V– 09.76 F +78.70 H+0.0863 F*F- 0.796 H*H + 0.00007 V*F - 0.00443 V*H + 0.288 F*H……………………..………………......….(4.12) |

Here,

T = grinding zone temperature

V = grinding wheel speed

F = infeed

H = workpiece material harndess

The four cutting environments under which investigation was done,

CA = Compressed Air

CMCA = CNT MQL with compressed Air

Dry = Dry Condition

MQL = Minimum Quantity Lubrication

The analysis is done in terms of uncoded units. The term $R^2$ in indicate the amount of variation of the response variable which can be explained by its relations with the input variables. The better the $R^2$ value, the better the fitness of the model with the data. Predicted $R^2$ is the measure of how well a new response value can be predicted with the given model. Predicted $R^2$ has the ability to reduce overfitting as it includes the points which are not included in the model estimation.

Overfitting refers to failing to predict the value of the response outside of the data set though it can explain the response values within the data set quite satisfactorily. Here the Predicted $R^2$ values are 69.70%. S value, $R^2$ values, and $R^2$ (Adj.) values are 95.536, 78.80% and 74.84% respectively. It could have been better if some more data is included. There may have some physical error too during the data acquisition process. Detailed statistical analysis has been given in Table 4.1.

**Table. 4.1** Regression Table of the for Grinding Zone Temperature Model

| Term | Effect | Coef | SE Coef | T-Value | P-Value | VIF |
|---|---|---|---|---|---|---|
| Constant | | 776.3 | 17.2 | 45.27 | 0.000 | |
| Speed (RPM | 24.29 | 12.14 | 8.44 | 1.44 | 0.153 | 1.00 |
| Infeed (μm) | 206.4 | 103.2 | 11.3 | 9.11 | 0.000 | 1.00 |
| Hardness (HRC) | 210.1 | 105.0 | 11.3 | 9.27 | 0.000 | 1.00 |
| Environment | | | | | | |
| CA | 68.3 | 34.1 | 14.6 | 2.33 | 0.021 | 1.50 |
| CMCA | -303.3 | -151.6 | 14.6 | -10.37 | 0.000 | 1.50 |
| Dry | 289.8 | 144.9 | 14.6 | 9.91 | 0.000 | 1.50 |
| Infeed (μm)*Infeed (μm) | 26.3 | 13.1 | 19.0 | 0.69 | 0.491 | 1.00 |
| Hardness (HRC)*Hardness (HRC) | -95.9 | -48.0 | 19.0 | -2.52 | 0.013 | 1.00 |
| Speed (RPM)*Infeed (μm) | 11.4 | 5.7 | 11.3 | 0.51 | 0.614 | 1.00 |
| Speed (RPM)*Hardness (HRC) | -34.9 | -17.5 | 11.3 | -1.54 | 0.126 | 1.00 |
| Speed (RPM)*Experimental Cond. | | | | | | |
| CA | -23.5 | -11.8 | 14.6 | -0.80 | 0.423 | 1.50 |
| CMCA | -14.4 | -7.2 | 14.6 | -0.49 | 0.622 | 1.50 |
| Dry | -37.8 | -18.9 | 14.6 | -1.29 | 0.199 | 1.50 |
| Infeed (μm)*Hardness (HRC) | 60.1 | 30.0 | 15.2 | 1.98 | 0.051 | 1.00 |
| Infeed (μm)*Experimental Cond. | | | | | | |
| CA | 6.2 | 3.1 | 19.6 | 0.16 | 0.876 | 1.50 |
| CMCA | -32.1 | -16.0 | 19.6 | -0.82 | 0.416 | 1.50 |
| Dry | -19.6 | -9.8 | 19.6 | -0.50 | 0.618 | 1.50 |
| Hardness(HRC)*Experimental Cond. | | | | | | |
| CA | 190.1 | 95.1 | 19.6 | 4.84 | 0.000 | 1.50 |
| CMCA | -68.9 | -34.4 | 19.6 | -1.76 | 0.082 | 1.50 |
| Dry | 83.5 | 41.7 | 19.6 | 2.13 | 0.036 | 1.50 |

Here, P-value is the indicator of which effects are the most significant. If the P-value is less than 0.05 then that effect is significant. It can be easily seen form the table that among the three numerical input parameters, infeed of the cutting action and the hardness of the workpiece material is significant. The confidence interval for this analysis is assumed to be 95%. Among the environments, compressed air (CA) environment is significant too. The interaction between infeed and CA, infeed and Dry cutting condition, hardness and Dry cutting conditions are significant too as their P-values are away less than 0.05. VIF is the variance inflation factor which is the measure of the increase of the variance of the estimated regression co-efficient because of co-linearity. It can be found out by dividing the variance of the model with multiple terms with the variance of the model with single term alone.

Analysis of variance (ANOVA), shown in Table 4.2 is also used to investigate the model relationship between the input parameters (predictor variables) and the output responses. Unlike regression analysis, predictors in ANOVA are categorical (qualitative) variables and the nature of relationship cannot be determined as the co-efficient of the variables are not included in the model.

**Table. 4.2** Analysis of Variance (ANOVA) for Temperature Model

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 20 | 32321513 | 161608 | 18.90 | 0.000 |
| Linear | 6 | 22344216 | 372369 | 43.55 | 0.000 |
| Speed (RPM) | 1 | 9827 | 9827 | 1.15 | 0.286 |
| Infeed (μm) | 1 | 600662 | 600662 | 70.25 | 0.000 |
| Hardness (HRC) | 1 | 643771 | 643771 | 75.29 | 0.000 |
| Environment | 3 | 1167679 | 389226 | 45.52 | 0.000 |
| Square | 2 | 57117 | 28558 | 3.34 | 0.040 |
| Infeed (μm)*Infeed (μm) | 1 | 8702 | 8702 | 1.02 | 0.361 |
| Hardness (HRC)*Hardness (HRC) | 1 | 46251 | 46251 | 5.41 | 0.022 |
| 2-Way Interaction | 12 | 561548 | 46796 | 5.47 | 0.000 |
| Speed (RPM)*Infeed (μm) | 1 | 45 | 45 | 0.01 | 0.943 |
| Speed (RPM)*Hardness (HRC) | 1 | 40362 | 40362 | 4.72 | 0.032 |
| Speed (RPM)*Environment | 3 | 69155 | 23052 | 2.70 | 0.050 |
| Infeed (μm)*Hardness (HRC) | 1 | 36040 | 36040 | 4.22 | 0.043 |
| Infeed (μm)*Environment | 3 | 23312 | 7771 | 0.91 | 0.440 |
| Hardness (HRC)*Environment | 3 | 400272 | 133424 | 15.61 | 0.000 |
| Error | 97 | 829349 | 8550 | | |
| Total | 117 | 4061502 | | | |

Let us explain the terms of ANOVA step by step. Sources stand for source of variation which may be factor, the interaction or the error. The sum of all sources in included in “total”. DF is the degrees of freedom for each source. For a factor having n levels, the degrees of freedom is (n-1). There are 118 observations for this analysis. So, the degrees of freedom are 117. SS is the sum of squares among the groups and the sum of squares within the groups as well. MS refers to Mean Square. It can be found by dividing the SS (Sum of Squares) by DF (Degrees of freedom). F-values are obtained by dividing the factor MS (Mean Squares) by the error is MS. These F-values are compared against critical F-values to determine whether the factor or the interaction is significant or not. P-values can also be used for this purpose. Usually, a factor or an interaction having P-value less than 0.05 is significant.

## 4.2 Modeling of Surface Roughness using RSM

To model any response using Response Surface Methodology (RSM), proper response surface design must be selected. Firstly, the number of significant factors needed to be identified. Secondly, minimum number of run should be determined. Thirdly, sufficient data must be taken to cover all the region of interest. Last but not the least, impact of other issues should be taken into consideration. In this work, a Response Surface Design is created using statistical software Minitab 17. To find out the relationship between the individual factors with the response (surface roughness) main effect plot has been created. Interaction plot has been generated as well to see the combined effect of the factors on output response.

In main effect plot, points are the means of response at all the levels of each factor [Fig. 4.6]. The plot depicts the variation of the magnitude of the responses individually with three input variables which are grinding wheel speed, infeed and the workpiece hardness. Value of individual parameters at each level is plotted horizontally and the response value is plotted vertically.

The main effects plot represents that surface roughness decreases with the grinding wheel speed. However, surface roughness increses with the increase of infeed. The roughness decreases as the hardness of the material increases up to 50 HRC hardness level then it increases with the increase of hardness. Another thing is notice is the mean surface roughness is highest for MQL condition and lowest for CMCA condition.

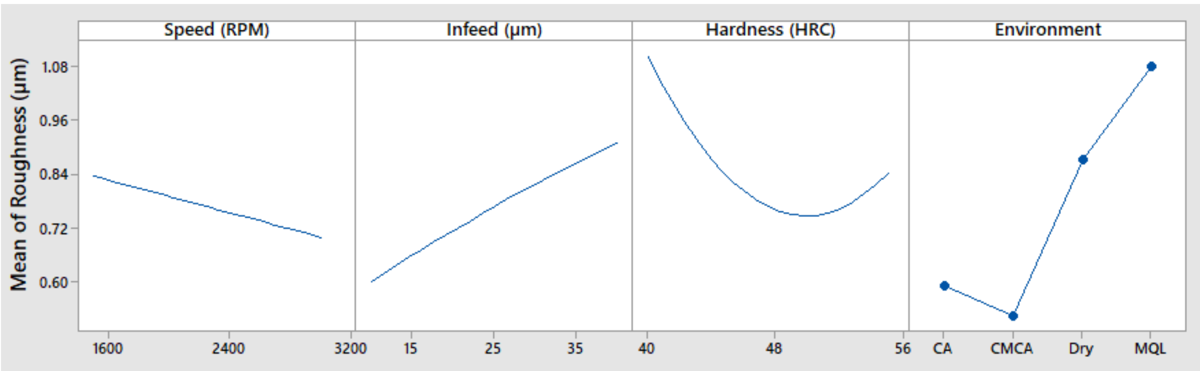



**Fig. 4.6** Main effects plot for surface roughness

Interaction plot shows the combined effect of input parameters on output response. Fig 4.7 delineates the interaction plot i.e. interaction between speed and infeed, speed and hardness, speed and environment; infeed and hardness, infeed and environment; hardness and environment.

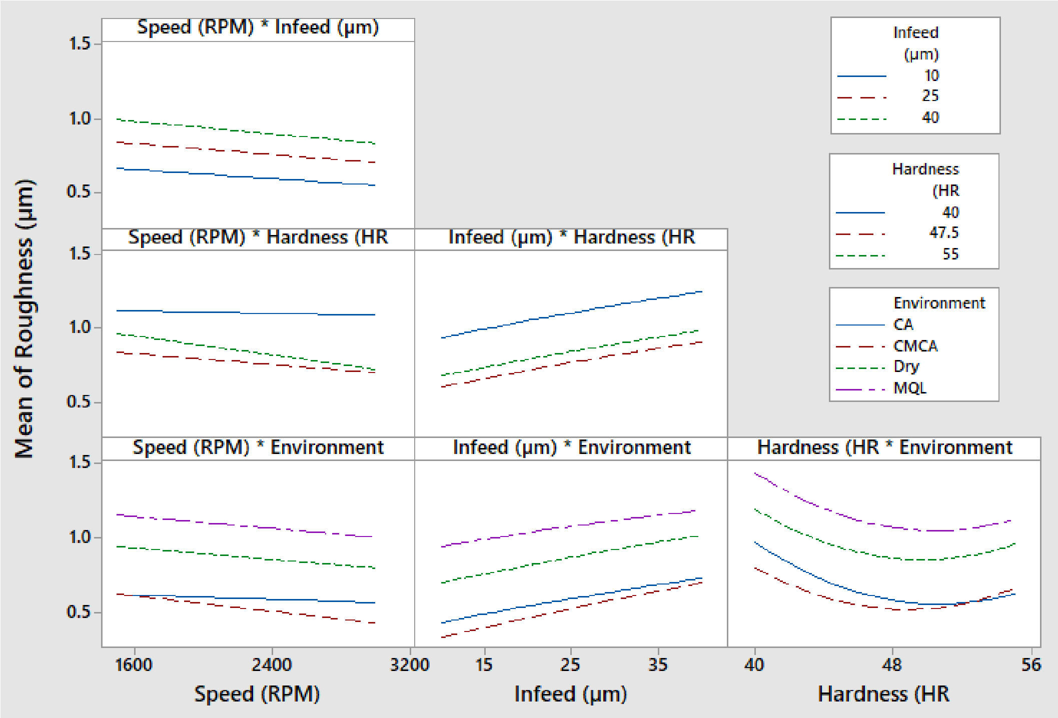



**Fig. 4.7** Interaction plot for grinding zone temperature

From the interaction plot it can be decided that form interaction between infeed and environment (CMCA), the interaction between hardness and environment (CMCA and Dry) are mostly significant. Other than these two interaction effects speed and infeed is moderately significant. A second-order mathematical model is developed and validated with experimental data to understand the significance of the interaction term as well.

Fig. 4.8 shows all the three surface roughness distributions of this analysis at a glance. Rather than showing a particular point, contour plot shows a range of points (a region) for optimum response values.

In case of surface roughness distribution against infeed and grinding wheel speed, the other two factors were kept fixed (material hardness at 47.5 HRC and environment at compressed air). The distribution indicates that the surface roughness value is lowest (lower than 0.45 μm) for wheel speed of 1600 RPM to 3000 RPM and the infeed of 10 to 12 μm.

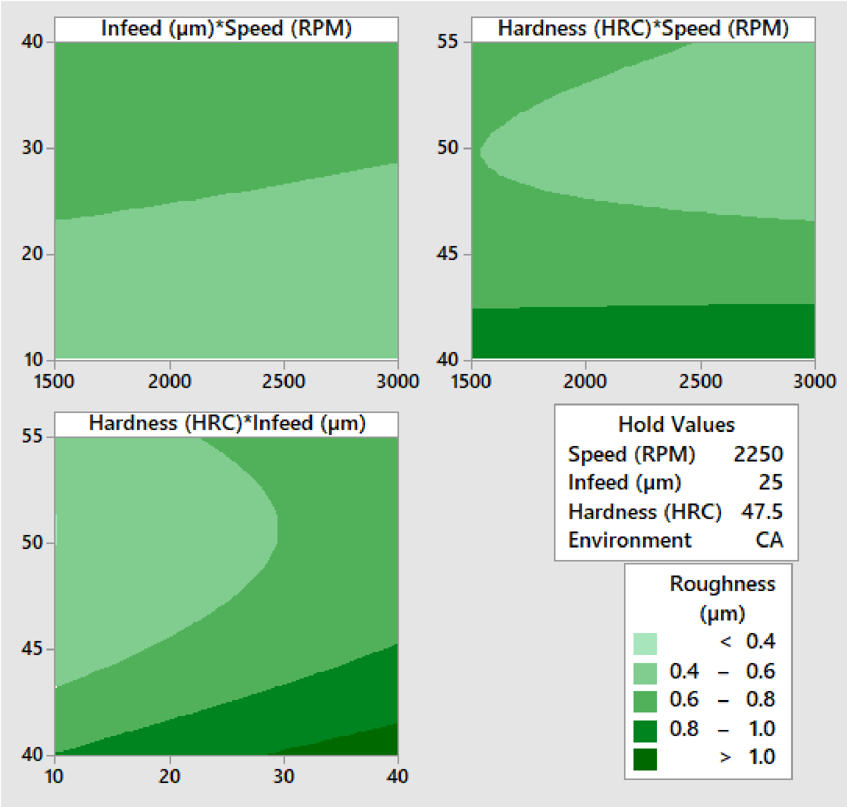
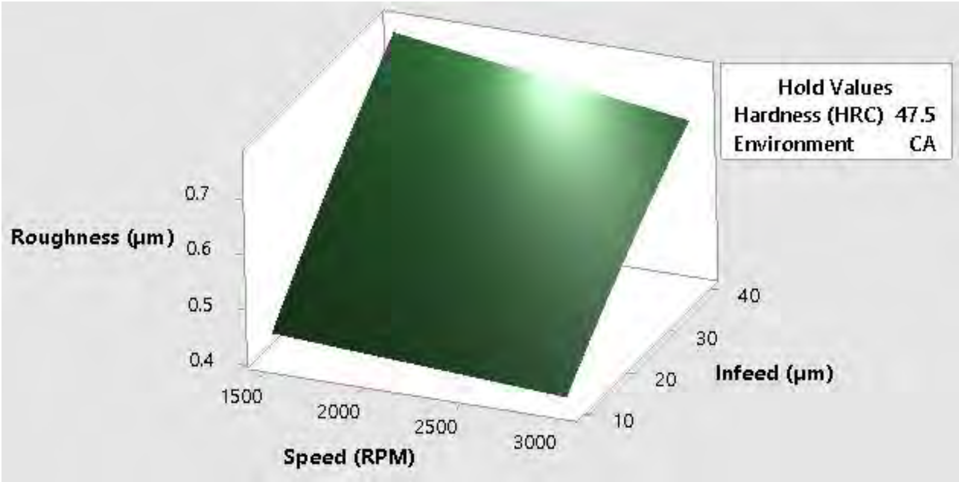



**Fig. 4.8** Computed surface roughness distribution against infeed, wheel speed, material hardness and environments

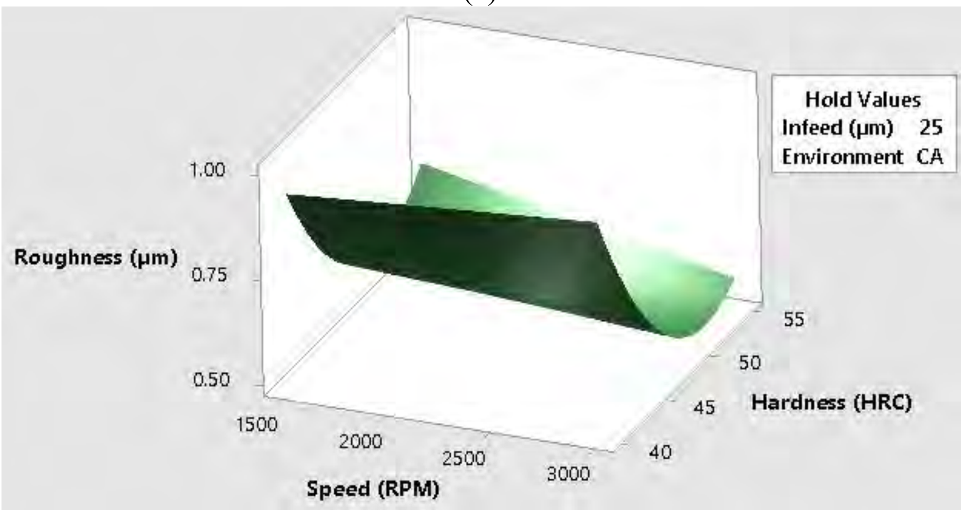
In case of surface roughness distribution against material hardness and grinding wheel speed, the other two factors were kept fixed (infeed at 25 µm and environment at compressed air). The distribution indicates that the temperature value is lowest (lower than 0.6 µm) for wheel speed of 1550 RPM to 3000 RPM and a material hardness of 47 to 55 HRC.

For surface roughness distribution against material hardness and infeed, the other two factors were kept fixed as well (wheel speed at 2250 RPM and environment at compressed air). The distribution indicates that the temperature value is lowest (lower than 0.40 µm) at the region of infeed of 10 to 30 µm and a material hardness of 43 to 55 HRC.

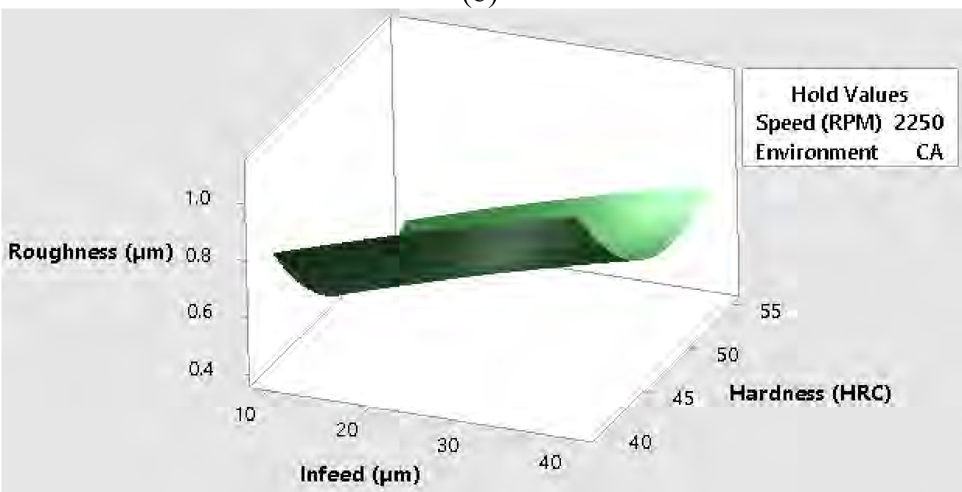
Surface plots are another three dimensional plot which represents surface roughness against different independent variables combination. Among the four predictors here in our analysis, two of them are kept constant and the other two are varied each time to see the effect on surface roughness. Fig. 4.9(a) shows the surface plot of surface roughness with variable infeed and wheel speed. Hardness and environment is kept constant at 47.5 HRC and compressed air respectively. It is observed from the plot that surface roughness does not increase with the increase of wheel speed. But, surface roughness significantly increases with the increase of infeed.




(a)




(b)




(c)

**Fig. 4.9** Surface plot of surface roughness with infeed, wheel speed and hardness under compressed air condition

Fig. 4.9(b) shows the surface plot of surface roughness with variable material hardness and wheel speed. Infeed and environment is kept constant at 25 μm and compressed air respectively. It is observed from the plot that surface roughness decreases with the increase of material hardness upto 50 HRC but there is isignificant change in surface roughness with the change in wheel speed.

Fig. 4.9(c) shows the surface plot of surface roughness with variable material hardness and infeed. Wheel speed and environment is kept constant at 2250 RPM and compressed air respectively. It is observed from the plot that surface roughness decreases with the increase of material hardness upto 50 HRC and increase with the increase of infeed If the hardness is further increased beyond 50 HRC then the temperature starts to increase as well.

Four separate mathematical model were developed for four different environments which are shown in Equation 4.13-4.16

| **Environment** | **Regression Equation** |
|---|---|
| CA | R = 8.166 + 0.000508 V + 0.01776 F - 0.3324 H - 0.000061 F*F + 0.003520 H*H - 0.000001 V*F - 0.0000011 V*H - 0.000039 F*H...(4.13) |
| CMCA | R = 7.471 + 0.000424 V + 0.02051 F - 0.3165 H - 0.000061 F*F + 0.003520 H*H - 0.000001 V*F - 0.0000011 V*H - 0.000039 F*H...(4.14) |
| Dry | R = 8.215 + 0.000447 V + 0.01856 F - 0.3251 H - 0.000061 F*F + 0.003520 H*H - 0.000001 V*F - 0.0000011 V*H - 0.000039 F*H...(4.15) |
| MQL | R = 8.734 + 0.000444 V + 0.01605 F - 0.3302 H - 0.000061 F*F + 0.003520 H*H - 0.000001 V*F - 0.0000011 V*H - 0.000039 F*H...(4.16) |

Here,

T = grinding zone temperature

V = grinding wheel speed

F = infeed

H = workpiece material harndess

The four cutting environments under which investigation was done,

CA = Compressed Air

CMCA = CNT MQL with compressed Air

Dry = Dry Condition

MQL = Minimum Quantity Lubrication

The analysis is done in terms of uncoded units. The term $R^2$ indicates the amount of variation of the response variable which can be explained by its relations with the input variables. The better the $R^2$ value, the better the fitness of the model with the data. Predicted $R^2$ is the measure of how well a new response value can be predicted with the given model. Predicted $R^2$ has the ability to reduce overfitting as it includes the points which are not included in the model estimation.

Overfitting refers to failing to predict the value of the response outside of the data set though it can explain the response values within the data set quite satisfactorily. Here the Predicted $R^2$ values are 84.83%. S value is 0.000265, $R^2$ value is 89.49 and $R^2$ (Adj.) value is 87.53%. It could have been better if some more data is included. There may have some physical error too during the data acquisition process. Detailed statistical analysis has been given in Table 4.3.

**Table. 4.3** Regression Table for Surface Roughness Model

| Term | Effect | Coef | SE Coef | T-Value | P-Value | VIF |
|---|---|---|---|---|---|---|
| Constant | | 0.7684 | 0.0200 | 38.47 | 0.000 | |
| Speed (RPM | -0.13594 | -0.06797 | 0.00983 | -6.91 | 0.000 | 1.00 |
| Infeed (μm) | 0.3066 | 0.1533 | 0.0132 | 11.62 | 0.000 | 1.00 |
| Hardness (HRC) | -0.2599 | -0.1299 | 0.0132 | -9.85 | 0.000 | 1.00 |
| Environment | | | | | | |
| CA | -0.3494 | -0.1747 | 0.0170 | -10.26 | 0.000 | 1.50 |
| CMCA | -0.4838 | -0.2419 | 0.0170 | -14.20 | 0.000 | 1.50 |
| Dry | 0.2081 | -0.1041 | 0.0170 | 6.11 | 0.000 | 1.50 |
| Infeed (μm)*Infeed (μm) | -0.0239 | -0.0120 | 0.0221 | -0.54 | 0.590 | 1.00 |
| Hardness (HRC)*Hardness (HRC) | 0.40099 | 0.2050 | 0.0221 | 9.26 | 0.000 | 1.00 |
| Speed (RPM)*Infeed (μm) | -0.0217 | -0.0109 | 0.0132 | -0.82 | 0.412 | 1.00 |
| Speed (RPM)*Hardness (HRC) | -0.1037 | -0.0518 | 0.0132 | -3.93 | 0.000 | 1.00 |
| Speed (RPM)*Experimental Cond. | | | | | | |
| CA | 0.0828 | 0.0414 | 0.0170 | 2.43 | 0.017 | 1.50 |
| CMCA | -0.0616 | -0.0308 | 0.0170 | -1.81 | 0.074 | 1.50 |
| Dry | -0.0084 | -0.0042 | 0.0170 | -0.25 | 0.805 | 1.50 |
| Infeed (μm)*Hardness (HRC) | -0.0028 | -0.0014 | 0.0177 | -0.08 | 0.937 | 1.00 |
| Infeed (μm)*Experimental Cond. | | | | | | |
| CA | -0.0107 | -0.0053 | 0.0229 | -0.23 | 0.816 | 1.50 |
| CMCA | 0.0594 | 0.0297 | 0.0229 | 1.30 | 0.196 | 1.50 |
| Dry | 0.0133 | 0.0067 | 0.0229 | 0.29 | 0.771 | 1.50 |
| Hardness(HRC)*Experimental Cond. | | | | | | |
| CA | -0.0870 | -0.0435 | 0.0229 | -1.90 | 0.060 | 1.50 |
| CMCA | 0.1181 | 0.0591 | 0.0229 | 2.58 | 0.011 | 1.50 |
| Dry | 0.0225 | 0.0113 | 0.0229 | 0.49 | 0.624 | 1.50 |

Here, P-value is the indicator of which effects are the most significant. If the P-value is less than 0.05 then that effect is significant. It can be easily seen form the table that among the four independent parameters, wheel speed, material hardness and the environments are significant. The confidence interval for this analysis is assumed to be 95%. All the environments are significant as their P-values are away less than 0.05. VIF is the variance inflation factor which is the measure of the increase of the variance of the estimated regression co-efficient because of co-linearity. It can be found out by dividing the variance of the model with multiple terms with the variance of the model with single term alone.

Analysis of variance (ANOVA), shown in Table 4.4 is also used to investigate the model relationship between the input parameters (predictor variables) and the output responses. Unlike regression analysis, predictors in ANOVA are categorical (qualitative) variables and the nature of relationship cannot be determined as the co-efficient of the variables are not included in the model.

**Table. 4.4** Analysis of Variance (ANOVA) for Surface Roughness Model

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 20 | 10.1480 | 0.50740 | 45.98 | 0.000 |
| Linear | 6 | 8.8077 | 1.46796 | 133.03 | 0.000 |
| Speed (RPM) | 1 | 0.4911 | 0.49113 | 44.51 | 0.000 |
| Infeed (μm) | 1 | 1.4749 | 1.47490 | 133.65 | 0.000 |
| Hardness (HRC) | 1 | 0.9713 | 0.97127 | 88.02 | 0.000 |
| Environment | 3 | 5.5201 | 1.84003 | 166.74 | 0.000 |
| Square | 2 | 0.9181 | 0.45905 | 41.60 | 0.000 |
| Infeed (μm)*Infeed (μm) | 1 | 0.3344 | 0.00440 | 0.40 | 0.529 |
| Hardness (HRC)*Hardness (HRC) | 1 | 0.9050 | 0.90502 | 82.01 | 0.000 |
| 2-Way Interaction | 12 | 0.4488 | 0.03470 | 3.39 | 0.000 |
| Speed (RPM)*Infeed (μm) | 1 | 0.0147 | 0.01468 | 1.33 | 0.252 |
| Speed (RPM)*Hardness (HRC) | 1 | 0.2373 | 0.23733 | 21.51 | 0.000 |
| Speed (RPM)*Environment | 3 | 0.0639 | 0.02130 | 1.93 | 0.130 |
| Infeed (μm)*Hardness (HRC) | 1 | 0.0006 | 0.00065 | 0.06 | 0.809 |
| Infeed (μm)*Environment | 3 | 0.0323 | 0.01076 | 0.98 | 0.408 |
| Hardness (HRC)*Environment | 3 | 0.1115 | 0.03718 | 3.37 | 0.022 |
| Error | 97 | 1.0704 | 0.01104 | | |
| Total | 117 | 11.2184 | | | |

Let us explain the terms of ANOVA step by step. Sources stand for source of variation which may be factor, the interaction or the error. The sum of all sources in included in “total”. DF is the degrees of freedom for each source. For a factor having n levels, the degrees of freedom is (n-1). There are 118 observations for this analysis. So, the degrees of freedom are 117. SS is the sum of squares among the groups and the sum of squares within the groups as well. MS refers to Mean Square. It can be found by dividing the SS (Sum of Squares) by DF (Degrees of freedom). F-values are obtained by dividing the factor MS (Mean Squares) by the error is MS. These F-values are compared against critical F-values to determine whether the factor or the interaction is significant or not. P-values can also be used for this purpose. Usually, a factor or an interaction having P-value less than 0.05 is significant.

## 4.3 Validation of Temperature and Surface Roughness Model

In order to validate the model, the measured cutting temperature for grinding AISI 1060 steel by CBN grinding wheel at different combination of cutting parameters has been compared with the predicted temperature. The cutting condition was CMCA. Table 4.5 shows the different combination of cutting conditions against which the experimental temperatures and predicted temperatures were compared.

**Table. 4.5** Test condition for temperature validation

| Test No. | Speed (RPM) | Infeed (µm) | Hardness (HRC) |
|---|---|---|---|
| 1 | 1500 | 10 | 40 |
| 2 | 3000 | 10 | 40 |
| 3 | 3000 | 30 | 40 |
| 4 | 1500 | 20 | 45 |
| 5 | 3000 | 20 | 45 |
| 6 | 1500 | 10 | 50 |
| 7 | 1500 | 30 | 50 |
| 8 | 3000 | 30 | 50 |
| 9 | 1500 | 40 | 55 |
| 10 | 3000 | 40 | 55 |

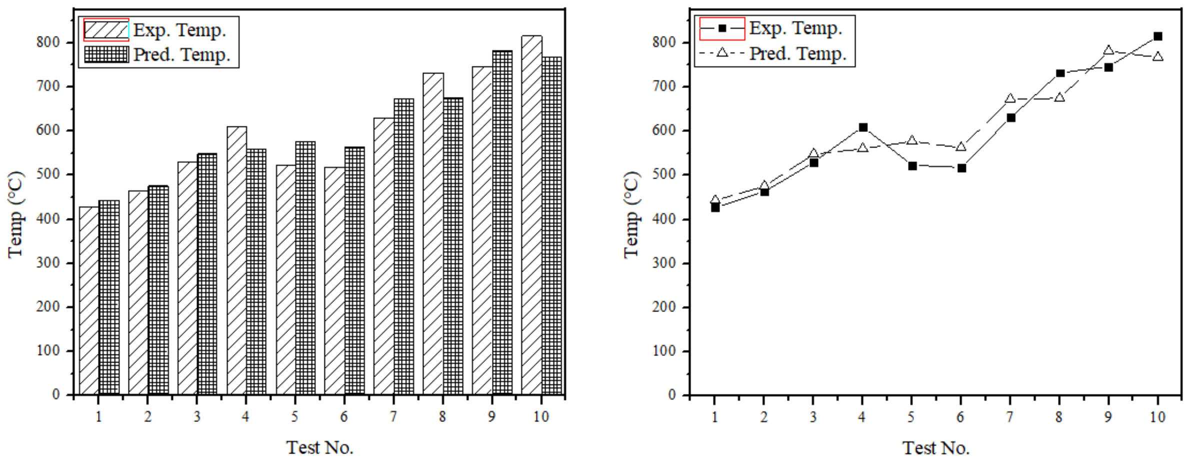
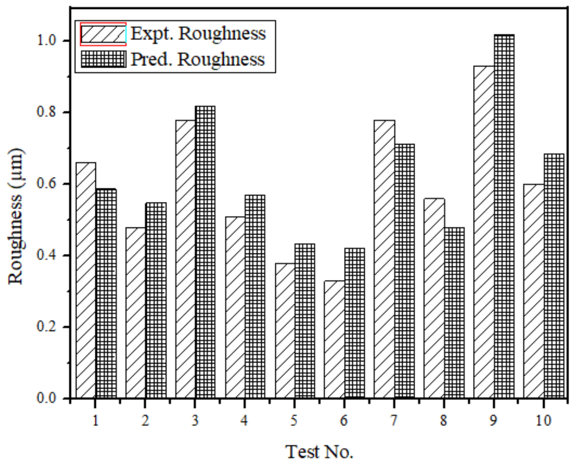



**Fig. 4.10** Comparison of experimental temperature with predicted temperature for wheel under pulse jet CMCA cutting condition

In order to validate the model, the measured surface roughness for grinding AISI 1060 steel by CBN grinding wheel at different combination of cutting parameters has been compared with the predicted surface roughness. The cutting condition was CMCA. Table 6.4 shows the different combination of cutting conditions against which the experimental surface roughness and predicted surface roughness were compared.

**Table. 4.6** Test condition for surface roughness validation

| Test No. | Speed (RPM) | Infeed (μm) | Hardness (HRC) |
|---|---|---|---|
| 1 | 1500 | 10 | 40 |
| 2 | 3000 | 10 | 40 |
| 3 | 3000 | 30 | 40 |
| 4 | 1500 | 20 | 45 |
| 5 | 3000 | 20 | 45 |
| 6 | 1500 | 10 | 50 |
| 7 | 1500 | 30 | 50 |
| 8 | 3000 | 30 | 50 |
| 9 | 1500 | 40 | 55 |
| 10 | 3000 | 40 | 55 |



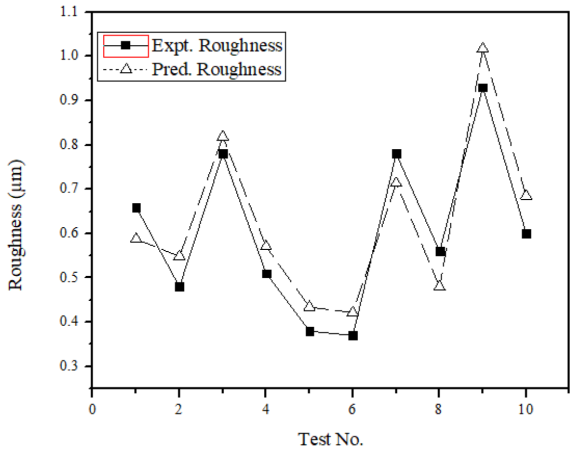




**Fig. 4.11** Comparison of experimental surface roughness with predicted surface roughness for wheel under pulse jet CMCA cutting condition

# Chapter-5

## Discussion on Experimental Results

### 5.1 Grinding Zone Temperature

Grinding temperature is one of the major factors which affect the performance of the workpiece material directly. Generation of the huge temperature can largely be attributed to the friction and the rubbing of the abrasive grains with the workpiece material. At every pass of the grains over the surface of the material, some portion of the material is removed. All the grains of the wheel surface are not involved with this task of chip removal. In down cut grinding, material removal occurs to the greatest extend at the beginning of the action as maximum penetration is happened at that time. Grinding force is normally lower and it results low wheel wear and surface roughness. On the other hand, in case of up-cut grinding maximum penetration occurs at the end of the action and thus maximum chip removal takes place at that time. High temperature during the grinding action severely deteriorates the performance of the workpiece material and tool life. A large amount of residual stress is accumulated that restraints its high performance application. Grinding is a surface finish operation which means this operation is done on the workpiece as the last operation before using the material. So, this sort of property deterioration is highly undesirable. So, the main concern of the present work is to find out the technique and the best combination of the grinding parameters to reduce this threat. Traditional flood cooling can cool the workpiece to some extend but its lubrication capability is not well enough. As the infeed increases it becomes tougher for the cutting fluid to penetrate into the wheel-work interface. The health hazard, expensiveness and wastage are several significant issues which have discussed earlier. For these reasons Minimum Quantity Lubrication has taken the place and this has also been modified for many more special operations. For this present work, MQL technique has been applied with pulse jet applicator for two different wheel speed, four different infeed, four different hardness levels and four different cutting conditions with CBN grinding wheel and AISI 1060 steel. Embedded thermocouple technique was used for measuring the grinding zone temperature. In this technique the constantan wire was placed in a slot on the workpiece with proper insulation and the copper wire was attached to the material. The other ends of the constantan and the copper wire were connected to the multi meter where temperature readings were obtained in mili-volt unit which were converted to degree Celsius unit with proper calibration curve. Detailed description of thermocouple fitting technique was explained in section 3.3.1 of chapter 3. The grinding zone temperature was plotted against different wheel speed, material hardness and machining environment [Fig. 3.7 -Fig. 3.10]. From all of those plots, it can be concluded that grinding temperature increases with the increase of the infeed as the material removal rate is high and energy consumption is more. But this increase is low in case of MQL and CMCA condition than dry condition. Furthermore, it appears that CMCA condition generates the lowest temperature in highest infeed grinding (40 μm). Most of the time CMCA demonstrate the best performance among the four cutting conditions as far as the temperature is concerned but the CMCA works best at higher infeed and harder materials. There are several reasons of best result of CMCA. CMCM (CNT mixed MQL with Compressed Air) contains carbon nanotube which has excellent thermal conductivity around 37,000 W/m.K. So, it helps to reduce temperature quite significantly. Additionally, pulse jet helps to penetrate into the tool-work interface. Another thing is the compressed air which instantaneously removes the micro chips from the wheel pores keeping the grits as sharp as possible thus reducing friction. It can be stated without any hesitation that grinding zone temperature is highly influenced by the process parameters including the cutting environment. The variables like wheel speed, nature of abrasive, bonding materials, infeed, coolant properties, flow rate of the cutting fluid, nozzle diameter, speed of the flow, direction of the nozzle etc. plays a great role in controlling the grinding zone temperature.

Thermocouple setup method also influences temperature measurement technique. Accuracy in acquisition of temperature largely depends on the perfection of setting up the thermocouple. Thermocouple normally inserted into the workpiece creating a hole or slot. The slot properly insulated before inserting the constantan wire into it. 1 mm slot was cut to make the space for both wire and insulation sheet. The diameter of that wire which was used to cut the slot was 0.18 mm. The slot width was just enough to hold the constantan wire with mica sheet around it. During grinding when the grinding wheel used to touch the constantan tip, the hot junction was created there and an EMF was generated because of Seebeck effect. In this experimental investigation, grinding zone temperature of hardened AISI 1060 steel is measured at two wheel speeds, four cutting conditions and four different infeeds. Though in practical scenerio, grinding operation is not confined to these combinations of experiment, a good extend of knowledge is gained with the experience of this practical work. A number of grinding conditions are used in industries. Response Surface Methodology (RSM) model has been produced to predict temperature values of various combination of wheel speed, infeed and material hardness. The developed mathematical equation from 4.9 to 4.12 can predict the temperature values with good accuracy. Main effect plot [Fig 4.2], interaction plot [Fig. 4.3], computed temperature distribution [Fig 4.4] and surface plots [Fig. 4.5] explain the relationship between individual input parameters with the obtained grinding zone temperature with reasonable accuracy.

## 5.2 Surface Roughness

Grinding is popularly considered as the final finishing operation because of its ability to fulfill the design and functional requirements. Surface finish is the most important criteria of evaluating a ground material as it directly affects other properties of the material service life of the ground material. In case of mechanical components, reliability is often depends on the surface finish of the material. In this research work, AISI 1060 steel is ground with CBN grinding wheel under dry, Compressed Air, MQL and CNT mixed MQL with Compressed Air condition after proper heat treatment to get four hardness levels (40, 45, 50 and 55 HRC). There were a number of overlapping scratches over the surface of the ground material. Fig. 3.14 to Fig. 3.17 show the variation of hardness of the ground material with variation of cutting speed, infeed and cutting conditions. In all cases, Compressed Air and CMCA condition demonstrated much better result than dry and MQL condition. The reason behind lower surface roughness is efficient lubrication and cooling condition. Proper lubrication facilitates the chips to slide smoothly over the material surface thus reducing friction and eventually the surface roughness. In case of CA assisted grinding, metal removal mainly takes place by the action of shearing and fracture. When material removal occurs due to plastic deformation, grain pull-out and ploughing, surface roughness it likely to be higher in those cases. Another thing to be observed is the surface roughness is lower in case of higher grinding wheel speed. In case of higher RPM, increased number of abrasive grains come in contact with the workpiece material surface and overlapping cutting occurs which eventually results smoother surface. There are some reasons of getting smooth surface in case of compressed air assisted grinding. Most of the times, grinding produces micro chips and that chip get clogged between the wheel grits. This phenomenon is known as wheel loading or wheel clogging. Roughness values increase with higher infeed. As more material is removed, grains penetrate deep and more chips get clogged into the wheel surface. For this reason higher surface roughness is created. Harness of the wheel grain also affects surface roughness. CBN grinding wheel is harder than conventional abrasive grains. So, they can retain their shape after a number of passes over the workpiece material which results in smooth surface finish.

Surface burn is noticed in case of dry condition grinding especially at high infeed and hardness. Burned surface becomes blackish. CA and CMCA conditions restrains burning of the surface as they retain the grain sharpness reducing rubbing and ploughing at high infeed unlike the dry conditions.

In this experimental investigation, surface roughness of hardened AISI 1060 steel is measured at two wheel speeds, four cutting conditions and four different infeeds. Though in practical case, grinding operation is not limited to these combinations of experiment, a good extend of knowledge is gained with the experience of this practical work. Numerous grinding conditions are used in industries liken automotive, aerospace, locomotive. Response Surface Methodology (RSM) model has been produced to predict roughness values of various combination of wheel speed, infeed and material hardness. The developed mathematical equation from 4.13 to 4.16 can predict the roughness values with good accuracy. Main effect plot [Fig 4.6], interaction plot [Fig. 4.7], roughness distribution [Fig 4.8] and surface plots [Fig. 4.9] explain the relationship between individual input parameters with the obtained surface roughness with reasonable accuracy.

## 5.3 Chip Morphology

The morphology of grinding chips which have been produced by different wheel speed, infeed, material hardness and cutting environment can be explained with the help of chip formation and material removal technique. SEM pictures of the chips are shown in Fig. 3.11 to 3.13. It has been observed that the chip of CA and CMCA produced relatively longer chips than dry and MQL condition. The chips are also less rough and of regular shape. Another visible thing is that due to infeed change there in no significant change in the chip morphology in terms of chip length and chip type. The only change which is noticeable is the chip width which is due to higher penetration. In case of dry grinding, chip formation is occurs due to shearing, ploughing and rubbing. For this reason the chips are rough, small and irregular shaped.

It can be summarized from the microscopic study of the chips that, the best quality of grinding chips are obtained in case of CMCA machining conditions. Chips were curly and thin. Cutting edges were as sharp as knife. These chips are flowing type chips. When grinding was done under MQL cutting conditions, the obtained chips were relatively wider and globular than other chips types. These types of chips are called shearing type chips. In case of Compressed Air assisted machining a special type of chips was generated which had subsurface layer and scratch mark over the chip generating direction. They were knife type chips. However, dry machining produced ground surface with poor surface finish. Most of the cases the chip surface were burnt. These chips were ripping type chips.

# Chapter-6

# Conclusions and Recommendations

## 6.1 Conclusions

The present work is solely dedicated to the practical investigations of grinding zone temperature and surface roughness by developing valid mathematical model. These models predict the two key responses with reasonable accuracy at various cutting conditions. Grinding of AISI 1060 steel is done with CBN grinding wheel. Mathematical model is then developed using Minitab 17 software package. The model is then verified experimentally. This work is mainly experimental but statistical analysis has been done to set up relationship between the wheel speed, infeed, material hardness and cutting condition with the grinding zone temperature and surface roughness. The following conclusions can be done based on the experimental investigation and statistical analysis of the present work:

- Grinding operation generates extensive amount of heat due to the friction of the grinding wheel with the workpiece material. This heat is carried out by the workpiece itself, grinding wheel, the formulated chips and the cooling fluid. This excessive temperature deteriorates the performance and longevity of the material. The tool-work temperature increases with the increase of the infeed and material hardness. This increase is lowest in case of CA and CMCA cutting conditions.
- The chips of CA and CMCA conditions are relatively longer and laminar than dry and MQL conditions. Efficient lubrication action and retention of the grains shape are the reasons for this.
- Surface roughness of the ground material (AISI 1060) was checked and CMCA cutting condition demonstrated the best surface finish. Surface roughness increases with the infeed, wheel speed and the material hardness.

- Using the experimental data Response Surface Methodology (RSM) model has been formulated for both grinding zone temperature and surface roughness in case of CBN grinding wheel and AISI 1060 steel. From ANOVA (Analysis of variance) table of both the models, it can be said that wheel speed, infeed and cutting conditions all are significant factors for the output responses. Among the interaction terms, interaction between infeed and environment; and interaction between hardness and environments are significant for both the temperature model and surface roughness model.

## 6.2 Recommendations

- Performance of carbon nanotube (CNT) in grinding is very fruitful. There are many other nanoparticles (silver, titanium, zinc etc.) which could be mixed with straight cut cutting oil and their performance can be tested doing some experimental investigations.
- Experimental investigations were done with two levels of wheel speed, four levels of infeed, four levels of cutting condition and four levels of hardness. Some more parameters could have been included in the RSM model like wheel abrasive grain material, cutting oil, nozzle dimension and orientation etc. to make the analysis much more viable.
- Workpiece material was AISI 1060 steel for this analysis but some other modern application material like titanium alloy, Inconel 718 etc. aerospace material could be used instead of AISI 1060 steel.
- Number of pulse of the pulse jet MQL applicator could have been varied to observe the result.

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